The Cosmic Serpent
Dis (evil) aster (star) [A nineteenth-century French caricature]
We dedicate this book to our Other Halves
Moira Clube and Nancy Napier
without whose perpetual encouragement
*The Cosmic Serpent* might never have uncoiled itself.
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Prologue

‘If the doors of perception were cleansed, everything would appear to man as it is, infinite.’

William Blake, The Marriage of Heaven and Hell

In this book we bring together hitherto unconnected strands in astronomy, biology and geology, and in the early history and mythology of man.

The unifying theme is the comet, currently thought of as a minor actor in the cosmic drama. We shall propose that it grows out of the cold, dense nebulae found in interstellar space; is captured into the solar system during a close encounter; and if not flung out again, is thrown either into the space between Mars and Jupiter where it becomes an asteroid, or into an orbit which will bring it eventually, in the form of an asteroid, into collision with a planet.

If the planet is the Earth and the asteroid of modest dimensions, the impact destroys life on a global scale and may initiate an ice age. Such visitations are not uncommon on geological timescales and we shall argue that they have played an important and yet unrecognized part in the evolution of life and the history of the Earth. Smaller collisions, catastrophic over say the area of a small nation, are much more common and bring us into the timescale of human existence. We propose that these have occurred in prehistoric and early historic times, and we interpret Biblical and mythological narrative as faithful records of past catastrophes. In this sense a catastrophist view is taken inter alia of biological evolution, geological phenomena, and the ancient history of at least the Mediterranean and Near Eastern peoples.

Of course nothing is really new and the belief that, for instance, comets might sometimes crash on to the Earth took root in the minds of scientific people almost 300 years ago. Thomas Wright wrote around 1755: ‘That comets are capable of destroying such worlds as may chance to fall in their way is, from their vast magnitude, velocity, fiery substance, not at all to be doubted.’ Fifty years later Laplace thought that ‘The seas would abandon their ancient positions, in order to precipitate themselves towards the new equator; a great portion of the human race and the animals would be drowned in the
universal deluge, or destroyed by the violent shock imparted to the terrestrial globe: entire species would be annihilated... and so on. With the data available in the nineteenth century, these ideas could only be speculation, and they were soon lost, submerged by the bold concepts of uniformity and evolution. But the great explosion of astronomical and other knowledge of the past few years has enabled us to put such early speculations on a scientific footing, and in the pages which follow our debt to scientists and scholars in many fields will be in no doubt.

But this explosion has brought with it a severe problem. No one individual has the breadth of knowledge to analyse, in full scholarly depth, more than a fraction of the evidence which can be brought to bear on the theme. On the other hand ever-increasing specialization of knowledge is a recipe for sterility and error: sterility because the comprehensive picture may go unrecognized, and even if it does not, error because the specialist will tend to over-emphasize the significance of this or that datum in his own field. The specialist is right to attach importance to details; but one does not judge the theory of evolution simply by its application to the flying squirrels of Eastern Asia.

We offer no solution to this problem. Certainly we do not urge the reader to agree with everything we have written, as inevitably any attempt to deal with such a wide range of material, most of it outside our own specializations, will have many shortcomings: the important thing is the overall view. We do urge the reader to assess the evidence in its totality, however, and to be wary of any 'consensus' of opinion which, often as not, seems to be based on little more than historical inertia: the primordial cloud of comets around the Sun, and the standard Egyptian chronology, may be cases in point. We urge the reader because, if he will bear with us, he will see in the end that we deal not just with esoteric theories and a world light years away, but with events in human history and facts that might materially affect the way we perceive our future on this planet. Crystal-ball gazing is not our business however, it is simply to expose the past and its rationale. That critical analysis of this rationale has become a matter of urgency will, we hope, speak for itself. But we do not take it for granted: even the guardians of knowledge, we are aware, sometimes take facts as mere words or statistics to be woven in whatever pattern they please. And if what is observed, namely catastrophism, disturbs the peace of mind, there can be a tendency to reject reality itself. The history of human thought shows that false patterns can survive for...
centuries while new discoveries, instead of correcting the errors, merely heap complexity upon complexity. If man becomes baffled by the convolutions of thought thus entailed, there tends to emerge a deepening conviction that forces for ever beyond his ken are controlling an essentially mysterious universe. Indeed, it is even possible to be so preoccupied with the logical niceties of an abstruse, fictitious paradise that one can lose sight altogether of the slings and arrows of the real world. So we urge the reader to keep in mind that there were mistaken defenders of Ptolemy’s epicycles in days gone by. Let us not forget that it is often only by *ex cathedra* statement that things like epicycles acquire a permanence and a reality that they might otherwise not have. By such means, black can become white and, more relevant to our theme, a disproof of Velikovskian logic can deprive ancient legends of their catastrophic message.

If then, in part, it is the thought of catastrophism that disturbs, we feel bound to remind the reader that the real, objective world is not in the end a matter of taste; it works only one way and no amount of wishful thinking can alter the reality. The aim of the scientific analyst, be he astronomer, geologist, archaeologist, historian or whatever, is simply to sift the evidence and search for that reality, establishing it all the while as fact with ever-increasing probability. His methods may or may not be the reader’s, but the truth in the end transcends them both. So, in urging the reader to bear with us, we hope he will recognize that there are greater things at stake than merely his bewilderment or our failings in the use of words.

*The Cosmic Serpent*, then, is a reconstruction of knowledge in several fields, an adventure in paradigm. There is something here to outrage everyone.
I. Universe to galaxy: the cosmic framework

We start with a brief review of cosmology and galactic astronomy. It is all too easy to picture our terrestrial base as virtually isolated from the remainder of the universe, so our aim in this first chapter is to see how the average galaxy works and then establish a connection between our Galaxy and the solar system. We shall look at the modern theory of galaxies with the wary eye of a sceptic, but in due course concentrate the reader's attention on the problem of spiral arms. Spiral structure is an important part of galactic machinery and we discuss two possible ways in which it might be formed. We draw particular attention to interstellar comets as constituents of spiral arms: it seems very likely that aggregations of interstellar comets are the precursors of star formation. We recognize the periodic capture of comets by the solar system as it circulates through the spiral arms in our Galaxy as a process of fundamental importance.

1.1 The universe: facts and fancies

Not so long ago, most people lived their entire lives in the vicinity of the town or village where they were born. Transport was by horse or on foot: one might have waited a decade or more for the explorer of distant lands to return. The Earth, then, must have seemed unimaginably vast; probably only the sailor or the desert nomad had even a partial grasp of terrestrial distances. But now we measure an Atlantic crossing for instance in hours. The aeroplane has done much to put our base in perspective. The size has not changed; but custom and usage have enabled us better to grasp the dimensions. So it is with the universe. Familiarity with the building blocks soon overcomes the otherwise impossibly huge scale of things. So let us start with a brief look at the modern astronomer's cosmic laboratory, and learn our way around.

Although the terrestrial globe is nearly 13,000 km across, it dwindles to a mere point against the distance at which it circles the
Sun. This distance is not far short of 150 million km, or 8 light minutes, but even this is only a small fraction of the distance to the outermost planet of the solar system. At around 6 billion km, light takes nearly 44 hours to reach Pluto. But we have hardly begun: the stars nearest to the Sun are still several light years away.

On such a scale of things, the Sun becomes but a tiny speck, notwithstanding its mass and volume exceeding those of the Earth by nearly a million-fold. The Sun is, of course, the dominant source of gravity in the solar system and effectively controls the planetary orbits. The planets, as it happens, all circulate in the same direction, and from our vantage point they are also seen to be confined to a rather narrow band in the sky called the zodiac. But why the solar system should rotate like this and be so flat is not immediately obvious. After all, the gravity field is spherical in structure and we can easily imagine planetary orbits randomly distributed in space going in all directions. Here then, we have significant facts which we might expect to explain only by understanding the origin and history of the solar system. In no time at all, we are in the realm of astrophysics—how do we suppose stars are made, and where do the planets come from? It is to questions like these that we shall turn first of all. And even though there is no definite answer, there is no doubt that the modern astronomer has a great deal to tell.

From radioactive dating of meteorites and the oldest rocks on Earth, we are aware that the solar system is of great age: it was formed something like 4.5 billion years ago. During this time, life has evolved on Earth, and the Sun has burned up quite a bit of its hydrogen content, producing radiation all the while. But all this happens in what is but a microcosm in the midst of a great galaxy of stars. Among these stars, our Sun turns out to be neither particularly distinguished nor particularly venerable. Thus, most of the stars that make up the Galaxy are two or three times older than the solar system, whilst the very brightest stars—which can be a million times more luminous than the Sun—are only a few million years old. In a short time, galactically speaking, these bright stars will burn up and some more will be formed. Quite simply then, we are in a solar system that somehow evolves, and the solar system is itself immersed in an ever-changing galaxy.

It is difficult to picture the great size of our Galaxy. The distance from star to star is on average a few light years, or in astronomer's units, about a parsec (3.3 light years). The stars we see with the naked eye, of which there are about 5,000, lie mostly within a few hundred
The cosmic framework of the Sun. But by far the great majority, 100 billion or so, are very much further off and in the Milky Way. It is substantially this band of light that is our Galaxy: a vast rotating disc of stars carrying with it also a certain amount of gas and dust, the whole system being 20 kiloparsecs or so in diameter. And then, almost as if this were not enough to overcome any lingering sense of our self-importance, there is beyond the Galaxy, and dwarfing it to complete insignificance, a universe of seemingly limitless proportions, containing million upon million of galaxies like our own. In any direction these galaxies extend for as far as the telescope can reach, certainly beyond a billion parsecs. They are apparently spread around in a more or less random way but even they would have a feeling of isolation if they were capable of thought since they occupy only a millionth or so of the available space. As one looks at photographs of this scene (Plate 1), it is all too easy to imagine these galaxies hang for ever in empty space just as we observe them, but that is simply an illusion created by distance and time. In fact, the whole display is a maelstrom of motion, each galaxy speeding along a path mapped out for it by the ever-changing but unseen gravity field of its surroundings. Just as we are tied to the Earth, so is the Earth to the Sun, the Sun to the Galaxy, and the galaxies to one another. Everything in the universe, then, is controlled by the all-pervasive hand of gravity.

In the space between the galaxies there are many smaller systems of various kinds, such as intergalactic clusters, minor galaxies, streams of gas and the like. But these are mostly invisible except as companions to the very nearest galaxies, and can be safely neglected in the following discussion. Despite the overall randomness, there is also an obvious tendency for galaxies to group together in clusters or cells of up to several thousand at a time. Our own Galaxy for example is a member of the so-called 'local group' and is an offshoot of the huge Virgo cluster. If our large motion with respect to the cluster is anything to go by, the system appears to be collapsing. But why galaxies should group, and possibly un-group, themselves like this rather than, say, just fill space uniformly is not yet understood. However, to the limit of observability, looking back through 1 or 2
billion light years, the clusters and their contents 'there and then' look very much the same as those 'here and now'. On this evidence and this scale at least, one might be led to believe the universe is more or less uniform in space and time, possibly of infinite extent and infinite age. Such uniformity inspires the so-called perfect cosmological principle, the belief that the universe presents the same general appearance to an observer in any place at any time.

However the light from galaxies is also found to be systematically shifted towards the red end of the spectrum by amounts that are proportional to their distances. This important fact has been known for nearly fifty years and has been generally interpreted as a doppler effect, that is as due to a velocity of recession: astronomers have come to accept that the universe is expanding uniformly in all directions. In that case, unless there is continuous creation of matter compensating the dilution with time and this idea is not now widely favoured—the universe is evolving and there can be no question of complete uniformity in space and time. This apparent and very immediate conflict between the simplest cosmological facts is the source of some quite fundamental difficulties in modern astronomy. Where in a stationary universe one might perhaps expect to see constancy and conservation on the largest conceivable scales, and fluctuation and deviation from the norm at smaller levels, the world view which most astronomers now tend towards is one in which there is unending change on the largest scale and a fair degree of permanence on the smaller one. Whether this topsy-turvy consensus will stand the test of time is still, in our view, an open question. Thus, where astronomers favouring an expanding universe tend to see all galaxies at the present epoch as mostly rather steady tranquil affairs with perhaps a more active phase discernible near the observational limit of our telescopes and confined to early on in the life of the universe, the observations, as we shall see, allow an alternative non-expanding view of the universe in which both nearby and remote galaxies periodically deviate from quiet to brief energetic states, being in this case much the same on average today as they were many aeons ago.

It is as well to remember for example that the idea of an infinite and basically non-evolving universe had begun to take root long before the above observations of uniformity had become available. This was at a time when it was thought the universe must go on working for ever like some huge and powerful perpetual motion machine. Towards the end of the last century, however, this idea had run into difficulties with the empirical second law of thermodynamics. Thus it
had become increasingly clear that it was a natural and inevitable property of all the machines we could study in the terrestrial laboratory that their energy eventually became randomized or degraded into heat. Bit by bit, the energy capable of doing productive work wasted away. The ultimate fate of the world seemed therefore to be to suffer a 'heat death'. Physicists were forced to accept what is called the law of increase of entropy (i.e. the irreversible dissipation of energy) on the largest scale and they became accustomed to the idea of an evolving universe. The ground was thus well prepared for the discovery of cosmic expansion. It follows then that if the large-scale uniformity referred to above, in space and time, were truly a fundamental fact, we might have to abandon the doppler interpretation of cosmological redshifts and the entropy problem could still be with us. The suspicion would be reinforced that, contrary to local thermodynamic laws, there exist places in the universe where entropy is reduced rather than increased, where dissipated heat energy is somehow collected and converted back into organized motion.

In this respect, one of the interesting surprises of modern radio astronomy is the quite extreme coldness of much material in the Galaxy and elsewhere. In optical astronomy, we have until quite recently been mostly conscious of only the hot parts like stars, and we have tended not to think about any colder stuff. Increasingly now however, astronomers are obliged to take note of matter that is very cold indeed—only a few degrees of absolute temperature at most. The question is how does it get so cold? For the most part, astrophysicists presume straightforward cooling by radiation, not a particularly non-random process. But it is interesting to speculate whether heat energy could somehow be fuelling organized motion. More and more now, astronomers are finding highly condensed stars in states approaching ultimate gravitational collapse. Many show signs of extremely rapid rotation. There is a suspicion that superstars of similar character may be formed in galactic nuclei. If these objects condense, gravity coupled with the conservation of angular momentum could be forcing heat energy back into rotational energy. Thus, although it is widely presumed at the moment that gravitationally collapsed objects always disappear into mysterious 'black holes', it is conceivable that, instead, this rapidly rotating material is thrown back into the universe in an extremely cold, condensed form perhaps as oppositely directed jets. Unfortunately, with the end-point of gravitational collapse as yet undecided, the complete pattern of evolution in the universe cannot be resolved. It seems that we cannot
avoid a paradox. If the universe is evolving and starts with a 'big bang',
then some singular initial state, unamenable to scientific enquiry, is
implied. If it is non-evolving, then thermodynamic laws are not
applicable on very large scales. Obviously there are big and important
mysteries here but the main point we wish to make is that it would be a
mistake to suppose modern astronomers have necessarily arrived at a
final and accurate picture of how the complete universe works. We
must continue to face facts keeping our minds and options as open as
possible.

This of course is not to advocate openness of mind to the point of
absurdity. The universe does have a unique explanation and it is
certainly not our intention here to suggest that almost any
explanation can be made to fit the available observations. There is a
definite requirement on scientists to seek the most probable
explanation in the light of all the data: it is this that the consensus of
scientific opinion normally represents, and it is this that the reader
would expect to see described. However, cosmology is an all-
embracing science and any single erroneous assumption at this level
can have far-reaching consequences throughout science. At this
particular level therefore, the responsible scientist has a special duty
to keep a wary eye on the possibilities that emerge if important
unsubstantiated assumptions are changed. In cosmology, there can be
no question that the single most important unsubstantiated
assumption is the velocity interpretation of cosmological redshifts,
and in this chapter, we shall be making a particular point of balancing
the standard paradigm against at least one alternative scenario that
could emerge if this assumption eventually proves to be erroneous. So
much for the widest arena in which we find ourselves—let us now
consider the character of the inmates.

1.2 Galaxies: gentle giants or temperamental monsters?
Although it is unfashionable, let us pursue, for the moment, the
possibility that cosmological redshifts are not a velocity effect but due
to some as yet unidentified influence on light as it journeys towards
us, in which case the expansion would not exist—the so-called 'tired
light' hypothesis. That the oldest stars have an age very roughly equal
to the expansion age of the universe has sometimes been taken to
mean there really was a big bang, but neither the distance scale nor
the theories of stellar nucleosynthesis have been well enough
established to make this line of argument secure. The kind of
observation that may settle the issue is a measurement of the light
Universe to galaxy: the cosmic framework

received from supernovae (exploding stars) in distant galaxies. If the universe were not expanding we would expect to see supernova explosions developing in distant galaxies at the same rate as those developing nearby. In an expanding universe on the other hand, the frequency of arrival of light waves would be diminished and the explosions would appear to be developing more slowly. But such information is not yet available, so most astronomers will for the time being probably hold on to the idea of expansion. And in these circumstances, they may well see it as confirmed by other kinds of observation. For example, it is now known that we are bathed in a uniform background radiation of very low temperature (3° absolute) coming from all over the sky at microwave frequencies. It has so far proved impossible to associate this very cold nearly ‘thermal’ radiation with any known material source and, since space is otherwise supposed to be empty—a very far-reaching assumption!—the microwave background has come to be accepted as a faint ‘echo’ of the big bang which is presumed also to have given rise to the general expansion. This is certainly a permissible speculation but it does not yet constitute a proof of expansion.

Another piece of evidence persuading modern astronomers that the universe is expanding and evolving relates to quasars. These objects are also far from being properly understood, but it is thought likely that most of them are exceedingly bright, highly energetic galactic nuclei, the parent galaxy usually being invisible. The quasars have very large redshifts. and inferring ‘doppler’ distances for them, astronomers place these objects at very large ‘look-back times’, so that they are supposedly now being seen as they were early on in the life of the universe. We can thus estimate their number density and brightness evolution with time far beyond the observable limit of ordinary galaxies. This way, the properties of the relatively few galaxies containing quasars can appear to be evolving. The argument would obviously cease to impress if the quasar redshifts were also due to some other cause like gravity. This is still an unsettled question in modern astronomy and is highlighted by observations of high redshift quasi-stellar objects (of which the quasars are a special category). Some QSOs for example are apparently associated with nearby, low redshift, galaxies. If there truly were physical connections then QSOs would not all be galactic nuclei and redshifts would not be a measure of distance. QSOs could not then be used as probes of remote regions of the universe. It is possible then that QSOs are evidence of the break-up of short-lived rapidly rotating
2. Six quasi-stellar objects in a small area of the sky less than a degree square. These are the brightest objects of their kind in the field but are nevertheless still very faint and at least as far from us as the furthest visible galaxies. Note the surprisingly accurate alignment of each triplet and the similar sequence of redshifts in each case. The redshifts are considered unlikely arrangements to occur by chance. The central object in each triplet may be a galactic nucleus at the distance indicated by its redshift whilst the aligned companions could be oppositely directed ejecta possessing large redshifts of unknown origin.
gravitationally collapsed nuclei recently or periodically formed in relatively nearby galaxies. The American astronomer Arp takes this view and attributes the excess redshift to special conditions in QSOs in which certain atomic constants are altered. He in fact still accepts expansion as the explanation of the underlying cosmological redshift, but speculates that the special conditions emerge in objects whose evolution has not got going until long after the big bang. It would probably be less upsetting to atomic physics however to think of QSOs as temporary very massive objects with excess redshifts created by the strong gravitational field. In this case, there is really no evidence from QSOs that we are dealing with an evolutionary universe, and the possibility that cosmological redshifts are not a velocity effect remains. The point again is that although a particular cosmological scenario may at this time have widespread support (i.e. an expanding universe of finite age with quasars all very old, no longer present in nearby galaxies), it is still only a hypothesis. The observational and theoretical foundations are not so secure that one can yet rule out alternative models (e.g. a stationary universe in which nearby galaxies can still produce temporary quasars in their nuclei). We have to be careful therefore that any preconceptions we may have about the universe at large do not force on us a particular view of the nature of galaxies that the observations do not exclusively support. The reader may find such ambiguities tiresome but they are common in sciences like astrophysics. Again, we must seek to avoid total commitment to a particular scenario and try to build our understanding of galaxies on the more unassailable facts.

We have said enough, however, to show that quasars are a crucial enigma in the modern universe. If the universe is expanding, quasars are evidence of a single blazing nucleus early on in the life of a galaxy. On this picture, each galaxy is thought to become comparatively tame thereafter. On the other hand, if the universe is in a steady state and not expanding, quasars can be interpreted as evidence of rather temperamental behaviour in nearby as well as remote galactic nuclei. Most of the while the galaxies are quiet but every 100 million years or so, the nucleus apparently flares up and destroys itself in a huge violent explosion lasting only a few million years. The choice then for the astronomer is between galaxies that are 'gentle giants' or 'temperamental monsters'.

All these problems simply set the scene however. They can be largely left to one side in these chapters. For our present purpose, it is sufficient to know that within certain limits, there is plenty of
evidence that most galaxies have retained more or less the same general appearance for several billion years. Furthermore, whether or not cosmic expansion is real, the effects are certainly small enough to make very little difference to the virtual isolation of many individual galaxies during this period of time. To a good working approximation then, every galaxy appears to be in a 'steady state' uninfluenced in the main by any external effects—it is, in essence, a virtually unchanging island in a sea of emptiness! Thus, although a careful look at the nearest galaxies, including our own, does reveal considerable movement and turmoil within, and there is the possibility of a periodically violent nucleus, we can deduce from cosmology that there is nonetheless a long-lasting regularity and order in all this motion. One of the principal aims of modern astronomy must then be to describe how this clockwork-like galactic mechanism functions.

1.3 Galactic machinery

The first fact of importance is that galaxies are composed mainly of stars. They also contain a significant fraction of gas and dust as well as a central nucleus. Their visual appearance however happens to depend to a large extent on the properties and evolutionary state of these secondary components. Indeed, whether or not it is detectable as a radio galaxy depends very much on its nucleus or its gaseous component. The underlying internal dynamics of galaxies are basically similar nevertheless, and are dominated by the stellar component which concentrates strongly towards the centre of a galaxy. The stars are for the most part bound to the system in a flattened spheroidal distribution, each one moving continuously in a large orbit under the control of the system's overall gravity. Some of the stars and most of the gas and dust make up a very flat disc which tends to project out of the spheroid.

Most galaxies are on the whole very like our own, that is of much the same mass and much the same size. But why galaxies should have their particular masses of a 100 billion suns and sizes of around 20 kiloparsecs is not yet known. The theoretical situation for galaxies thus contrasts very markedly with that for stars: for the most part, we can understand why stars have their particular masses and sizes. So, in describing the physical behaviour of galaxies, we have to accept rather severe boundaries to our knowledge at the present time. We can assemble into a composite picture only those properties that seem to have a coherent physical pattern. This is perhaps not entirely
Typical galactic disc observed 'edge-on'. Its catalogue number is NGC 5170. The surrounding stars are, as usual, foreground objects in our own galaxy. Note how the disc and its dust lane appear to project out of a central spheroidal component.

Spheroidal components are mostly composed of old ('red') stars whilst the discs include spiral arms containing very young ('blue') stars.

Satisfactory but it is the best that can be done in the circumstances. It seems the very bright nuclei of some galaxies, and the quasars, are merely the latest conundrum in a very old puzzle.

How are we to comprehend the presence of gas and dust in galaxies? Essentially it seems, they are part of the clockwork mechanism. We believe stars are somehow formed out of gas and dust, and many stars, we know, end their lives in explosions scattering their contents into the void. We thus imagine a cycle in which gas and dust go to stars and thence back to the interstellar medium. There is certainly a rough and ready agreement between the amount of gas and the starlight we observe, the latter being related to the rate at which stars evolve and die. But a problem is that astronomers have not yet really worked out how stars are formed. For this reason, we do not quite understand those somewhat less common galaxies, perhaps 20 or 30 per cent of the total, which have very little gas and dust. These are the so-called elliptical galaxies. Are they so old that most of
the stars, being less massive, are producing only a little gas? Is the gas perhaps being blown away by a strong wind from the nucleus? Or are the galaxies so young that they have not yet formed very much gas? It is difficult to be certain, especially when so many of these galaxies are apparently associated with quasars and huge double radio sources which have been shot out of their nuclei. On the one hand, the presence of such quasars might imply youth as their prodigal spending of energy cannot last; but on the other hand the colours of the stars tell us most of them are red giants which are known to be comparatively old. Thus although astronomers have arrived at a working model that goes much of the way towards explaining the presence of gas and dust and stars in a good many galaxies, the overall evolution remains unknown and there are too many loose ends for comfort.

Since the random velocities of stars and gas clouds are observed to be mostly around 10 km per second, the process we have described is essentially one in which gas, dust and stars rotate more or less together around the centre of the galaxy. We appear to be picturing a continuous cycle of material through gas and stars which spreads locally evolved products, such as high atomic weight elements formed in the centres of stars, only very slowly throughout the galaxy. This 'local' hypothesis is however as speculative as the very process of star formation itself. We have to keep in mind the possibility that much of the gas, especially in the central parts of the galaxy, may not stay where it is. It may be more inclined to gravitate towards the middle of the galaxy where it can build a giant nucleus. Since massive nuclei will evolve quite rapidly, perhaps they end their lives by blowing up and scattering the products of their evolution throughout the galaxy: perhaps it is mostly these products that are then responsible for triggering star formation. If this picture is correct, new stars may not be produced simply from local condensations of gas. It is conceivable that galactic nuclei and spiral arms are an integral part of the gigantic clockwork mechanism.

1.4 Spiral structure: density wave or nuclear explosion?

Spiral structure is in fact a very common property of galaxies, and it is generally present in the 60 or 70 per cent containing gas and dust. It usually takes the form of a pair of arms stretching one or two revolutions around the system with reflection symmetry through the centre. Spectroscopic measurements indicate that the arms are commonly rotating around the centre with velocities of nearly
4. Typical galactic disc observed 'face-on'. Its catalogue number is NGC 1365. Although there is a central concentration of stars corresponding to the spheroidal component, the nucleus, as is the case in most galaxies, is not particularly conspicuous. Note the overall 'grand design' of the spiral and the ragged fine structure: both these and the immense variety of spiral structures observed in the universe suggest such patterns may last for only 100 or 200 million years.
The revolution periods are thus a few hundred million years, considerably less than the average ages of stars. These are more like a few billion years. At first sight then, it seems the arms have lasted for ten or a hundred revolutions since they were formed. If such were the case, one would probably be envisaging the arms as the locus of a large spiral wave running through the galactic disc in which the local excess pressure continually compresses gas into forming new stars. This is because, if a wave of this kind were not involved, the observed differential rotation would very soon tear the arms to shreds. The situation may well not be as simple as this however. One problem is that the density waves seem to be incapable of compressing diffuse gas into the cold dense clouds actually observed in spiral arms. For such reasons, some astronomers question whether the density wave picture is correct.

Usually the trailing and leading ends of the spiral arms are ill-defined and the system as a whole simply describes a kind of ring or flattened doughnut several kiloparsecs broad. And sometimes, there are signs of additional sets of arms in galaxies. A galaxy may for example possess a very large outer ring of gas and dust, or it may have a small central pair of spiral arms which seem almost to connect to the galactic centre. The spiral structure tends therefore to be extremely varied and complex. Instead of imagining it as a uniform pattern going round and round, it is more in accord with the variety of appearances to suppose that it is formed and reformed again and again, each time spreading out from the nucleus and being rapidly destroyed by shearing forces caused by the rotation. Sometimes a new set of arms seems to be created even before the existing ones have died away. With this scenario, we are no longer obliged to think of spiral arms as density waves. They simply emerge from the nucleus at intervals in the form of cold, dense clouds, and then break up under the influence of differential rotation.

Although the main spiral arms are very conspicuous, it turns out they are not a particularly massive part of a galaxy. In fact, they make up only a few percent of the total mass, and the main reason why they are so obvious is that they represent the principal location of recent star formation. The arms happen to delineate great concentrations of gas and dust even within the galactic plane where most of this material lies, and it is in these narrow concentrations that we evidently see the newest stars being created. Since, in general, stars are formed in a range of masses and the largest stars, perhaps up to a hundred solar masses, are especially luminous and short-lived, it is
these relatively few new stars that render the spiral arms so conspicuous. Elsewhere in the galaxy all the really massive stars have long since died out.

Another remarkable property of spiral galaxies is the extreme flatness of the dust and gas plane containing the arms. Thus, although the central star system possesses an ‘oblate spheroidal’ structure, the disc and the arms, as we have remarked already, seem to project out of this in an exceedingly thin plane. Its thickness is at most only about one-hundredth of its diameter. This property reminiscent of the solar system, has been none too easy to explain theoretically. Why should so many stars be confined to a flat disc when the natural shape of a collection of these objects is the spheroidal distribution we observe nearer the centre of the galaxy? One rather popular idea is that every galaxy starts off as a rotating cloud of gas. This collapses under its own gravity, until balanced by rotation at a certain size; the inelastic collisions between gas clouds are then supposed to be frequent enough to dissipate the random motions and cause the gas to settle into a very flat rotating disc. A few ‘halo’ stars are supposed to form while this is going on but most of the stars do not start appearing until after the gaseous disc is first constructed. One problem with this scheme is that it does not provide us with a very satisfactory sequence of star ages in relation to the actual observations. Another is that we have not yet discovered any proto-galactic gas clouds. If the universe is evolving, they could be out of sight and this might not then be such a worry, but if it is not, the theory is much more suspect. For this reason, the flatness of the disc may have to be regarded as a feature of galaxies imposed by some other mode of star formation. A possibility is that the arms are thin because they are ejected from very flat rotating objects. The narrowness of the plane would then be evidence that successive sets of arms result from objects which are themselves derived from material with a common rotation axis, that is just typical material of the galaxy itself. The natural place to look for such objects, possibly in a state of violent disruption, would obviously be in the centre of the galaxy. We have noted already there is a small percentage of galaxies in whose centres very violent things are going on. Most of these nuclei have properties very like those of quasars.

To summarize, we have now drawn attention to two possible, perhaps extreme, but unproven scenarios consistent with modern observations of galaxies. One of them, currently enjoying the support of most astronomers, would have quasars at large look-back times, as once-and-for-all bright nuclei formed fairly early on in the lifetime of
a galaxy, and the spiral arms visible in nearer galaxies as waves circulating through the disc of gas, the pressure enhancement being responsible for triggering star formation. The other scenario would have a universe in which high redshift quasars are not so remote, being indicators of recurrent activity associated with successive gravitationally collapsed superstars in the nuclei of relatively nearby galaxies. According to this picture the active spells are short-lived and may result in the ejection of cold spiral arms, each set of which survives for a few hundred million years. If this latter theory is correct the concentrations of gas and dust in the arms are the natural end products of the evolution of supermassive stars in galactic nuclei, and it is gravitational instability in this material that gives rise to star formation. A great deal of observational work with large telescopes is being undertaken and hopefully it will be possible to discriminate between these—and other—possibilities within a decade. In the meantime, until such hard evidence is forthcoming, we would again be wise to keep open and sceptical minds on these theoretical exercises.

1.5 Our Galaxy: the spiral arms and the solar neighbourhood

The trail we follow really begins with the arms of our own Galaxy, which seems to be a typical two-armed spiral, and we shall now look at this spiral structure in a little more detail. The Sun happens to be quite close to the central plane and the Milky Way's brightness and structure are simply due to the distribution of clumps of recently formed bright stars and the ever prevalent dust clouds in the nearest spiral arms. By the 1930s, optical astronomers had disentangled this structure and we were aware that the centre of our Galaxy was in the direction of the constellation of Sagittarius but generally obscured by great clouds of dust. By 1950, they were also aware of the so-called Sagittarius arm spreading along the Milky Way roughly perpendicular to the line of sight towards the galactic centre. They also knew about the so-called Orion arm perpendicular to the opposite direction which is, rather obviously, designated the galactic anticentre. When we peer through the Orion arm, it is possible to see signs of another arm further out in the Galaxy. This is known as the Perseus arm. If the spiral structure in our Galaxy is at all similar to that in the other galaxies, and there is no reason to question this at the moment, then it would be reasonable to suppose the Perseus arm is an extension of the Sagittarius arm. Although each of these arms is no more than a kiloparsec or two from us, it is important to appreciate
that the Sun is not really part of them. The arms are young and the Sun is old! They may be quite near in galactic terms but we do not belong to them in the same sense as the Earth belongs to the solar system, for example.

In the 1950s and later, radio astronomers placed the spiral character of our Galaxy beyond any further doubt. The radio emission from the Milky Way is mainly from gas which is very cold, ranging in temperature from a few degrees above absolute zero up to one or two hundred degrees absolute. Since gas is one of the principal components of the spiral arms and radio waves are relatively unobscured by the dust, we are able to see to vastly greater distances than before throughout the galactic disc. Though it is difficult to be sure of the precise distance of a gas cloud giving rise to any particular radio emission along any one line of sight, it is at least possible to separate out the different features, and continuity of features over considerable stretches of the Milky Way soon made it clear that we were observing long narrow spiral arms. The very nearby arms first observed by optical astronomers were extremely prominent, but unfortunately, the lack of detailed knowledge of the pattern of velocities in the Galaxy has made
32 Universe to galaxy: the cosmic framework

for difficulty in disentangling the rest of the structure. Nevertheless, in
the anti-centre direction beyond the Sun’s distance from the galactic
centre, there are clear signs of further windings of several rather weak
arms and close to the galactic centre, within a radius of about 3
kiloparsecs, there is an obvious inner system of arms possessing very
strong outward velocities of expansion. All these facts were originally
derived from observations of the so-called 21-cm line which was the
first studied by radio astronomers. This spectrum line emitting at the
radio wavelength of 21 cm comes from the neutral hydrogen gas in the
arms, but in more recent years searches have been extended to other
lines, particularly those originating from very cold molecular radicals.
All tell substantially the same story, but the molecular lines have made
particularly clear the zone between radii of about 4 and 8 kiloparsecs
containing the strongest spiral arms. These are the ones in which the
Sun is ‘immersed’. They have also shown up a strong concentration of
very cold material right at the galactic centre, suggesting that whatever
spiral arms are composed of is also to be found in a very condensed
form near the galactic nucleus. Taking a broad view it looks as if our
Galaxy might have as many as three sets of spiral arms, one set of which
is especially conspicuous. Of course on the nuclear ejection hypothesis
this would imply three nuclear explosions within the last few hundred
million years. The most recent of these, responsible for the innermost
system, would have taken place about 30 million years ago, while the
ejecta from the oldest are now far out in the Galaxy and falling back
towards the centre.

It would be a mistake however to suppose from this simplified
account that all this structure is nice and tidy—it is not. Spiral arms
may look fairly smooth from a great distance, but when examined in
detail, they have a ragged and clumpy appearance indicative of really
quite rapid if not violent evolutionary processes. Thus, although the
gaseous arms display large-scale continuity over tens of kiloparsecs,
they are nevertheless broken into individual bits and pieces which
may be only tens of parsecs in dimensions. Some of these pieces may
be particularly concentrated and it is these that are often most
associated with current star formation. The solar neighbourhood in
particular has long been recognized as being rather close to a major
irregularity in the nearest spiral arm. Thus, the very brightest massive
stars visible to the naked eye define a broad strip across the sky which
is inclined to the Milky Way at about 20°. At one end in the southern
hemisphere we observe the Scorpio–Centaurus association, a large
cluster of young, blue stars, which is ‘above’ the galactic plane. At the
other end, $180^\circ$ away ‘beneath’ the galactic plane, we observe the Pleiades cluster which is not so far from the massive gas clouds in Orion. The whole of this strip, full of young stars, gas and dust, some 500 parsecs long and 100 parsecs distant from the Sun, is known as Gould’s Belt and evidently relates to some kind of disturbance in the Orion arm—perhaps 30 million years ago. Gould’s Belt looks rather like a finger projecting inwards from the Orion arm.

Obviously, then, the Sun lies in the vicinity of particular local events which are typical of what may be some kind of rapidly evolving grand design in the Galaxy. What is perhaps a little difficult to appreciate at first glance is that the behaviour of our Sun, and indeed any fairly old star, can be discussed, at least to a first approximation, almost independently of the underlying spiral structure. Because spiral arms are generally not all that massive and other stars are usually a long way off, it happens that the major gravitational influence controlling the orbit of a star like the Sun is that of the Galaxy as a whole.

We can think of the Sun moving in a circular or elliptical orbit, tracing its way through successive spiral arms at a rate dictated by the relative velocity of the Sun and this underlying structure. In fact, the Sun’s orbit is an ‘osculating ellipse’, describing a kind of rosette, moving at such a speed relative to the nearby spiral arms that it is bound to cross them at intervals of about 50 million years. Not only that, it is moving in such a direction that it must have passed through Gould’s Belt only 10 million years ago. The rough periodicity in many geophysical processes is so similar to these intervals that it has long been recognized that terrestrial processes themselves might be triggered in some way by our passage through spiral arms (Table 1). The problem has been to identify the mechanism giving rise to the geophysical effects.

Some investigators have drawn attention to the fact that each spiral arm crossing might bring the Earth in close proximity to a supernova—a star that explodes—and they have placed great emphasis on the radiation blast that might then be suffered together with its possible biological consequences. Others have preferred a somewhat quieter scenario in which the Sun passes through dense interstellar gas clouds leading to the slow onset of ice ages. No investigator has previously considered the view we shall develop in subsequent chapters. This is that the spiral arms of the Galaxy contain large solid bodies; that the solar system, acting as a large gravitational scoop, captures billions of such bodies when it crosses
### Table 1. Periodicity of geophysical processes

<table>
<thead>
<tr>
<th>Dates of major geological boundaries during Phanerozoic period</th>
<th>Interval between dates</th>
</tr>
</thead>
<tbody>
<tr>
<td>QUATERNARY</td>
<td>0 Myr b.p.</td>
</tr>
<tr>
<td>TERTIARY</td>
<td>65</td>
</tr>
<tr>
<td>CRETACEOUS</td>
<td>135</td>
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<tr>
<td>JURASSIC</td>
<td>190</td>
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<td>TRIASSIC</td>
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<tr>
<td>PERMIAN</td>
<td>280</td>
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<tr>
<td>CARBONIFEROUS</td>
<td>345</td>
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<tr>
<td>DEVONIAN</td>
<td>395</td>
</tr>
<tr>
<td>SILURIAN</td>
<td>435</td>
</tr>
<tr>
<td>ORDOVICIAN</td>
<td>500</td>
</tr>
<tr>
<td>CAMBRIAN</td>
<td>570</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Periods of intense igneous or metamorphic activity on a world-wide scale</th>
<th>Interval between periods</th>
</tr>
</thead>
<tbody>
<tr>
<td>65</td>
<td>335</td>
</tr>
<tr>
<td>400</td>
<td>600</td>
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<td>300</td>
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<tr>
<td>1700</td>
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<tr>
<td>2100</td>
<td>500</td>
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<td>2600</td>
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Note: Myr b.p. = Million years before present

<table>
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<tr>
<th>Principal ice ages</th>
<th>Interval</th>
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<tr>
<td>0–1</td>
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<td>2250</td>
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spiral arms: and that in consequence episodes of planetary bombardment occur, with profound biological and other consequences. The bodies we shall consider will generally be of sub-planetary dimensions and the term ‘planetesimal’ was coined for these many years ago. There is not enough information to specify the types, but we envisage them as cold material of ice or possibly rock, or icy conglomerates, and we shall interpret the comets of the solar system as captured planetesimals. Comets are conglomerates of ice and dust, perhaps with larger boulders, perhaps with a rocky core. The ices vaporize as the Sun is approached and a comet may appear with a long spectacular tail. There could be captured rocky bodies in comet-like orbits, and these could be just as common, but their chance of discovery is very much smaller.

Astronomers have not until recently considered planetesimals as a likely constituent of spiral arms. In one sense this is reasonable because cold planetesimals would be difficult to detect and confirm, and astronomers are rightly cautious about postulating the presence of something they cannot see. On the other hand, as we have noted, there is plenty of dust and cold molecular gas in spiral arms, and there is no a priori reason why this material should not be considered a natural component of a population of very cold icy conglomerates. Indeed much independent evidence favours the origin of the solar system itself from essentially cold solid material and the cratering history discussed in a later chapter shows that the planets were very early on immersed in a vast dense cloud of planetesimals which has since been thrown into interstellar space. Thus, the presence of planetesimals in spiral arms seems well nigh inescapable if the formation of the Sun was not fundamentally different from that of other similar stars. And to suppose otherwise would be to take a remarkably heliocentric view.

1.6 Spiral arms and planetesimals: the source of comets

These arguments lead then to the possibility that star formation itself may be a process involving the accumulation of cold, solid material. The traditional view has been that stars are made by the collapse of huge, relatively hot masses of gas under their own weight. Of course a gas, as it contracts, heats up, and a heated gas wants to expand, and collapse would quickly be brought to a halt. However it could be that the density is by then so high that individual regions of the cloud are able to collapse separately, until they themselves fragment and so on, down to the point where the gas is so dense and opaque that
further contraction initiates nuclear fusion, and stars are born.

This concept, as we have indicated already, is facing severe difficulties. The collapse of a large cloud has recently been simulated on computers and the hierarchy of fragmentations essential to the picture does not take place: a cloud will collapse moderately and no more. There is the vexatious problem, never quite overcome, of the spin-up of a collapsing cloud. Even a small rotation is so magnified by collapse from nebular to stellar dimensions that the final object could not hold itself together. Then there are observational difficulties. The theory predicts that the final assembly of stars will be a dense, concentrated cluster with a smoothed-out density of about 100 million atoms per cubic centimetre. The observed star clusters have mean densities about a millionth of this.

The traditional concept of star formation has its roots in a period before the radio astronomers had discovered the ubiquity and importance of cold, dense clouds in the spiral arms of the Galaxy, and it is tempting to speculate that these clouds, with their hypothesized constituent planetesimals and dust, provide us with a hitherto missing ingredient, and that the true mechanism of star and planet formation involves not simply the collapse of gas clouds but also the aggregation of already cold planetesimals. Not only would this fit in better with the planetesimal population known to have existed in the early solar system, but there are some indications now that protostellar objects composed of planetesimal material do in fact exist. They occur in spiral arms in the form of cold dusty objects of solar mass or greater, known as globules. Concentrations of these objects abound in regions of intense star formation such as IC 2499. In the vicinity of two well-studied and exceedingly active stellar associations, namely the so-called Gum nebula and the Orion nebula, there are also observed what appear to be gigantic interstellar comets. These are obviously much more massive than the solar system examples; they are just globules with huge long tails very like their smaller counterparts. The tails are not only pointing away from the centre of the parent association where most of the local radiation originates, but the heads seem to be in highly eccentric orbits moving away from the central source. We thus have an indication that we may be dealing with large, loose aggregates of cometary material which are either about to be or are in the process of forming new stars.

Further evidence for the existence of interstellar comets comes from chemical abundance arguments. In the first place, it has been
A family of 'globules' in the young cluster IC 2499. The cluster is a concentration or association of spiral arm stars immersed in the general field. Note how the cluster lies within a diffuse, glowing mass of gas in front of which are several cold, dense absorbing clouds which are about a parsec across. These are the globules, short-lived progenitors of new stars.
6. A few of the huge 'interstellar comets' observed in the vicinity of the so-called Gum Nebula (an association of young stars in the Carina extension of the Sagittarius spiral arm). The tails are attached to globules which are apparently fleeing away from the central association. Though not evident in these pictures, the heads point towards the centre of the association just as solar system comets point towards the Sun. The tails are not therefore trailing in the paths of motion but
to be the result of a powerful stellar wind. It has to be emphasized that the interstellar comets are detectable only on photographs taken with the most powerful optical telescopes and then only when care is taken to bring up the contrast. They are vast compared to solar system examples, the tails being up to a

true interstellar comets or planetesimals of the kind captured by the solar
known for some time that, apart from hydrogen, the interstellar material has quite similar chemical composition to that of the comets. Further, if the steady state model of galaxies is correct, the under-abundance of metals in the interstellar gas relative to stars indicates that these atomic species must be locked up in something fairly invisible like faint comets. Thus, although the question cannot be regarded as finally settled, the galactic evidence favours spiral arms containing planetesimals or comets in all their variety of forms. It is inevitable then that the solar system interacts with such material as it passes through the spiral arms. And each passage will result in a capture episode leading to a flood of comets into the inner solar system.

As far as we can see therefore, planetesimals as constituents of spiral arms are a fact we may have to live with. But with the genesis of spiral arms still uncertain, we run into theoretical difficulties. If the spiral arms are density waves running through the underlying disc, it is still not at all clear how they can make stars and planetesimals out of initially warm gas and dust. If, on the other hand, they are ejected fragments from an evolved nucleus, it is necessary to have a dynamical explanation of how this ejection works. Almost inevitably this brings us in conflict with the modern explanation of gravity implicit in the general theory of relativity. This is because the tangential velocity of ejecta is inversely proportional to their distance from the point of ejection, and so typical spiral arm material in the solar neighbourhood must have had relativistic velocities when close to the nucleus. It is true that some quasars are seen to have small components moving apart at such speeds, and more extended double radio sources have apparently been ejected at relativistic speeds from galactic nuclei. The requirement of velocities in excess of say 250,000 km sec is not therefore particularly awkward from an observational point of view. But from the theoretical viewpoint, there is the very awkward fact that such velocities are greatly in excess of the normal escape velocity from a galaxy and the ejecta could not normally remain bound to the system. The difficulty can be overcome only by 'new physics'. If the ejecta which will form spiral arms come from a temporarily hypermassive nucleus the necessary gravitational restraint can be applied to them. Such new physics, if valid, would have ramifications throughout astrophysics. For instance light emitted from a hypermassive nucleus would be strongly redshifted, and this might account for the high redshift of quasars. The brief 'switching on' of such gravity would have the effect of squeezing in a
Fig. 2. Line-of-sight velocities (in kilometres per second) of globular clusters seen in the general direction of the galactic centre. These are plotted against their distances from the Sun (in kiloparsec) projected on to the solar galacto-centric line. The distance to the centre of the Galaxy is marked by the dotted line. Note the trend which is one of velocities that generally approach us on the near side of the galactic centre, and that tend to recede on the far side. These systematic 'expanding' motions seem to indicate that our Galaxy is in a recently disturbed state, but if so, the enormous force responsible for the effect has not yet been properly identified.

Whether the current difficulties of astrophysics do indeed require new physics for their resolution is a matter of controversy: we may be facing either a failure of physics or a failure of imagination. Fortunately we do not here need to choose: it will be enough to assess the evidence that capture of interstellar planetesimals takes place and to pursue the consequences. But our starting point is on the fringe of these problems, and the possibility exists that discriminating evidence will be found, not simply in remote and exotic regions of the universe, but in a sample of deep-sea sediment, or in a meteorite somewhere in the world's museums.
2 · Galaxy to comet:  
the interstellar connection

The currently prevailing view is that comets derive from a huge primordial cloud attached to the solar system. We believe this idea to be at best only partially correct and that many comets are captured from interstellar space. Where conditions outside the solar system were once considered unsuitable for the growth of comets, modern observations, especially with radio telescopes, have now uncovered cold dense clouds where the conditions are entirely suitable. In this chapter, we discuss the mechanism whereby each capture episode, as the solar system passes through a spiral arm, gives rise to a temporary flux of cometary bodies in orbit around the Sun. Lunar soil analyses are shown to support a scenario of episodic bombardments controlled by the Galaxy.

2.1 Solar system comets: the basic facts

‘There was not a cloud in the sky, but looking due east one saw the tail of the Comet stretching upwards, nearly to the zenith, and spreading with a slight curve. Not a breath stirred, the sky was a dark blue almost to the horizon. The scene was impressive in its solemnity and grandeur. As the Comet rose, the widened extremity of its tail extended past the zenith and seemed to overhang the world. When dawn came, the dark blue of the sky near the point of sunrise began to change into a rich yellow, then gradually came a stronger light, and over the mountain and among the yellow, an ill-defined mass of golden glory rose, in surroundings of indescribable beauty. This was the nucleus of the Comet. A few minutes after, the sun appeared, but the Comet seemed in no way dimmed in brightness, and although in full sunlight the greater part of the tail disappeared, the Comet itself remained through the day easily visible to the naked eye; with a tail about as long as the moon is broad.’

Not all comets are as spectacular as that of 1882, here described by the Cape astronomer Gill. In fact, although four or five long-period comets approach the inner planetary system each year, most go unnoticed, requiring at least binoculars to be seen. Every few years a comet may be widely observed with the naked eye, but only a few times per century will one approach the grandeur of, say, the 1882
7. Successive photographs of Halley's comet during its 1910 return. Note the elongation of star images as the telescope follows the comet. Observe also the motion contrary to the apparent direction of the tail and the changing appearance of the tail as a fragment detaches itself from the main body.

comet, or Halley's comet, due to return in 1986. They can arrive from any part of the sky, in elongated elliptical orbits whose major axes may be up to about 50,000 astronomical units. It is convenient here to measure distance in astronomical units, or a.u. An astronomical unit is the mean distance between Earth and Sun: there are about 200,000 a.u. to a parsec, the unit of the previous chapter.

A great comet is made up of a bright, star-like nucleus surrounded by a hazy coma, streaming away from which is a tail which may be tens of millions of kilometres in length. There has been much controversy over the nature of the central regions of a comet and probably only the close fly-by of a probe will finally satisfy all parties. Evidence has accumulated, however, in favour of the dirty snowball
model developed by the American astronomer Whipple, in which the nucleus is seen as a lightly packed ball of ices including ammonia, methane, carbon dioxide but about 50 per cent water ice. Imbedded in the ice are solid particles about 0.01 per cent of a millimetre in diameter, that is about the size of interstellar grains. There is evidence also for grains of sub-millimetre dimensions. One school of thought regards the nucleus as an icy gravel-like conglomerate of this sort throughout: another that the ice overlies a solid rocky core. The characteristic diameter of a nucleus is taken to be only a few kilometres, much too small for telescopic resolution. Typically the tail may have only a thousandth of the mass of the nucleus.

Fig. 3. Schematic perspective view of the inner planetary system including the asteroid belt. A typical path of a comet in a highly eccentric orbit is shown together with an illustration of the relative size and orientation of the tail (S = Sun, M = Mercury, V = Venus, E = Earth, M' = Mars).

At a great distance from the Sun a comet will normally appear star-like, but a coma and tail will begin to grow as the Sun is approached and solar heating takes effect, evaporating the ices. Normally within 3 or 4 a.u. of the Sun there is evidence of activity although sometimes this is seen at greater distances. The brightness grows much more rapidly as the comet approaches than is consistent with mere reflection of sunlight by a solid body, and there are erratic outbursts as if pockets of material were being thrown out. The tail itself may comprise gas and fine dust and will stream away from the Sun, the whole thing giving the impression of being caught up in the tenuous wind that blows out from the Sun at 400–600 km sec. Sometimes the tail is immensely long and straight, sometimes it extends in an arc,
8. Predawn photograph of the bright Ikeya-Seki comet during October 1965. Note the very small nucleus and the huge tail which is nearly one astronomical unit in length. In spite of their sizes, comet tails contain very little matter.

sometimes there is more than one tail, a very curved anomalous tail of large dust particles streaming off separately. Usually there is a very fine structure, little understood, within the tail (Plate 8). Close to the Sun, the gas will fluoresce with a bluish-white light. The far end of the tail of a great comet may be a deep red, because of selective absorption of sunlight by the dust in the tail.

The orbital periods of long-period comets are of the order of 4 million years, so generally we see them only once. Their enormous distances of arrival indicate that they are only just gravitationally bound to the Sun: a slight perturbation would throw them into open (hyperbolic) orbits and they would escape into interstellar space. These simple facts alone can lead to far-reaching consequences. For if four or five long-period comets come close to the Sun each year, and if orbital periods averaging a million years are involved, there must be at least several million comets currently associated with the solar system. And if say 10 or 20 per cent of incoming comets are ejected by
the gravitational action of the major planets then a solar system age of 4.5 billion years implies a loss of several billion comets at least. One may well be thinking of a huge cloud of comets around the solar system, reaching almost halfway to the stars. But it is important to know whether the cloud is as old as the solar system or whether it is a recent acquisition.

In Chapter 1 we have seen how the solar system may capture interstellar debris sporadically as it crosses and recrosses spiral arms. On a simple view of solar and galactic motion this would happen at 50-million year intervals although vagaries of orbit and arms make this no more than a characteristic figure. With the emergence of the Sun from the Gould Belt extension of the Orion spiral arm about 10 million years ago, the last capture episode may have come to an end. In the picture we shall be developing, each passage gives rise to a temporary cloud of comets in the solar system which then decays, either by expulsion into interstellar space, or by conversion into short-period orbits followed by rapid dissipation under the influence of solar radiation, or by collision with planets. The present comet population on this hypothesis is thus a recent acquisition and in a declining phase.

2.2 The interstellar medium

We outlined the evidence for interstellar planetesimals in the previous chapter but the idea that kilometre-sized bodies like comets may inhabit interstellar space goes back at least to Laplace in 1806, it was then based on the enormous distances from which these objects are seen to arrive. Around the turn of the century, however, the idea of interstellar comets began to wane in popularity because none was seen to fly through the solar system in open orbits as might be expected. It was then that the concept of a primordial cloud of comets attached to the solar system gradually came into favour. Indeed it strengthened as the low density of the interstellar medium came to be appreciated since the calculated growth times of comets by random accretion of atoms and dust were found to be incredibly long. If all interstellar gas atoms heavier than hydrogen or helium accrete on collision with a body, then in a typical region of the interstellar medium, containing say 1 atom per cubic centimetre, it would have taken 100 million years for it to acquire a coating of frost 0.1 per cent of a millimetre thick! So if a capture mechanism is now to be preferred, this problem still remains: how are we to grow comets out of the interstellar dust and gas? How indeed do we know they are to be
assembled from the dust and gas? Whatever the mechanism there must of course also be sufficient heavy element material in the Galaxy to match the observed numbers of comets. Let us start with the question of heavy elements.

On the conventional picture of galactic chemical evolution, one begins with metal-poor stars and an environment largely comprising hydrogen and primordial helium. Hydrogen burning proceeds in stellar interiors, being converted into helium, and a helium core is formed. If the star is sufficiently massive the temperature and pressure in the central regions will increase to the point where helium itself becomes the fuel, the helium burning producing a further core of nitrogen, carbon and oxygen. This further core will itself, above a certain temperature, become a fuel, and so heavier elements are progressively built up. If the star’s mass exceeds that of the Sun by more than 40 per cent or so, it will build heavier elements up to iron, but beyond that stage, the iron reverts to hydrogen. The energy expended in burning hydrogen to iron is now repaid and the star becomes a supernova, imploding violently, the rebound scattering metal-rich debris into interstellar space. What remains should be a highly condensed star. The theories of stellar evolution and nucleosynthesis have been calculated in considerable detail and this picture must certainly tell a good part of the truth. Thus, a few galactic supernovae have been recorded over the centuries and at least two of them have left a rapidly rotating neutron star as a remnant.

Inevitably, then, with this picture, the interstellar medium is steadily enriched by heavy elements produced in supernova explosions. This may not be the whole story however. The medium may, as we have seen, also be processed through supermassive stars in the galactic nucleus. Such objects achieve much higher central temperatures than ordinary disc stars and the heavier elements would tend then to break down. As a result of this, there could be a balance and relatively little enrichment of the Galaxy with the passage of time. In practice, the mean metal abundance of stars shows very little actual increase with decreasing age, perhaps favouring the second alternative. But whichever scheme is correct since, as we remarked in Chapter 1, the interstellar gas is deficient compared to the atmospheres of the youngest stars in a whole range of elements heavier than helium, much more than can be identified in the interstellar dust, much of the interstellar material could be concealed in less visible bodies. To account for the deficiencies of heavy
elements such as metals, several hundred million solar masses would have to be locked up in such bodies. This is about 10 per cent of the mass of the interstellar medium and would imply a population of about a billion billion billion comets. The remark of Kepler (1571-1630) that there are 'more comets in the sky than there are fishes in the sea' would be literally true! One thing seems to be certain, then. Even without the evidence of Plate 6, interstellar comets would be a sensible hypothesis, but they would have to be easily made. The question is how?

The realization in recent years that extremely cold, dense and dusty nebulae are a major constituent of spiral arms to the extent that a typical interstellar gas atom may spend half its lifetime within one has put an entirely different perspective on the problem of growing interstellar comets. For there are forces at work within such clouds tending to segregate grains from gas. Gravity, radiation pressure, vortex motion and so on, all may act in a cloud so as to cause moderate enhancements of the dust to gas ratio. Normally these would be smeared out by internal motions, but if a cloud has a density of more than 1,000 atoms per cubic centimetre, these enhancements probably collapse. Two neighbouring stationary dust grains for example will partially shield each other from the surrounding radiation field. Starlight will not then arrive on each grain uniformly because of this mutual shadowing. Since ultraviolet light is energetic enough to knock atoms off the underlying substrate and there is a rocket effect as the atoms fly away, the grains are pushed together. As the grains approach, the effect is further magnified and the end result is they stick together. Now, if the local dust enhancement is too small, the collapse rate will not offset the random motion of the grains and it will disperse. If the enhancement is too large, the aggregation into comets will not be complete within the gravitational collapse time of the nebula. that is, a huge star is created before the much smaller comets can form. In practice, something between these two extremes takes place and the bodies formed have the characteristic dimensions of comet nuclei. Its constituent atoms and molecules obviously reflect the temperature of the medium in which coagulation occurs and although the clouds are cold (10° absolute), they are generally warm enough for hydrogen, the most volatile of elements, to be gaseous. Apart from hydrogen then, each body will be a conglomerate of ice and dust whose chemical composition will reflect interstellar conditions. The striking resemblance between the chemical composition of comets and the interstellar medium need not be surprising
therefore, even though it has gone unexplained for some years.

Thus the chief objection to an interstellar capture view of comets, namely the problem of growing them in interstellar space, seems to have been overcome at least one mechanism will conglomorate icy conglomerates out of the spiral arms of the Galaxy, and there may well be others. Of course the origin of the dense, very cold clouds from which the planetesimals condense remains problematic, as we have already seen: they might be formed by compression and cooling of nebulae as density waves sweep round the Galaxy, or they might be fragments of giant nuclear explosions, and no doubt other possibilities can be conceived. But the overall picture is of spiral arms in which the interstellar medium is quite inhomogeneous. Embedded in a hot, tenuous background are cold, dense clouds of gas, dust and comets. Close encounters between the Sun and such nebulae, say to within a few light years, have probably occurred more than fifty times during the lifetime of the solar system. Actual penetration has probably occurred more than a dozen times, several such involving passage of the Sun to within about a light year of the cloud centre. Let us now take a look at the problem of capturing comets from the nebulae.

2.3 The capture mechanism

In general, a comet approaching the Sun from infinity with a finite velocity would simply continue past, receding to infinity; capture of an interstellar comet by the Sun is thus theoretically impossible in a strictly 'two body regime', in the absence of dissipative or other forces. The capture of bodies from interstellar space, therefore, must always involve at least a third body. In the mechanism under discussion the cold dense nebula may itself be the third body. A typical mass is tens of thousands of times that of the Sun, and the escape velocity from the surface may be several kilometres per second. During a close encounter, solar gravity will predominate over nebular gravity only within about 50 thousand astronomical units of the Sun. There is a sphere of influence of this radius within which a comet’s motion is controlled by solar gravity. If the motion of the Sun relative to the nebula is modest and the velocity dispersion in the neighbourhood of Sun and nebula is not too large, then say 1 per cent or less of comets entering the sphere of influence during the close encounter will be captured. If a tenth of the mass of the nebula is in the form of comets then it turns out that a mass 100–1,000 times that of the asteroid system will be captured into the solar system during
each such close encounter. Of course the interstellar medium is irregular and the solar system, passing through a spiral arm, will be buffeted by tidal forces of various magnitudes and durations. But calculations indicate that enough bodies are likely to be captured during each encounter to reproduce the observed input rate of long-period comets. The implication is that there may be a rough balance between supply and loss of comets in the solar system.

Another capture mechanism might involve Jupiter as a third body. The problem here is that Jupiter’s sphere of influence is only about 1 a.u. in diameter and with this small target only a minute fraction of the required capture rate is possible, unless by chance the Sun were to encounter a very dense swarm of interstellar comets.

But there is another, even more stringent, requirement to be satisfied by the interstellar capture theory. We have to account for the fact that the great majority of long-period comets arrive at perihelion from distances of several tens of thousands of astronomical units, halfway to the nearest stars. These enormous distances indicate, as we have seen, that comets are only just bound to the solar system. Small perturbations induced by the planets may thus have a large effect on the orbits. For example a comet whose orbital period was 10,000 years on entering the planetary system may have a period between 5,000 and 15,000 years on leaving it. The system of comets is therefore in a state of rapid evolution. A statistical examination of this problem is possible since the periods of the planets are so short (Jupiter less than twelve years, Saturn less than thirty years) that their positions are more or less random when a comet arrives from a great distance. Random walk analyses of this problem have been carried out recently by the Japanese astronomer Yabushita.

Assume that comets approach from any direction in space. As we are concerned only with those that become visible we need consider only those comets approaching to within a few astronomical units of the Sun. Following their evolution by a random sampling of the energy perturbations to which they are subject, one finds that 90 per cent are expelled from the solar system after 3 million years, 99 per cent vanish within 300 million years and so on. In general the proportion of comets surviving N returns to the planetary system, without expulsion to interstellar space, varies as $1/N$ (Figure 4).

The agitation of orbits by the planets has greatest effect on those comets of shorter period since in a given time interval their numbers of returns are greater. There is therefore a progressive clearing of comets from the inner regions of the solar system outwards. It is this
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Fig. 4. Probability that a typical long-period comet has of making more than a given number of returns to perihelion. Apart from the risk of being thrown out of the solar system altogether by planet encounters, comets may be lost also by collisions or by perturbation into orbits with perihelia of a few astronomical units, whence rapid outgassing will occur causing them to evolve into asteroidal bodies.

Fig. 5. Graph showing the relative numbers of long-period comets corresponding to given values of the semi-major axis of their elliptical orbits. Since smaller values of the semi-major axis correspond to shorter periods, such comets return to perihelion relatively more often. They thus experience many more encounters and suffer most from solar radiation. As a consequence the inner solar system clears rapidly and the comets that remain are in highly eccentric orbits and spend most of their time far from the Sun.
which gives the preponderance of long-period comets which we observe. Thus the visible long-period comets are a rapidly evolving system, so much so that after a few million years, not only have 90 per cent of comets escaped but there is no trace of the initial distribution of orbits. The surviving comets have virtually ‘lost their memory’ of their initial orbits and are almost all in very elongated orbits with semi-major axes greater than 20,000 a.u. By matching the semi-major axis distribution with that observed it is possible to determine the epoch at which the last capture event ended. Yabushita finds that the observations are reproduced if there was a capture event ending somewhere between 3.6 and 9 million years ago. It must be seen as a very satisfactory confirmation of the interstellar capture hypothesis that the solar system completed its passage through Gould’s Belt within the last 10 million years. In another 40 million years, on this hypothesis, the number of comets attached to the solar system will be about half the present. But by this time we may be re-entering another spiral arm and a new episode of capture will begin. Currently, then, the arrival rate of long-period comets is within a factor of two or three of the mean arrival rate, averaged over very long periods of time. There is then no great problem in explaining the solar system comets in terms of capture from interstellar space. It is therefore rather remarkable that astronomers today usually dissent from this picture. As it happens this is not so much because of any active opposition to the capture hypothesis as such, but because most have become accustomed to another way of looking at things.

2.4 Problems with the primordial cloud

As we have seen, the great distance from which the long-period comets arrive is commonly interpreted in terms of a vast, primordial cloud of comets bound to the solar system. This view was quantified by the Dutch astronomer Oort in 1950. Although proposed by him only as a working model, the hypothesis has in the course of modern time acquired the status of an axiom. That this ‘cloud’ exists follows directly from the observed semi-major axis distribution. That the cloud is ‘primordial’ follows not at all from these observations, and tacit adoption of this premiss has led to a good deal of cosmogonic obfuscation.

One such obfuscation arises in imagining how to form the enormous primordial mass of comets implied by the hypothesis. Over a long period of time the primordial Oort cloud will have been traversed by many stars. Gentle perturbations by these interlopers
would continually randomize the motions of the comets on a timescale of perhaps 100 million years. Thus the comets we see, with eccentricities 0.9999 or more, can be only a minute sub-set of the total. Seen from 50,000 a.u. the radius of the Earth’s orbit is only 4” and the angular area it sweeps out is at the most one part in 100,000 million of the whole sky. In the case of randomized orbits therefore, for every comet that is diverted into an orbit directed towards this small target there are about 100,000 million which are not. To reproduce the observed rate of arrival of comets from a primordial Oort cloud the total number in the cloud has to be 100 or 200,000 millions. As usually envisaged the Oort cloud was formed through the expulsion, say by Jupiter, of comets from a primordial solar nebula, the size of the planetary system. Random expulsion, it is recognized, is an inefficient process; over 99 per cent of expellees being ejected to infinity. The original numbers expelled must have been in excess of 20 trillion! With a mean comet diameter of 1 or 2 km, the original mass ejected is about thirty times that of the Earth. This, the argument goes, the large planets could cope with.

But, as we shall demonstrate shortly, many of the missiles which currently produce craters on the Moon and planets are ultimately long-period comets or rather their corpses in the form of Apollo asteroids (see Chapter 3), and the mass distribution inferred from craters is such that the bulk of the mass resides in the small proportion of larger bodies. In fact this is just what we observe for comets and the main belt asteroids directly: half the total mass of the asteroid system is concentrated in the largest body (Ceres). If this mass distribution holds up to Ceres- or Tycho-producing missiles, then the average mass of a comet really is forty times that adopted in the above calculation. The mass to be expelled now becomes an impossible 1,000 Earth masses: in expelling this quantity of material, the outer planets would spiral into the Sun. There is a fallacy then in arguments basing the characteristic comet mass on that of the majority of comets.

A conceivable possibility is that the comets condensed in the outer regions of the planetary system, perhaps just beyond Neptune. But the disturbances created by the outer planets are small and computer trials have shown that such comets could not possibly be the main source of the Oort cloud. In any case a nearby comet belt of more than about an Earth mass would by now have been detected through its disturbance of the orbits of Uranus and Neptune.

The concept of the Oort cloud as primordial and permanent is further weakened when interstellar perturbers are examined. For the
very forces which cause planetesimals to be captured can, with the
same efficacy, cause them to escape. Numerical studies have been
carried out in which a close encounter with a massive nebula was
simulated, and it has been found that even a single encounter can, with
a typical fly-by velocity, deplete the outer regions of the Oort cloud by
30–90 per cent of its comets. But over the last 4 billion years the solar
system has probably passed within 10 light years or less of about twenty
such clouds. It follows that a primordial Oort cloud has been subject to
strong interstellar disrupting forces, and its original mass, if
unreplenished, would have had to be many thousands of times greater
again.

So long as it is thought that the present comets have to grow along
with planets in the dense regions around the early Sun then an
ejection into the observed cloud has to be postulated with the
resulting absurdities. But if we see star formation as co-eval with (or
consequent on) the formation of comets throughout an extended
globule, these problems disappear because in that case the primordial
comet cloud is formed in situ. We envisage the stars formed in the
globule dispersing, each carrying with it an attendant cloud of
comets. As time passes the comets are thrown into interstellar space
by the planets or passing nebulae and the population declines.
Eventually there comes an equilibrium, when the sporadic capture of
interstellar comets balances on average the losses. Thus as time goes
on the primordial population is gradually replaced by a captured one.

Some indication that the cloud may have reached a state of
equilibrium between capture and ejection comes from the cratering
history of the Moon. The lunar highlands in particular reveal that the
cratering flux over 3 billion years ago was 1,000–10,000 times the
present value. This dropped off rapidly until, to within the
uncertainties, it reached a steady state about 3 billion years ago,
which rate it has maintained since. There is evidence also in the
cratering record of brief recurring episodes of bombardment of
uncertain magnitude and duration, but the time resolution is very
poor (Figure 6). Episodic bombardments of this sort are expected on
a picture of sporadic capture and temporary replenishment of the
reservoir of comets from spiral arms. A close encounter between solar
system and massive nebula or star complex would in any case perturb
the comet cloud, primordial or not, and temporarily flood the inner
solar system, leading to a brief episode of bombardments.

Further evidence of an interstellar connection has come from
studies of the distribution over the sky of the major axes of long-
period comets. It has been found that these are not distributed randomly over the sky but rather lie in a preferred plane inclined at about 20° to the Milky Way. Furthermore, they also cluster around the solar apex. This is the point on the sky to which the Sun is moving relative to our local galactic environment. The actual distribution of long-period comets therefore relates in a quite significant way to the Sun's motion as one would expect if interstellar perturbations or capture were involved.

Fig. 6. Impact cratering rate (on a logarithmic scale) during lifetime of the solar system. This is a schematic diagram derived from the work of Hartmann. It shows a rapid decline from high rates in the early stages of solar system formation, settling down to a steady average rate during at least the last 3 billion years (see text). There is evidence nevertheless that the cratering rate is episodic but the data are too sparse to give accurate measures of either the peak to trough ratio or the intervals between peaks. The start of the geologic period known as the Phanerozoic is marked and it is during this period that multicellular life on Earth has shown its greatest development.

Thus, the primordial assumption leads to several difficulties, which the capture mechanism seems to avoid. One might then ask why, in that case, the primordial cloud concept is such a firmly entrenched part of the prevailing wisdom, often being taken as axiomatic in university courses, textbooks and so on. The original objection to interstellar comets was that we should see them moving through the solar system at speeds greatly in excess of escape velocity, whereas (apart from marginal cases) the comets we see are bound to the system. But of course with a capture episode ending 10 million years ago this is not a valid point. Then it was held that the concentration of comets at large distances was 'explained' by such a cloud. So it is, but a capture episode equally 'explains' this. However, probably the main difficulty was that a comet-growing mechanism has not until now been available: the primordial cloud was assumed fifteen years before the widespread existence of cold dense nebulae was known from radio
astronomy. Had their existence been known then, along with the coagulation mechanism, it is unlikely that we would now be devoting so much space to its refutation. The current dominance of the primordial Oort cloud concept in astronomical thinking then is probably nothing more than historical accident.

2.5 Episodic capture: the evidence on the Moon

As we have seen, theoretical calculations of the rate of decay of the temporarily captured population show their total numbers to decline smoothly between capture episodes, the peak to trough ratio being perhaps 3 or 4 to 1. However material in a spiral arm is lumpy and irregularly distributed; dense clouds may occur in complexes rather than at random; the drift velocity of the Sun relative to the ambient medium is likely to fluctuate appreciably, and so on. The supply end of the chain linking long-period comets to impact craters is likely to be an erratic one.

That the input is indeed erratic is indicated by a study, carried out by Lindsay and Srnka in 1975, on a core sample of lunar soil brought back by the Apollo 15 astronauts. The Moon and inner planets are being continually bombarded by microscopic particles. These submillimetre-sized bodies, impacting on lunar soil at say 25 km sec, will generate enough heat to melt and fuse together a volume of soil. The size of the fused agglutinate is a measure of the kinetic energy and hence mass of the microscopic particle which impacted.

Lindsay and Srnka sampled the core at 0.5 cm intervals over a depth of 120–240 cm, measuring the size distribution of the microscopic particles and correlating the soil depth with age, the sample covering the range 900–1,700 million years ago. From 900 to 1,300 million years ago the micro-meteoroid flux shows three broad cycles with periods of 100–200 million years and comparable durations (Figure 7). At its peak, the flux of these microscopic particles was about three times the modern value. From 1,300 to 1,600 million years before the present, an interval of 300 million years, the character of the flux changes. The departures from background form a series of ‘spikes’, two of which correspond to flux enhancements of about fifteen times the modern value. In fact one spike appears to be part of a complex enhancement of duration about 50 million years. Overall, the sporadic component of this flux is at least equal to the background flux. But within this general trend are short intervals of high bombardment rates. Almost certainly, the microscopic particles whose impacts are being measured do not arise from the asteroid belt. Several pioneer
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Fig. 7. Meteoroid deposition rate on the lunar surface derived from the work of Lindsay and Srnka (1975). The episodic variation is interpreted as due to major variations in the cometary flux in the inner parts of the solar system over the period 1,000–1,600 million years ago.

spacecraft have passed through the asteroid belt equipped with cosmic dust sensor apparatus. These experiments have shown that the asteroid belt is not at present a source of microscopic dust particles. The remaining possible sources are interstellar dust, or comets.

The particles observed from the reddening of starlight to be imbedded in the interstellar gas have diameters of about a thousandth of a millimetre whereas those impacting on lunar soil are probably 1,000 times as large. If 1 per cent of the mass of a cloud were in the form of these larger micrometeoroids, then the solar system, passing through a dense cloud (say with more than 1,000 atoms per cc) at 20 km sec, would experience a flux enhancement about three times the modern value. But passing through such a cloud is an event occurring once in several hundred million years and enduring perhaps 100,000 years, and is therefore quite incapable of giving the prolonged enhancements we observe. Less dense clouds are more common but supply a correspondingly decreased flux of particles. Unless there is an extreme concentration of heavy elements in grit-sized particles, then, direct passage through interstellar dust clouds cannot supply them.

On the other hand the strongly curved tails which sometimes arch out of the nuclei of active comets comprise dust particles in the sub-millimetre range. The particles detected by Lindsay and Srnka must therefore come from active comets. The presence of a single large comet in Earth-crossing space would appreciably increase the small particle flux on to the lunar surface. This recent study of the lunar soil therefore supports the theory of Galaxy-controlled bombardments.
2.6 Comets and stars: a scenario

The supposed primordial reservoir of comets is widely seen as having been created from a primordial solar nebula, a disc-shaped region the extent of the planetary system from which not only the comets but also the asteroids, planets and Sun condensed; this solar nebula concept has been with us from the time of Laplace or earlier. Sometimes it has been seen as a hot gas, ejected from the proto-Sun, from which the planets condensed, sometimes as a thin disc of dust which coagulated into progressively larger bodies, icy in the outer regions, rocky in the inner. There are in fact over forty theories of the origin of the solar system, about half of which involve this concept in some form or another.

Of course solar system formation has to be seen in the context of star formation as a whole; and stars are formed, it is observed, not usually in isolation but in clusters ranging from a handful to large groups of up to 1,000. That so many stars are now single is attributed to the eventual break-up of these clusters. And it is natural to see the cold dense nebulae we have discussed as precursors of star formation.

However, as we have tried to demonstrate, these nebulae may also be the sites of comet formation. We have therefore been led to a scenario in which stars and planets are formed in concentrations in the midst of a great mass of dust, gas and planetesimals comprising such a nebula. These are identical with the globules and heads of cometary globules referred to in Chapter 1. As the nebula evolves and breaks up, its contents—comets, stars and so on—will disperse into interstellar space. But with the view now arrived at, as the stars separate they will each carry with them a retinue of planetesimals and dust, these debris forming an extensive cloud. Subsequent gravitational buffeting will, as we have seen, disperse the comets in the outer cloud, but there will probably be an intermediate region, a few thousand a.u. in radius in the case of the Sun, which remains relatively stable, with comets bound to the star for its lifetime. Thus, orbiting into the planetary system there will generally be a mixture of primordial material and captured interstellar material. Our understanding of what we see in the inner solar system should therefore be qualified: there are probably primordial bodies as well as recent captures.

It is usual to see the small body populations of the solar system—the satellites and asteroids to be discussed—as having grown within a few a.u. of the Sun, in the conditions peculiar to the solar nebula.
if most observed comets are interstellar the picture we arrive at may be quite different. For we now envisage an interstellar connection: in the first place many of these small bodies have grown, perhaps light years apart, in the conditions of a dense nebula, prior to capture; secondly, capture events may continue throughout the lifetime of the solar system. We might hope eventually to discriminate between these pictures by dynamics. For in one scenario we expect stability and quiescence in the solar system over a timescale of 4.5 billion years, in the other we might expect to see rapid orbital evolution and other evanescent phenomena, arising from a temporary immigrant population of small bodies. We shall take a closer look at these small bodies.
3 · Comet to asteroid: solar system debris

Comets entering the planetary system may undergo close encounters with the major planets. Most are perturbed out of the solar system again, but a very few are captured into more or less stable orbits. We consider that some of these become asteroids or satellites: an interstellar origin for some asteroids is thus implied. Others become short-period rapidly decaying comets, and evolve into asteroids in Earth-crossing orbits.

3.1 The asteroid belt

By and large, the planetary distances from the Sun increase smoothly from Mercury outwards. There is an exception to this regularity in the form of a large gap between Mars (1.5 a.u. from the Sun) and Jupiter (5.2 a.u.) where intuitively a planet might be expected. From the mid-eighteenth century onwards it had been suspected that a planet might exist undetected in this gap, and in 1796 a corps of 'celestial police' was organized by von Zach to search for this hypothetical planet. As it happened, they were forestalled by an Italian monk, Giuseppe Piazzi, observing from Palermo in Sicily. Checking the accuracy of a star catalogue on 1 January 1801, Piazzi recorded the positions of several stars in the constellation Taurus. On the following night he was surprised to see that one of the stars had moved. On the third night it had moved again. Assuming that he had discovered a peculiar comet, Piazzi sent his findings to other astronomers. But in those days communications were slow, and before others had detected the object it had wandered into the twilight sky and been lost.

By this time it was believed that Piazzi's star was the missing planet, and it became a matter of great urgency to find some mathematical technique for calculating the body's orbit and forecasting its position. The young mathematician Gauss applied himself to the problem, solved it, and on 31 December 1801 the body was relocated. It turned out that Piazzi's star was indeed a little planet moving in the gap between Mars and Jupiter. Piazzi named it Ceres after the titular goddess of Sicily.

In March 1802 a second star-like body was discovered in Virgo by the German amateur astronomer Olbers. This was named Pallas, and
Gauss found that it too had an orbit that lay between Mars and Jupiter, although with large inclination and eccentricity. Olbers speculated that a major planet had once orbited between Mars and Jupiter and had somehow been destroyed, a view still maintained by some. Other fragments, he predicted, would be found in the gap, and soon two more bodies were discovered, Juno in 1804 and Vesta in 1807. Forty years were to pass before a fifth minor planet was discovered, in 1845, followed by two more in 1847, another in 1848 and so on. The introduction of photography in 1891 by Wolf of Heidelberg revolutionized the discovery of these minor planets, or asteroids. A time exposure of a few hours guided on the stars will reveal an asteroid as a streak on the photographic plate as it moves relative to the stellar background. Currently over 2,000 asteroids are known, mostly orbiting in the large gap between Mars and Jupiter, and about 100 are added to the list annually.

The structure of the main asteroid belt is rather like a napkin ring, or a doughnut stretched along its axis. There is a hole or deformation in the outer region of this doughnut, the hole following Jupiter as it orbits the Sun. In essence the asteroid orbits are such that close approaches to Jupiter are avoided, the planet being surrounded by a
zone of avoidance of radius more than an astronomical unit. This can be explained as a sort of selection effect: anything which approached too closely to Jupiter would be perturbed, possibly out of the solar system altogether. There are other asteroid groupings outside the main belt. These are the Trojans, bodies in roughly the Jovian orbit but 60° on either side of the planet. They are held in these apparently stable configurations by a combination of solar and Jovian gravity.

Most asteroids are seen as no more than points of light in a telescope. The light received often varies cyclically over periods of a few hours, indicating that a spinning, irregularly shaped body is being observed. To determine the dimensions, however, indirect techniques must be used. One approach is to observe the eclipse of a star as the asteroid drifts in front of it, the duration of eclipse (usually a few seconds) being a measure of the angular extent of the occluding body. For example teams of observers have been situated along the shadow path of Eros during its eclipse of a star. The occultation timings were used to show that Eros is shaped like an ellipsoid or brick measuring about 30 × 19 × 7 km.

The absolute size of an asteroid may also be calculated if the reflecting power of its surface rock is known: for a given brightness in the telescope, a dark asteroid must be larger than a bright one. However the darker the surface the more sunlight is absorbed and re-radiated in the infrared and the less sunlight the surface reflects. Measures of both infrared and reflected (visible) brightness therefore give the reflectivity and so the dimensions of the asteroid.

Light reflected from a surface is generally polarized, and the degree of polarization can be measured. Laboratory experiments have shown that the darker a rock is, the more polarized is light reflected from its surface. Measurements of an asteroid’s polarization, as the angles of viewing and illumination change, give a measure of the reflectivity of the asteroidal rock and hence, again, the diameter. It turns out that the known asteroids range from almost 1,000 km (Ceres) to probably 1 km (e.g. Hermes) or less across.

There is fine structure within the asteroid belt, but overall their numbers increase enormously towards the small end of the scale, only the difficulty of discovery causing them seemingly to peter out. There may be about 400,000 asteroids more than 1 km in diameter. In spite of this enormous preponderance towards the small end, the mass of the system is concentrated in the few largest bodies, probably about half the total residing in Ceres alone. The entire mass of the system may be a thousandth that of the Earth.
3.2 The origin of the asteroids

Many opinions have been held as to why there are thousands of small irregular bodies, instead of a planet, between Mars and Jupiter. They have been seen as fragments of an exploded planet; but the problems involved in exploding a planet seem to be insuperable. They have been seen as an incipient planet, their accretion not yet complete; but with collision velocities of about 5 km/sec they form a decidedly fragmenting system. And they have been seen as collisional fragments of an initial handful of large planetesimals, of which Ceres is an unbroken fragment; this is the view largely held now. At any rate the belief is all but universally held that they are indigenous to the system, having grown from a flat primitive disc of gas around the Sun—the primordial solar nebula. This seems a reasonable view: the existence of planets implies an accretion phase and hence planetesimals en route, and the very high cratering rate in the early solar system testifies to their past existence at least.

But at the end of Chapter 2 we described a hypothesis in which not only are there interstellar planetesimals in the early stages of solar system formation but there is capture during the later voyage through the Galaxy. A reappraisal of the canonical view is therefore called for, and to this end we shall examine the relationships between comets and asteroids.

An influx of rocky bodies from a capture episode could not populate strictly stable orbits as the main belt asteroids seem to be in. It is a fact of celestial mechanics that between stable and unstable orbits there is a barrier, and so long as gravity is the only force operating this barrier cannot be crossed: an unstable orbit will always remain so. But the barrier can be crossed with the aid of non-gravitational forces, and it happens that many comets are subject to precisely such forces.

This was first demonstrated for a faint telescopic comet studied by Encke in 1818. There are many remarkable features about the orbit of comet Encke and it will feature prominently in our tale in due course. It has the shortest known period of any active comet (3.3 years), a low inclination (12°) and a high eccentricity (0.847). Encke found that the comet’s period was shortening by the intolerable amount of 0.1 days per orbital revolution, far more than could be explained by planetary perturbations. Over the subsequent 150 years the force has varied enormously. The great majority of short-period comets studied since then have been found either to accelerate or to brake in their orbits.
A ‘rocket effect’ is implied. It arises from the fact that there is a time lag between the heating of an area of comet and the subsequent vaporization of the ices. Generally the nucleus is rotating and the ice will be hottest (and evaporation strongest) not at local noon on the comet but some time in the afternoon. This asymmetry of ejection will accelerate or retard the comet depending on the direction of rotation and the time lag. These non-gravitational forces may sometimes be very much stronger than the gravitational perturbations caused by the planets, and they may operate systematically rather than randomly. Large meanderings of orbit are sometimes possible. Inevitably the barrier between stable and unstable orbits must be crossed from time to time by active comets, and if the comet happens to become inactive when in a stable orbit, it will be dynamically indistinguishable from an asteroid.

Fig. 8. Plan view of the inner solar system showing the terrestrial and jovian orbits together with the mildly eccentric orbits of several well-known short-period comets. Most of these objects are relatively weak compared to the longer-period comets which, being for most of the time very far from the Sun, tend to have suffered much less outgassing and are thus considerably brighter during perihelion passage. Encke’s comet is a principal actor in the present drama, and its orbit is in the general direction of the vernal equinox. In fact, it appears out of the Taurus constellation which gives its name to the Taurid meteor stream associated with this comet. The period of the orbit is approximately 3.30 years.

There are probably many ways in which a comet could jet itself into an asteroidal orbit. One route would involve perturbation, by Jupiter, of a short-period comet into an orbit of even shorter period, with passages close to the Sun so that strong outgassing developed. If the rotation of the nucleus were retrograde so that a braking effect
were exerted, the orbit would tend to circularize and this could happen rapidly enough for further close encounters with Jupiter to be avoided. The degassed nucleus would then have joined the asteroids.

Now the fundamental dynamical difference between comets and asteroids is that comet orbits are unstable, while those of asteroids are apparently stable. We have already noted that the asteroids avoid close approaches to Jupiter whereas comets do not. The transition probability from cometary to asteroidal orbit may be small but this might be offset by the large comet flux in the neighbourhood of Jupiter: an injection rate of one comet in 5,000 years would be adequate to account for the entire asteroid system. While such a process must occur, its rate of occurrence is at present an unsolved theoretical problem. If it is significant, however, one might expect to see transitional objects, lying ambiguously between the cometary and asteroidal camps. As it happens such objects have come to light. Orbitally there are now known to be comets in asteroidal orbits and asteroids in cometary orbits. For example there is a group of six comets moving in near circular orbits very similar to those of some asteroids (the Hilda group) in the outer regions of the belt; in fact the comets and asteroids intermingle. Temporary capture into such orbits therefore seems to be quite a common occurrence, and although these comet orbits are not quite stable, their proximity to those of the (presumed stable) Hilda asteroids indicates that the relatively small non-gravitational effects, operating over some revolutions, may on occasion push such comets across the barrier into an absolutely stable regime. Further, Neujmin I and Arend-Rigaux, comets with practically asteroidal appearance, are in quasi-asteroidal relatively stable orbits which avoid close passages to Jupiter: it has already been suggested by Marsden that these may be transitional objects. And at least two large ‘asteroids’, Hidalgo and Chiron, are in unstable comet-like orbits.

In the next chapter we shall study asteroids whose orbits bring them into the inner regions of the solar system, within the orbits of Mars or the Earth. There are strong grounds for considering that most of these are degassed comets. In part the arguments are dynamical. Additionally one of these asteroids (Hephaistos) has an orbit sufficiently like that of comet Encke to imply both are fragments of one disintegrated object and that the asteroid is therefore a dead fragment of a comet. Another of these asteroids, 1979 VA, has the unstable orbit of a short-period comet, with an aphelion which brings it close to Jupiter. The reflectivities of these little objects correspond to those of
the main-belt asteroids, the outer ones in particular. Here then is evidence that degassed comets cannot be distinguished from many of the main-belt asteroids at least so far as surface mineralogy goes.

The size distribution of comets has also been determined recently, although there are severe problems of interpretation and observation—the nucleus cannot even be seen—and the errors are large. Within these errors the size distribution is that of the asteroids, with a great preponderance of small bodies, giant comets being comparatively rare. Long-period comets seem to occur down to about 1 km diameter. The maximum possible size is a matter for speculation, but if Chiron and Hidalgo are truly inactive comets, then comets can have the dimensions of the larger asteroids.

We seem then to be approaching the view that in comets and asteroids we are not dealing with fundamentally different objects at all, that perhaps an asteroid is an inactive comet, and that perhaps also the asteroid belt is an ancient reservoir, containing not only truly primordial bodies but also an admixture of interstellar ones.

### 3.3 Problems with asteroids

We can further examine this question of interstellar asteroids by looking more closely at the structure of the belt. Figure 9 shows the distribution of eccentricity of the main-belt asteroids. Jovian perturbations would introduce mean eccentricities of only 0.03 and

![Graphs showing the fairly broad distribution of eccentricities and inclinations of orbits in the asteroid belt. These characteristics are highlighted in this chapter since they are difficult to explain in terms of the conventional flat nebula theory of the origin of the solar system. Thus the eccentricities of main-belt asteroids, if induced by Jupiter, should lie to the left of the vertical line shown. They are more easily explained however if the asteroids were formed over a wider region of space, as in a cometary globule, and indeed if some of the asteroids have been captured as comets from interstellar space.](image)
maximum eccentricities of 0.06. This difficulty applies equally to the asteroidal inclinations. It has been known for some time, for example, that Jupiter cannot have perturbed Pallas from the plane of the solar system to its current orbit, inclined at 35°. But how, then, can such a large solid body (the second largest asteroid) have grown in such a steeply inclined orbit? Given the simple picture of growth from a primitive solar nebula, which was flat, a collision might have deflected Pallas. But the colliding body would have had to be extremely large; collisions are very inelastic; and in any case the net effect of internal collisions is to take energy out of the system, i.e. flatten it.

The essential point is that the asteroid system ought to look like the rings of Saturn rather than a doughnut. It has too much internal energy, and ad hoc mechanisms have to be added to the conventional picture to puff the system up. One such proposed mechanism is the gravitational stirring of asteroids by massive planetesimals which were once scattered into the belt, but which have since vanished. Even a grazing fly-by of the Moon at 10 km/sec would only perturb an asteroid by about 0.3 km/sec. A passage at 0.1 a.u. would disturb the asteroid by 6 cm/sec. To reach the internal velocities of 5 km/sec, either a very large number of massive bodies or long residence time in the asteroid belt would be required. With the mass distributions one expects of growing bodies these invaders would be accompanied by a host of secondary bodies which would be quite enough to destroy the asteroids by collisions. One could of course make the further postulate that only massive unaccompanied planetesimals were injected, and one must further assume that, having stirred the system up, they are then ejected. While one can probably find a range of properties which would inject energy into the asteroids without destroying them, one has to ask about the plausibility of the circumstances, keeping in mind that the mechanism is ad hoc in the first place. While this is a matter of subjective judgement, it seems to us that on the flat primordial nebula cosmogony there is a second problem: the asteroid belt has too much internal energy. On the other hand, this particular difficulty would not assume so much importance if asteroids were formed in a primordial solar globule or captured from interstellar space.

Another manifestation of this problem is that accretion from a quiescent state would grow only to the point where the bodies begin to deflect each other in orbit, the collision velocities are enhanced, and they begin to break up. Evolution should only proceed to a state of
equilibrium between accretion and fragmentation. That the asteroid belt is not in this state but rather is fragmentation-dominated, is also obvious from the internal random velocities of about 5 km sec which ensure destruction on impact.

The asteroids seem to occupy every available stable or quasi-stable orbital niche. This is qualitatively expected if they are regarded as degassed short-period comets subject to appreciable random walk due to the rocket effect. The Trojans lie beyond the normal outgassing distance of comets. Whether they represent a difficulty with the capture mechanism remains to be seen. They might be part of a class of body with surfaces more volatile than water ice; but there is no evidence to say whether they are in truly stable orbits, numerical work having shown, for example, that bodies in chaotic orbits leading to ejection from the solar system may linger in the Trojan region for long periods of time.

The scenario we have described then leads to the rather startling conclusion that some asteroids may have grown in interstellar conditions, and that indeed many may in fact be comparatively recent captures from the spiral arms of the Galaxy. From the observational point of view it seems that one cannot yet discriminate between this hypothesis and the standard paradigm, although the puffed-up structure of the belt and the existence of apparently transitional types are suggestive. Until quantitative work is done on the orbital transfer problem, the idea that many or most asteroids derive from interstellar capture or primordial globule or both will remain a shot in the dark. But the usual picture of asteroids as entirely primordial is equally a shot in the dark, even if hallowed by familiarity and not recognized as such. In astrophysics, where experiment is not usually possible, there is a danger of uncontrolled theoretical speculation untested against predictions. Paradoxically this can be a case for more speculation rather than less. Bandwagons can fall over cliffs, and the forensic fitting of data in ever greater detail on to some prescribed ‘wisdom’ can give the illusion of progress: it is the unrecognized speculation which is the real danger. In our view there are many hints that all may not be well with current views on solar system cosmogony: there is the ad hoc nature of the usual planetesimal growth theories; the increasingly vague distinction between comets and asteroids; the (as we shall see) failure to identify most meteorites with anything in the asteroid belt from which they are supposed to have come; and so on. Special explanations can and have been devised for all these problems; but it is prudent to range more widely, to see whether
radically different interpretations of the data might not be more satisfactory than perturbations on received views.

3.4 Short-period phenomena in the solar system:
an interstellar connection?

One interesting hidden assumption is that the solar system was set up 4.5 billion years ago and has been running smoothly ever since. It is true that the near-circularity of the orbits of the major planets, and their more or less regular spacing, are in harmony with this view, but the situation is less clear for the smaller bodies of the solar system.

This is exemplified by theories of the rings of Saturn. The classical assumption has been that the ring system was formed along with the planet, and in studies of the origin of the ring it has been quite common to reject this or that model on the grounds that it would make the rings younger than the planet.

The ring system seems to be 1–3 km thick and in fact comprises many hundreds of rings. It was thought to lie wholly within the so-called Roche limit, within which tidal forces would break up a weak satellite to form a ring system, but the Pioneer 11 and Voyager 1 flybys showed that they extend well beyond the limit, that is to regions where tidal effects cannot have broken up a larger body. Radio and radar observations are best fitted by supposing the bulk of the ring comprises icy particles 4–30 cm in diameter. Bodies of this size however are disrupted by inelastic collisions, and this should have shrunk the ring system to 100–200 metres thick. The current thickness is more consistent with an age of only 10–100 million years.

Erosive forces due to ultraviolet radiation and micrometeorite bombardment on icy particles must be at work also, and the latter in particular could destroy the ring system within a million years.

There are in any case observations of the ring system extending back to 1610. Many of these are strongly suggestive of variability within the rings, and even possibly spreading of the inner ring, ring C, towards the surface of the planet on a remarkably short timescale. The C ring itself was not discovered as such until 1850 so that what the earlier observers were measuring is open to question, but 1850 onwards was the era of the micrometer men, the accuracy of whose measurements can hardly be surpassed now, and there are no evident systematic effects over the last 100 years to produce a spurious drift. If the measurements are taken at face value a very recent evolution or origin for the Saturnian ring system is implied. Similar remarks can be made for the Jovian ring system discovered in 1979 by Voyager 1.
the ring particles seem to be of microscopic dimensions and must be resupplied on a timescale of 100 years or so. A primordial origin for these systems would now seem to be a risky assumption!

Other short-lived phenomena (Table 2) are to be found among the smaller bodies of the solar system, ranging from the well-established to the conjectural. The object Chiron which orbits between Saturn and Uranus and whose brightness corresponds to that of the larger asteroids, is in an unstable orbit and will most probably be ejected from the solar system in a few hundred thousand years. If it is an escaped satellite or a refugee from the main belt, then we are observing a very rare event. Another "asteroid" in this category is Hidalgo, in a Jupiter-crossing orbit. Its probability of ejection at each crossing is about 1 in 100,000 and it is unlikely to remain in the solar system for more than another 1 or 2 million years. Amongst the satellites also there are short-lived objects. For example Phobos, the innermost satellite of Mars, is spiralling in under the action of

Table 2. Short-lived or recent solar system phenomena

<table>
<thead>
<tr>
<th>Object</th>
<th>Phenomenon</th>
<th>Characteristic timescale (years)</th>
<th>Probability</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHIRON</td>
<td>Ejection from solar system</td>
<td>50,000</td>
<td>1/100,000</td>
<td></td>
</tr>
<tr>
<td>HIMALGO</td>
<td>Ejection from solar system</td>
<td>1,000,000</td>
<td>1/5,000</td>
<td></td>
</tr>
<tr>
<td>TRITON</td>
<td>Spiralling in towards planet</td>
<td>10–100 million</td>
<td>1/1,000</td>
<td>Largest satellite (diameter about 3,700 km), retrograde orbit indicative of capture</td>
</tr>
<tr>
<td>PHOBOS</td>
<td>Spiralling in towards planet</td>
<td>60 million</td>
<td>1/100</td>
<td>Faint inner ring apparently spreading towards since discovery in 1859</td>
</tr>
<tr>
<td>RINGS OF SATURN</td>
<td>Spreading in towards planet?</td>
<td>500–10,000</td>
<td>1/100,000</td>
<td>Satellites of Saturn whose orbital periods are in a 2:3 resonance, which was formed or disturbed only a few hundred million years ago</td>
</tr>
<tr>
<td>MIMAS/TETITHYS</td>
<td>Evolving</td>
<td>200 million</td>
<td>1/25</td>
<td></td>
</tr>
<tr>
<td>resonance</td>
<td>Evolving</td>
<td>400 million</td>
<td>1/10</td>
<td>Orbits retrograde, indicative of capture, and unstable</td>
</tr>
</tbody>
</table>

Various short-lived or recent solar system phenomena. The spreading of the inner ring of Saturn, if real, implies evolution on a timescale of millennia, and Voyager observations have placed the active state of the rings beyond doubt. The probabilities (column 4) are simply the relevant timescales of the phenomena divided by the age of the solar system (4.5 billion years). An active rather than quiescent small body population seems to be implied, and if so episodes of capture of bodies into the solar system are indicated.
The planet Saturn photographed during the Voyager I fly-by November, 1980

Tidal forces and will crash on to the Martian surface in about 60 million years if it is not first broken up into a ring system. Triton, the largest satellite of the solar system, is in a retrograde orbit about Neptune and appears to be spiralling in towards the planet on a timescale of 10–100 million years. Should it reach the surface the angular momentum transferred will be sufficient to reverse the direction of rotation of the planet, but not before it has transformed Neptune into an incandescent ball of vapour!

In all there are fewer than fifty known satellites, ring systems or Chiron-sized bodies in the solar system, and five or ten of these appear to be short-lived on timescales characteristically 1–100 million years. It is hard to see this situation as consistent with the classical quiescent picture. One is inevitably led to enquire whether the sporadic capture mechanism might produce these phenomena. However the mechanics of satellite capture and ring formation are currently unsolved problems, and any proposal of this sort must remain for the moment speculative. Nevertheless the intermittent capture hypothesis does provide a single, simple explanation of diverse phenomena which have so far required a whole variety of ad hoc theories in so far as they have been discussed at all, and the possibility that bodies from the spiral arms of the Galaxy are in orbit around the planets seems to deserve further investigation.
4. Asteroid to crater: 
the anatomy of impact

The inner planets are studded with craters caused by the impacts of asteroids and comets. Modern studies reveal a history in which the bulk of the craters were formed early in the life of the solar system. Subsequently, however, the impacts have been dominated by Apollo asteroids which are, we suggest, periodically repopulated by bursts of interstellar comets and steadily depopulated by planetary encounters. According to this picture, the meteorites are ultimate fragmentation products of the original solar globule and on the whole are less massive than comets. During capture episodes they are simultaneously perturbed into Apollo orbits. They predominantly sample the primordial solar system.

4.1 Comets as the source of Apollo asteroids

That some asteroids may approach the neighbourhood of the Earth was appreciated by 1898, with the discovery of Eros, which is capable of approaching to within 22 million km, that is about sixty times the distance of the Moon. Its orbit, however, does not cross that of the Earth. The first asteroid in a true Earth-crossing orbit, and therefore a potential collision hazard, was discovered by Reinmuth of Heidelberg in 1932. It was named Apollo after the Greek god of the sun. In the same year a second asteroid, Amor, was discovered with an orbit marginally outside that of the Earth, its point of closest approach to the Sun being 1.08 a.u. These bodies have given their names to two classes of asteroids: those in Earth-crossing orbits are the Apollo asteroids, those with orbits which cross that of Mars but not the Earth are the Amor asteroids.

A second Earth-crosser, Adonis, was found in 1936. Hermes, a third, was discovered by Reinmuth in 1937. It approached to within 800,000 km, twice the distance of the Moon, moving at up to 5° an hour, and completely crossing the sky in nine days. The effect was 'much like that obtained by standing near the railroad track when the evening express roars past'. Hermes has since been lost. With the use in recent years of wide-angled telescopes for sky surveys, and the systematic search programme carried out by the Americans Shoemaker and Helin, the list is now being added to at a rate of about four a year. Discovery of Apollo asteroids is a haphazard affair and the forty-odd
now known are probably only a few percent of the total. All are points of light even in the largest telescopes and their sizes cannot be directly measured. However the indirect techniques already described are applicable, and it turns out the size distribution of the known Apollos is similar to that of main belt asteroids.

Obviously the discovery of these objects is strikingly incomplete. For example Hephaistos, the largest known asteroid of the group with a diameter of 10 km, was discovered only in 1978. However calculations of true abundance can be made by estimating the completeness of telescopic search. The estimated numbers of Earth-crossers, in the size range 1 km upwards, have increased dramatically in recent years. Öpik in 1963 thought there might be as many as forty; in 1973 Whipple thought there might be up to a hundred. Shoemaker and his colleagues, a few years later, put the number at 750 ± 250; and with the discovery of 'Aten' objects whose orbits lie mostly within the Earth's it is now appreciated that there may be over 1,300 Earth-crossing asteroids.

An Apollo asteroid may collide with Venus or the Earth, or less probably with the Moon, Mercury or Mars, or it may be gravitationally perturbed out of the solar system altogether. The mean life expectancy is about 50 million years, which for a population of say 1,300 asteroids more than a kilometre across means that one asteroid is lost from the system every 40,000 years. If the Apollo asteroids are the tail end of a decaying population, then 3 billion years ago their numbers would have been many times greater. Since Apollo asteroids are a prime source of craters on the inner planets, the cratering rate would have been correspondingly higher. In fact, the cratering rate has been roughly constant on average over the past 3 billion years and so the Apollo asteroids must be continually replenished from some other small body population.

Only two such populations are known, the main-belt asteroids and the system of comets. Unfortunately it is not generally possible to calculate past and future orbits in great detail, small uncertainties magnifying rapidly. Most calculations involving three or more solar system bodies are unreliable beyond a few hundred years. Some general statements can be made, however. If Apollo asteroids evolve from the main belt by the random accumulation of many small perturbing forces, then there should be a great preponderance of asteroids in Mars-crossing orbits, and this is not observed.

The only other possibility is that certain critical orbits are very unstable. Such orbits have been found, in the main belt, in which
Jupiter 'pumps up' the eccentricity in a resonant interaction, to the point where an asteroid is perturbed into an Earth- or Mars-crossing orbit and brought under the control of either of these planets. Of course asteroids would be quickly depleted from these critical orbits. To keep the supply going, collisions between asteroids are envisaged. An asteroid orbiting at the edge of a resonance zone would have to be bumped at about 0.2 km/sec in the right direction to enter it. However, the theoreticians find that only 7–10 per cent of Apollo asteroids may be supplied from the main belt in this way and we must look elsewhere for the major source.

The only other known small-body population capable of supplying the Apollo system are the comets or, to be precise, those comets which have orbital periods of only a few years. It is true that most comets have enormously long periods of orbit around the Sun. We have seen in Figure 5 that there is remarkable concentration of semi-major axes around 25,000 astronomical units, and this leads to revolution periods of about 4 million years. Of the 600 comet orbits which have been computed, however, about 100 have revolution periods of less than a century. Unlike the long-period comets, these form a flattened system, mostly co-rotating with the planets, with a mean inclination of about 15°, not very different from the mean of the Apollo system. The first known of these so-called periodic comets was discovered by Halley, who found that the bright comets of 1531, 1607 and 1682 were almost identical in orbit, being highly inclined and moving in a retrograde sense. He deduced that they were the same comet. Having last passed its perihelion in 1910 and aphelion in 1948, at which point it was further away than Neptune, Halley's comet will re-appear in early 1986 passing within the Earth's orbit on its way once more to perihelion. It is doubtful however whether it will be as spectacular a sight as it has been on earlier visits.

Although comets as a whole seem to have little resemblance to asteroids, developing comae and tails whenever they approach to within 3 or 4 a. u. of the Sun, we have seen in Chapter 3 that the distinction between comets and asteroids at greater distances is nowadays becoming increasingly blurred. Indeed they could represent an evolutionary sequence, and it is perhaps the frequent changes in the appearance of comets that provide the clue as to what is going on. They can transform before our eyes as they lose mass and energy and must therefore have finite lifetimes. Indeed within the last 200 years several short-period comets have vanished. Probably a typical lifetime for a short-period comet is between 100 and 1,000
Asteroid to crater: the anatomy of impact

years, although of course a large one might persist for millennia. The Estonian astronomer Öpik has suggested that mass loss through evaporation of volatiles shrinks the diameter of a comet by \(1/(250\sqrt{q})\) kilometres for every perihelion passage, \(q\) being the perihelion distance in a.u. Thus, if a typical periodic comet is about 1 km in diameter, it would have a lifetime of only 500 years. It is then a question of whether a comet evaporates completely, or leaves a solid residue, thereby becoming an Apollo asteroid. It may be that a definitive answer will require a space mission, but certainly the activity of a comet decays with time, suggesting that either the porous surface structure becomes overlaid by more compact, less easily evaporated material, or that there is a non-volatile material, dust or rock, below the surface. For example Encke's comet is now very weak and, it has been estimated, will become an Apollo asteroid some time in the 21st century.

At present Encke's is the only known active comet in the inner solar system. Wetherill has followed the evolution of such comets in the inner solar system, assuming they become asteroids, by a computer simulation of gravitational perturbation from the inner planets and Jupiter. Test objects were injected initially into the orbit of comet Encke, and random walks of their semi-major axes and eccentricities followed. Soon after injection the orbits are close to that of Encke, but beginning to drift. After about 5 million years a few Amor asteroids have appeared, after about 30 million years the whole inner region is homogeneously filled, with about equal numbers of Apollo and Amor asteroids, and after about 100 million years an approximate equilibrium is reached in which there are twice as many Amors as Apollos.

The existence of transitional objects provides further evidence for this evolutionary sequence. One Apollo asteroid, 1979 VA, has an orbit like that of a short-period comet; with aphelion close to Jupiter it is probably in a very unstable orbit. And in addition to comet Encke we have met in the previous chapter the two periodic comets, Arend-Rigaux and Neujmin I, which have been virtually asteroidal in recent years. It seems from these studies that comets in short-period orbits must decay into objects which, in appearance and orbit, are indistinguishable from Apollo or Amor asteroids.

It only remains to be seen whether long-period comets can produce short-period comets at a sufficient rate to account for the present population of Apollo asteroids. Once again, computer simulations come to our aid. Everhart has shown that long-period comets can...
occasionally be deflected by Jupiter encounters eventually into Apollo-type orbits, and with the present density of comets in the inner solar system, this would result in an object of the appropriate size, diameter exceeding 1 km, once every 10,000 years or so. This is considerably more rapid than the Apollo depletion rate, and the present stock of around 1,000 is thus easily explained if the comet flux has been maintained through something like the last 10 million years. Such a timescale coincides very nicely with the solar system passage through Gould’s Belt.

It follows that if the interstellar comet theory is correct, the Earth-crossing asteroids must also in large part be interstellar in origin. There may, in addition to this sporadic component, be a slowly declining ‘primordial’ population leaking into the Apollo system out of extremely long-lived orbits. But amongst the kilometre-sized objects this background is not likely to be dominant. Even if the asteroid belt were entirely composed of primordial material it could not contribute with present estimates more than 10 per cent to the Apollo population.

4.2 Encounters with Apollo asteroids: impact craters

A capture episode, then, gives rise to a decaying deluge of bodies in the planetary system, most bodies being rapidly ejected, others finding more or less temporary orbital niches and lasting longer, and yet others striking the planets. But episodic capture implies episodic bombardment, and with the data we have now assembled the impact energies and current collision frequencies can be calculated.

It turns out that if the current population is typical, an Apollo asteroid of at least 1 km diameter will collide with the Earth every 250,000 years or so. If such an asteroid has the density of water ice, its mass is 4 billion tons and for a mean impact velocity of 25 km/sec the impact energy is 3 million megatons. For a rocky constitution the energy will approach 10 million megatons. The unit of energy employed here is the ‘megaton equivalent of TNT’, one megaton corresponding to the explosion of a million tons of TNT. The Hiroshima explosion had an energy of about a fiftieth of a megaton; a sizeable hydrogen bomb will release 1-10 megatons of energy; the Krakatoa eruption of August 1883 was about 50 megatons; and a major earthquake may involve the release of over 100 megatons.

From the size distribution of Apollo asteroids, again if the current population is typical, then since Precambrian times (say within the last 600 million years) the Earth has probably been struck about ten
times by missiles with impact energies in excess of 150 million megatons, and once or twice with energies in excess of 3 billion megatons. These are colossal impacts, occurring within timescales of biological and geological significance. According to the argument which has unfolded, they occur, not randomly, but with a galactic modulation, the impact rate at some epochs being several times higher than at others. Such collisions cannot fail to have catastrophic global consequences, and these we shall examine in the next chapter. Firstly, however, we shall look at the evidence on the ground, in the form of craters.

In the spring of 1610, in a little book entitled *The Sidereal Messenger*, Galileo announced that the Milky Way was composed of myriads of stars, that four satellites orbit the planet Jupiter, and that the Moon is covered with craters. The three domains explored in this book—galaxy, solar system and planetary surface—were also the first astronomical targets of the telescope.

Galileo described the craters as ‘a great quantity of small blackish spots sprinkled everywhere over the area illuminated by the sun ... the said small spots always having their dark parts towards the sun’s position, and on the side away from the sun they have brighter
boundaries as if they were crowned with shining summits.' He recognized the small blackish spots as shadows thrown by rings of mountains, or craters.

For 350 years following Galileo's discoveries, only the Moon and Earth were known to possess craters, and only the Moon in abundance. Then in 1965 the spacecraft Mariner 4 sent back the first close-up photographs of Mars. In spite of only 1 per cent photographic coverage and a large dust storm, several craters were detected on the planet. In 1971 Mariner 9 photographed the little Martian satellites Phobos and Deimos, revealing densely cratered surfaces. In 1972 mapping of the entire Martian surface was completed, revealing a planet in which one hemisphere was heavily cratered, the other lightly so. Also in 1972 scientists at the Jet Propulsion Laboratory in Pasadena penetrated the clouds of Venus by radar, revealing, again, a cratered surface. And in 1975 Mariner 10 passed close to Mercury and transmitted photographs showing a surface hardly distinguishable from that of the Moon.

Details of the cratering vary from body to body. Mercury shows a slight relative deficiency of very small craters and overall is not quite as saturated as the Moon. Craters of the order of 100 km across are as common on Venus as on the older surfaces of Mars but the planet is strikingly deficient in smaller craters. On the Moon and Mars, the crater density is patchy, ancient volcanic activity having covered 15 per cent and 50 per cent of the surfaces respectively, no doubt obliterating earlier craters. It is likely that the crater production history of all these bodies has been similar but that the crater obliteration history has varied, depending on the extent and duration of vulcanism on the body. Craters are therefore ubiquitous and must be symptomatic of some process occurring, now or in the past, throughout the solar system.

In 1667 Robert Hooke had dropped bullets into a stiff clay, creating little impact craters. However, he had also boiled a mixture of powdered alabaster and water, and the bursting bubbles had also formed craters. A lively controversy over crater cosmogony, engendered by these simple experiments, has swung back and forth for 300 years, and only within the last decade or so has something like a consensus been reached.

Some craters are produced by internal processes. Apart from terrestrial examples there is Olympus Mons, an edifice about 1,000 km in diameter rising about 27 km above the Martian 'ground level.' The summit caldera is pitted with subsidence craters and the whole
Impact craters on the planet Mars. Note the dry valleys indicative of extensive water erosion which is not yet explained. It is believed that these canyons were gouged out in the space of a few days. Catastrophic flooding events would probably be precipitated by the impact of ice-bound comets of a few kilometres diameter.

Structure is plainly volcanic. In 1979 Voyager 2 encountered the four Galilean satellites of Jupiter. Io, the innermost, was found to possess craters whose volcanic nature is indisputable: several were erupting. Hooke himself had dismissed the impact hypothesis as he could not conceive of a source of projectiles. But in spite of these counterexamples there is now little doubt that the great majority of craters are caused by impacts. No internal mechanism could account for their range of sizes, from microscopic to global, and the fact that they are found on the most diverse bodies including small moons with no sources of internal heat. In any case, geological studies of ancient terrestrial craters often reveal shattered bedrock and meteoritic iron, putting an impact origin beyond reasonable doubt in the minds of most, although not all, geologists.

Impact craters are therefore a record of collision events which may have been very remote in time, and they play the same part in the study of solar system history as do fossils in phylogeny.
Interpretation of this fossil record may be complicated: on the lunar highlands there are craters within craters, craters on craters, craters overlapping craters and near-submerged craters. On the other hand, a single large crater has a simplifying effect; it obliterates everything below it. It can therefore act as a recorder of younger, smaller craters formed within it. Thus, in conjunction with absolute dating of lunar rock samples, has history been reconstructed.

The lunar maria—dark patches visible to the naked eye—provide a suitable background for crater counting. Galileo himself had remarked on the sparseness of craters on these darker areas. Lunar rock samples indicate that the maria are seas of lava which solidified about 3.5 billion years ago. Lunar cratering history from then to the present time is therefore easier to disentangle.

To study the crater production rate in the remotest eras we have, as mentioned in Chapter 2, to go to the lunar highlands. These are probably the oldest surfaces in the solar system, more than 4 billion years old. The crater density in these regions is several hundred times greater than in the maria. That is, hundreds of times as many craters fell in the interval 4–3.5 billion years ago as have fallen in the interval 3.5 billion years ago to the present. Furthermore, the crater production rate seems to have fallen to something like its modern value by 3–3.5 billion years ago, maintaining a steady average rate to this day. Making up this mean trend is an underlying flux interspersed with spikes in the crater production rate, that is, brief periods of enhanced bombardment superimposed on a weaker background. Only so much information can be extracted from crater counts, unfortunately, and the intensity and duration of these bombardment episodes, and their separation in time, are not well known. The results are summarized schematically in Figure 6. Broadly speaking, we may interpret the early rapid decline in terms of the mopping-up of the primordial solar nebula or globule. This process would continue indefinitely in principle, but there evidently came a time when a non-declining source of impacting bodies began to dominate. Though certainly constant in rate if averaged over a long enough time, it is essentially a fluctuating source, the peaks occurring at intervals of perhaps 100 million years or so again, the characteristic galactic modulation which we have predicted.

It remains to be seen whether the size distribution and number of craters are consistent with Apollo asteroids as the prime missiles. On the Moon, for every crater 100 km or more across there are 100 10 km or more across and 400 in excess of 5 km across. Lunar craters
Asteroid to crater: the anatomy of impact

smaller than these are more often secondary, derived from a shower of lumps thrown out from a larger primary impact, and so tell us less about the impacting missiles. Small craters are much more abundant than large ones, and this is true of Apollo asteroids. To see whether these size distributions are compatible we have to look at the mechanics of impact.

Coming in at 20-30 km/sec an asteroid will be brought to a halt in a distance about equal to its own diameter, being literally turned inside out in the process. Pressures of several million atmospheres and shock temperatures of tens of thousands of degrees are immediately generated. At these extremes the material of the asteroid and crust around it are transformed into a ball of hot gas and the ground behaves like a fluid. A shock wave spreads beyond the fireball, dissipating energy and momentum. Below a million atmospheres, large volumes of rock are melted. In the later stages of shock the pressure drops to below 100,000 atmospheres and the strength of the crustal material becomes important, although its properties are unfamiliar: boulders, for example, may deform and bounce like rubber. Below about 10,000 atmospheres, rock strength and gravity become dominant, crater walls are formed and the process is brought to a halt. The formation of a large crater may take a few minutes.

Dust, boulders, and melted rock and vapour are thrown out. A rim of debris, kilometres high in a large impact, is formed round the hole, but beyond this a blanket of ejecta is hurled. The largest fragments may have about a third of the diameter of the original missile. In this way chains of secondary craters may sometimes be formed. Such chains, one 100 km long with craters up to 5 km across, are seen radiating from Copernicus (Plate 11). For a terrestrial land impact, dust and nitric oxides are thrown high into the atmosphere. If the crater is sufficiently large the melted rock will fall back into it and the crater will flood with lava: about 90 per cent of the affected rock is crushed, rather more than half the remainder being vaporized, and the rest melted. In fact the larger collision structures on Earth are covered with thick sheets of rock once melted by impact.

For very small craters the volume of material excavated is proportional to the impact energy. If the volume of a crater scales as the cube of its diameter D, then so also will the energy: $E \propto D^3$. For very large craters, the hole excavated may be kilometres deep and the crater rim kilometres high: the collision has transported large masses over large vertical distances. An additional factor proportional to the linear dimensions of the crater and local gravity is therefore
introduced and so the energy scales as the fourth power of the diameter: \( E \propto gD^4 \) on this simple model, where \( g \) is the acceleration due to gravity.

Through geological studies coupled with theoretical calculations of this sort based on the physics of collision, impact energies as a function of crater diameter have been derived. It turns out that the impact energy represents a compromise between these theoretical extremes: measuring \( D \) in kilometres and \( E \) in megatons it is found that \( E = 2.4 \times 10^4 \) \( D^4 \). This relation holds also for many chemical and nuclear explosion craters formed in the desert alluvium of Nevada, although of course the scale is entirely different. Very roughly, for the larger impacts, an asteroid will excavate a crater about twenty times its own diameter. Knowing how asteroid size relates to energy of impact, and energy of impact relates to crater diameter, we are now in a position to relate Apollo asteroid size distribution to crater size distribution. It turns out that agreement is excellent, consistent with Apollos being a prime source of missiles.

Table 3. Crater diameters and impact energies and rates

<table>
<thead>
<tr>
<th>( D ) (km)</th>
<th>( \delta t ) (million years)</th>
<th>( E ) (megatons)</th>
<th>( d ) (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>9.2</td>
<td>7.1 million</td>
<td>3.9</td>
</tr>
<tr>
<td>100</td>
<td>14</td>
<td>15 million</td>
<td>5.0</td>
</tr>
<tr>
<td>200</td>
<td>58</td>
<td>160 million</td>
<td>10.9</td>
</tr>
<tr>
<td>500</td>
<td>360</td>
<td>3600 million</td>
<td>30.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Phenomenon</th>
<th>( E ) (megatons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hurricane</td>
<td>500</td>
</tr>
<tr>
<td>Major earthquake</td>
<td>100</td>
</tr>
<tr>
<td>Krakatoa eruption</td>
<td>50</td>
</tr>
<tr>
<td>Tunguska event</td>
<td>40–100</td>
</tr>
</tbody>
</table>

The typical interval \( \delta t \) between impacts of planetesimals of diameter at least \( d \) whose impact energies are at least \( E \) and which produce craters of diameter at least \( D \). The energies associated with several violent terrestrial phenomena are included for comparison.
Active comets must also collide with the Earth from time to time. At present a major impact will most probably be asteroidal, but during a capture episode it is possible that collisions with long-period comets will be competitive or even dominant: the information is not yet available to be more precise. The size distribution of comets is similar to that of their presumed degassed remnants, the Apollo asteroids, and so yields the same crater size distribution, within the errors.

4.3 Galactic modulation of the cratering rate

If the missile supply is erratic then we should not expect a precise matching between the average lunar cratering taken over a long period and the rate one would infer from the current missile numbers. With a capture event ending 10 million years ago and the depletion rate of Apollos, a mismatch by a factor of two or three is feasible. Because terrestrial craters can be dated, one should also look at the cratering rate on Earth in geological times to see whether discrepancies ascribable to galactic modulation exist.

Impact craters on the Earth have gone unrecognized until recent times. Undoubtedly the rapid erosion and deposition on top of a terrestrial crater accounts for their rarity. A crater 1 km across may typically have a lifetime of 1 million years, one 0.1 km perhaps 10,000 years. The Arizona crater, about 1 km in diameter, was discovered in 1870, but its impact origin was widely doubted for some time. Geological studies, which included the discovery of about 30 tons of meteoric iron in the vicinity, have settled the matter. In 1928 a crater 160 metres across was found at Odessa, Texas, also surrounded by meteoric debris. In 1930 thirteen craters were found in Henbury in central Australia, ranging from 1 metre to 200 metres in diameter. Again many iron meteorites were found around these craters.

By 1950 only about a dozen terrestrial impact craters had been discovered, mostly by accident. With the advent of systematic searches, however, this number has been increasing by about four a year, and at present about ninety terrestrial impact structures are known. Their distribution over the surface of the Earth is very irregular. This may reflect in part those areas where searches have been carried out, but in addition the Canadian and Baltic shields and their surrounds provide the geologically stable surfaces on which ancient craters may be recognized. They date from about 450 million years before the present and the record of impacts on Earth cannot be reliably traced earlier than this.
On the Moon and Mercury, with little erosion and no atmosphere, the dominance of impacts on all scales is obvious. Some of these impact structures are very large: the Mare Imbrum is 700 km in diameter, and the Mare Caloris on Mercury is 1,300 km across. But the impact histories of Earth and Moon must have been very similar. Thus in spite of the effectiveness of the erosion and sedimentation in general, terraforming on this very large scale would be difficult to obliterate. Hudson's Bay and the Gulf of Mexico may be ancient impact structures, and many more such features are beginning to come to light. One of the first to review this possibility seriously was the amateur geologist Gallant in 1964. The geologist Norman in 1977 claimed to have detected many large circular structures, often more than 1,000 km across, and suggested that any large-scale crustal feature with an arcuate outline deserves scrutiny. Faint, almost perfectly circular patterns were also detected by Saul in 1978, over 1,000 being detected by him on topographic maps. These were characterized by high rims and a wide range of sizes (up to 700 km), with fracturing along part of their rims. Saul found that these structures placed extraordinary control over local geology in general and ore mineralogy in particular. It seems that on all scales from the local to the very large, topographic features due to impact can be discerned—this is no more than one would expect on astronomical grounds—but are very difficult to detect and have generally gone unrecognized.

At any rate, arguing from well-defined and recognizable craters formed on Earth over the last 500 million years, one finds that the current Apollo population alone would give twice as many craters as are observed: there are too many Apollos. The situation is even more extreme for the Moon: the current Apollo population would give five times as many lunar craters as are observed.

These results are considered to be statistically significant. Of course terrestrial craters have been produced over the last 500 million years, lunar craters over the past 3,500 million years. The cratering rate has therefore been higher in 'recent' times. This cannot be understood as a mechanism arising within the solar system, and the implication is that there has been some change in the galactic environment over the last 500 million years. Another result, of marginal significance, is that the observed ratio of Apollo to Amor asteroids is not an equilibrium one. The observed numbers fit better a capture event which ended 30 million years ago. The sample of bodies is too small for this figure to be reliable, however.
We have now discussed five tests for episodicity of bombardment. These are the lunar soil micrometeoroid data, the evidence of irregularity in the lunar cratering history, the matching of the current Apollo population with terrestrial craters, likewise with lunar craters, and finally the observed minus calculated equilibrium numbers of Earth- and Mars-crossing asteroids. Some of these standing alone, give information of only marginal significance, but cumulatively the evidence appears to support a sporadic rather than a steady supply of missiles.

4.4 Problems with meteorites

We have now traced the path of planetesimals from their growth in the spiral arms of the Galaxy, to collision with the Earth. We have seen that within geologically significant timescales there have been impacts on Earth of several hundred million, and probably several billion, megatons. In the next chapter, we shall turn to the terrestrial consequences of such devastating collisions, but first we must examine rather more carefully that remaining class of solar system missile—the meteorites.

Shooting stars, points of light which move swiftly and silently through the constellations, can be seen on any clear dark night. Very occasionally one can see a fireball, a brilliant orange or bluish flare brighter than Venus. The occasion of the fall of a meteorite is outside the experience of the great majority of people. In the course of a few seconds a fireball as bright as day comes down from the sky, accompanied by hissing and thunderclaps culminating in a bang. A trail of dust marks its flight and can remain suspended for hours in the sky. These terrifying apparitions have been known from earliest times and were given names such as ‘fiery serpent’, ‘dragon’ and so on. Records of meteorite falls have been found on Egyptian papyrus dating from 2000 BC on the conventional chronology. Chunks of material may reach the ground: these are the meteorites.

Probably about 500 meteorites enter the Earth’s atmosphere each year, most of them falling into the sea. There are about 2,000 meteorites preserved in museums, a third of which were ‘falls’, that is they were seen to fall from the sky, the others being ‘finds’. Between ten and thirty new meteorites are found each year. They are broadly divided into irons and stones with a small intermediate group of stony irons. Stones outnumber irons by about ten to one immediately after a fall, but the number of finds is more or less evenly balanced between the two main types. This is partly because a meteorite, if stony, is less
easily recognized as such; and in addition stones erode more quickly.

There are numerous sub-divisions of these main groups, stones in particular being divided broadly into chondrites and achondrites. By far the largest group of stony meteorites are the chondrites, so-called because they contain grains or chondrules varying from microscopic to centimetre-sized. The strength and composition of these chondrules varies enormously from quasi-volcanic to crystalline. They are not found in terrestrial rocks.

The mineralogy and petrology of meteorites is a vast, complex and controversial topic, no single model fitting all the data. Meteorites generally have been seen as cooled from a molten phase, the solidification age being derived by radioactive dating. Many have apparently been part of a regolith, that is the fractured outer layers of a planetesimal; most show signs of exposure to cosmic rays and the solar wind. In many cases, the exposure age is much less than the solidification age, indicative of later fragmentation. It is considered likely that most meteorites were once part of larger bodies, probably asteroid-sized. Comets of this size that get deflected into short-period orbits steadily disintegrate into objects which are, as we have noted, indistinguishable in appearance and orbit from Apollo asteroids. Some are associated with meteor streams. The exposure ages of meteorites are often strikingly similar to the orbital lifetimes of short-period comets. It is thus intuitively attractive to consider comets as the prime source of meteorites. In this picture, one has to regard the comets as the result of cold accretion even though the meteoritic component originates from an earlier hot regime.

The ages of meteorites confront us with an immediate difficulty however. These indicate that the meteorites cannot be predominantly recent captures from interstellar space. Ages are measured in terms of isotope ratios, the products of specific radioactive decays following solidification. Some radiometric ‘clocks’ measure gas retention ages and can be ‘reset’ rather easily by collision, that is, impact causes the
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material to lose the gas. The rubidium/strontium clock, however, is insensitive to such processes and can be reset only by very intense metamorphism. It is therefore a good measure of the real age of a meteorite. Among the achondrites and irons, only a few such ages have been determined, though there are many more among the more prevalent chondritic meteorites. Most of the ages cluster around 4.5 billion years, indicating a contemporaneous origin and presumably measuring the epoch when the material formed in the primordial solar nebula or globule. Such ages indicate the meteorites cannot be predominantly recent captures from interstellar space.

So long as the asteroid belt is regarded as indigenous to the solar system and of the same age, it will be natural also to attempt to identify meteorite types with particular asteroids and to suppose that the composition and structure of meteorites provides information about the belt. The meteorites are seen as debris thrown off asteroids during a collision. This alternative view, although widely accepted, also presents difficulties.

Spectrophotometric measurements in the near infrared are available for several hundred asteroids and it has been found that the belt is a very heterogeneous place. Over eighty spectral signatures are recognized, and hardly any two asteroids are completely identical. In spite of this diversity, they are divided into a few distinctive groups. Seventy-five per cent are extremely dark and neutral in colour and are designated the C-group; the S-group are objects of moderate reflectivity and red in colour. Correcting for bias of discovery due to the different reflectivities, one finds similar size distributions for the two types, but the distribution through the asteroid belt is markedly different. The S-type asteroids prefer the inner part of the belt and the numbers decrease smoothly from the inner edge at 2 a.u. from the Sun. The C-type inhabit the outer regions. Thus the percentage of S-types to all others drops smoothly from about 60 per cent at 2.2 a.u. to 10 per cent at 3 a.u. and less than 3 per cent at 3.4 a.u. The two main types may indicate progressive surface degradation or different modes of origin and thus different ages. It would be helpful if there were any dynamical calculations to give any credence or otherwise to the latter hypothesis but unfortunately, the assumption that asteroids provide most meteorites and are therefore of the same age has tended to discourage investigations of this kind. Now, many meteorites have infrared spectra resembling those of the asteroids. The assumption that similarity of composition implies parenthood is however less secure. For example, a meteorite that fell near Kapoeta has a reflection
spectrum very similar to that of the large asteroid Vesta but there seems to be no plausible dynamical way of transferring a fragment of Vesta to the Sudan. For transfer to be possible, the fragment must be injected into an unstable orbit, with resonant perturbations by Jupiter building up until the meteorite orbit intersects that of the Earth. Vesta, however, is far from any such resonant orbit. In general, it has not proved possible to explain dynamically how meteorites could be generated from the asteroid belt. Another difficulty is that whatever the merits of particular identifications, over 85 per cent of the meteorites entering the Earth’s atmosphere are chondritic and these cannot be certainly identified with anything in the asteroid belt.

We seem to have arrived at an impasse therefore, both rival theories running into difficulties: on the one hand there seems to be no adequate dynamical means of extracting most meteorites from the asteroid belt and there are severe identification problems, on the other hand we have excluded the present comets on the grounds of age. The problem may well arise from trying to identify meteorite parents with things we can now see. Another possibility is that meteorites originate from ancient planetesimals. We have seen (Figure 6) that the planetesimal flux about 4 billion years ago, deduced from cratering on the lunar highlands, was about 1,000 or 10,000 times the modern value. With such an impact rate the local meteorite production rate must have been prodigious. Of course, prior to the formation of the lunar surface the planetesimal collision rate must have been many orders higher. It is then inevitable that a swarm of meteoritic parent bodies formed early in solar system history and was flung by planets or their nuclei into intermediate sized orbits, beyond the planetary system, which are not affected by encounters with massive nebulae. Inevitably such material must be continually perturbed into short-period orbits by Jupiter. It is therefore reasonable to see the present-day meteorites as the much fragmented and considerably diminished vestiges of this original huge cloud of boulders.

Some meteorites do have distinctly anomalous ages. The implication of the Nakhla meteorite for example is that igneous formation was taking place only 1.24 billion years ago (an independent technique gives 1.39 billion years). The crystalline structure is that of a body which was once part of a large, slowly cooling volume of molten rock. Similar conclusions have been reached for the Shergotty meteorite which is 1.1 billion years old and must have been part of a large volume of melt at that time. Even with a large asteroid impact
on Earth, only a small percentage of rock is melted, and at the low strengths and retaining gravities of the asteroid belt it is not to be expected that a collision could produce a large volume of very slowly cooling molten rock. It seems that meteorites such as Nakhla and Shergotty do not fit into the standard pattern—ages close to 4.5 billion years—and that an interstellar capture hypothesis for these bodies is at least as likely as any other. It is of course a firm prediction of the capture hypothesis that a certain proportion of meteorites will have anomalous ages: the measurement of a rubidium/strontium age greater than that of the solar system would put an interstellar origin beyond doubt.

The great heterogeneity of both asteroids and meteorites also seems to argue against their having been produced in a narrow strip of solar nebula, the properties of which would presumably be restricted. For example the abundance patterns of trace elements in iron meteorites have been examined by the metallurgist Sears and compared with thermodynamic models of the hypothetical solar nebula. It turns out that the iron meteorite groups have formed over a very wide range of pressures, covering 10,000 to one. Sears proposes that these meteorites were formed in widely separated regions of the solar nebula and brought together in the asteroid belt by some unspecified mechanism before transfer to Earth. It is of course not necessary to have so complicated a history. Once more, what we are probably looking at in the meteorites are not primarily ejecta from the asteroid belt but primordial material arriving from a much wider region of the solar system.

We have now arrived at a view of meteorite origins quite different from that usually envisaged, which view should be testable by chemical and mineralogical studies. Of course meteorite data are generally interpreted in terms of condensation from the supposed hot, gaseous solar nebula, and it might be considered absurd to suppose that this huge body of data could be fitted into the vastly different conditions of a cold dense globule.

As it happens, however, the meteoriticist Clayton has recently proposed a radical model for meteorite origins, which he considers to solve many old chemical anomalies, not least the ubiquitous presence of the chondrules. He points out that interstellar grains, accumulated into larger bodies within a cold dense nebula, contain a large store of chemical energy, which energy can be released very rapidly when the accumulates are warmed to say 100°C. The explosive release of this heat is sufficient to create a molten droplet of centimetre dimensions
which, on recoiling, is identified as a chondrule. The creation of these very abundant, once-melted inclusions in meteorites is a very old problem. The important feature of this argument of Clayton’s is that it removes the need for any hot, primordial solar nebula and places meteorite and planetesimal growth generally in the wider domain of the cold interstellar medium; the conclusion we have already arrived at from a quite independent route. If Clayton’s model is correct, it is still necessary to envisage prior aggregation and differentiation in bodies of sub-planetary size which subsequently fragment. This is certainly possible if the initial state of the solar system material was a cold dense material of the kind that is observed to exist deep within giant molecular clouds. Before this, however, we are in the realm of uncertainties discussed in Chapter 1.

The conclusion at the end of this brief foray into the field of meteoritics is as follows. The most conspicuous craters and their history of formation are a record of planetesimal impacts both in the primordial solar globule and from subsequent captures. With the passage of time, however, the families to which the earliest missiles belonged have fragmented and dissipated leaving a plentiful population of relatively inconspicuous smaller objects. Each crossing of a spiral arm by the solar system captures a new cloud of relatively large planetesimals, the comets, into highly eccentric orbits. At the same time, there is perturbed into similar orbits a flood of relatively smaller planetesimals, mostly remnants of the original solar globule. There should therefore be a population of interplanetary boulders, in orbits like those of the short-period comets and Apollos. The meteorites will derive from this collision-dominated population and their age distribution will to a large extent mirror the integrated planetesimal flux throughout the lifetime of the solar system. The meteorite population is thus largely composed of objects as old as 4.5 billion years.
5 · Crater to catastrophe: the aftermath of impact

Collisions of asteroids and comets with the Earth have been generally neglected by Earth scientists. In fact the rate of bombardment is very much higher than was realized until recently, and we explore here some of the probable consequences. We are led to propose that great impacts, occurring within bombardment episodes as the solar system moves through spiral arms, have been a major controlling factor in the evolution of life, being responsible for catastrophic mass extinctions of species. Fundamental geological phenomena such as frequent sea-level changes, the occurrence of ice ages and plate tectonic episodes, including mountain building, may also have been triggered by impacts. We therefore put forward a neo-catastrophist view of Earth history.

5.1 The significance of impacts

That the occasional impact of a cosmic body may have dramatic global consequences, including the extinction of species, is a very old speculation. We have quoted the Marquis de Laplace (writing in 1806) to that effect in the prologue. Occasional papers on the subject are to be found scattered throughout the scientific literature of subsequent years. In 1956 the palaeontologist de Laubenfels suggested that hot winds from a giant meteorite impact may have caused the famous dinosaur extinction. Ōpik in 1958 pointed out that hot ash from an asteroid collision would spread far from the site of impact, destroying life below by heat. McLaren, in his presidential address to the palaeontological society of America in 1970, suggested that a giant meteorite impacting in the palaeozoic Pacific might have caused turbidity in the shallow seas of that era and choked filter-feeding creatures.

On the whole, such ideas have not been taken seriously, the influence of impacts on Earth history being generally overlooked; one can open almost any text book on palaeontology or geology to find the evolution of the Earth discussed as if the planet existed in isolation. The view we take here is that, on the contrary, far from being negligible, collisions are a major determinant of Earth history, to the extent that geological periods may be initiated by the occasional very large impact. It is therefore worth briefly enquiring why, if this is so,
14. Serra da Cangalha, a meteorite crater of 12 km diameter, in a remote part of central Brazil. First discovered by an airline pilot (Guilherme Winter) in the 1950s, it was later identified on Landsat satellite photographs. It is believed to have been formed 220 million years ago, though most impact craters of this size on Earth are much obscured by subsequent erosion.

The catastrophic effects of large impacts have generally gone unrecognized.

One reason, very likely, is what must have seemed to be the speculative nature of the proposition. The tendency has been to look for internal phenomena as causing, say, mass extinctions or continental drift. With this view an impact or other extra-terrestrial hypothesis would be seen as a last resort, something one could do without. In any case until recently very few impact craters had been recognized on Earth—only a handful, mostly insignificant, were known until the middle 1960s. This is of course a consequence of the rapid erosion of terrestrial craters—most are less than 300 million years old and only three craters are Precambrian. In, say, the middle 1960s there was a widespread belief that lunar craters were volcanic and there were no quantitative data on impact rates. This, coupled with a lack of cross-fertilization between say astronomer and
palaeontologist, probably contributed to the neglect. Finally, the atmospheric consequences of a large impact have even yet not been fully studied, and their truly devastating nature has still to be generally appreciated. A great deal of analysis has still to be done and the processes involved can still be described only in a qualitative way. This is true also of ocean impacts.

Another reason may lie in conservatism; in evaluating hypotheses one is tempted to prefer the mundane over the spectacular. The Canadian palaeontologist Russell has described this as 'the principle of minimum astonishment'. To this one can only reply that an incoming Apollo asteroid is indifferent to the psychological predilections of the creatures below!

A deeper reason for bias against catastrophism may lie in the circumstances of history. Around the time of Laplace's speculation, Baron Cuvier, the founder of palaeontology, was proposing on the basis of fossil evidence that six great catastrophes—mass extinctions of species—had occurred in the history of the world. Construction work in Paris had turned up the fossil remains of sharks, reindeer, turtles, mammoths, crocodiles and so on, in superimposed layers. He concluded that the fauna had changed suddenly at different times, the final catastrophe in particular (the mammoth extinctions) indicating that a sudden dramatic freezing on a continental scale had taken place within a few minutes. The six extinction events were equated with the six days of creation, new species having appeared after each extinction. The catastrophists' views were popular in the early part of the nineteenth century. Against this was the uniformitarian approach of the Edinburgh geologist Hutton, apparently substantiated by Lyell: on this view the physical and biological features of the Earth in the past were produced by the action of the same forces which operate at the present time. The uniformitarian view gradually prevailed so that by the middle of the nineteenth century catastrophism was dead in scientific circles. Of course the advent of Darwinism was apparently the final blow.

The principle of uniformity pervades geology in particular at the present time. The irony is that, seen astronomically, large and devastating impacts are common within geological timescales; catastrophism is uniformitarianism. We can take this view because in recent years many terrestrial craters have been discovered, largely by the Landsat satellite, the cratering history of the Moon has been determined with the help of lunar soil samples; and the Apollo asteroid population has been investigated with wide-angled Schmidt
telescopes. With these new data the cratering history of the Earth can now be determined with some degree of confidence.

There is in fact no reason to expect a detailed equivalence between the current Apollo asteroid population and the cratering rate, and indeed we have seen that the observations seem to indicate an overabundance of current Apollos by a factor of two or three. The impact rate deduced from terrestrial craters will, however, represent an average of the past 500 million years, covering the period of evolution of multi-celled life. A head-on collision between the Earth and a body in a parabolic retrograde orbit would produce a 72 km/sec impact. In practice the system of Apollos is a somewhat flattened, co-rotating system and the mean impact velocity is 25 km/sec. Adopting this mean value, the impact energies and rates shown in Figure 10 are easily found. They are uncertain to within a factor of two or more. Within the past 500 million years, then, there been about fifty collisions of energy more than 7 million megatons, ten of more than 100 million megatons, and one or two of energy in excess of 3 or 4 billion megatons. These energies are listed in Table 3 along with those of various documented phenomena for comparison.

So we begin with the question what are the likely effects of a billion-megaton impact, of the sort expected to have occurred a few times in the last 500 million years and equivalent in energy to the detonation of a hydrogen bomb on each square kilometre of the Earth's surface?

**Fig. 10.** Graph comparing the energy of impact explosion (in millions of megatons of TNT equivalent) with average interval (in millions of years) between arrivals of missiles corresponding to at least the given energy. Major geological boundaries at intervals of approximately 200-million-year intervals may be associated with billion-megaton events which cause physical and biological disruption over at least a terrestrial hemisphere.
5.2 The effect of a large land impact

The lethal effects of a land impact are partly due to drastic atmospheric disturbances. At present detailed numerical work on these disturbances has still to be carried out, and the partitioning of energy between the various factors, and indeed the proportion of the total going into atmospheric effects, is not well known. Our description is therefore necessarily qualitative.

The comet or asteroid will enter the atmosphere at hypersonic speed and a shock wave will hug its forward hemisphere and extend backwards as a long cylinder. Essentially it punches a hole in the atmosphere, the displaced air being thrust sideways from the cylinder at about the speed of the missile, creating a blast wave of about 10 million megatons. The great bulk of the kinetic energy of the asteroid therefore reaches the ground, and the crater develops in the manner already described. Much of the energy is expended in the fragmentation and shifting of the rock, a few per cent going into the creation of a high-temperature ball of vapour. A crater of about 200 km diameter is formed within a few minutes, ejecta being raised through several kilometres and deposited in part in a rim. The atmosphere around the crater will be violently disturbed by these rapid ground motions and by the expansion of the fireball. Further, the passage of ejecta ranging from kilometre-sized lumps to hot ash is expected and strong interaction will occur between these ejecta and the atmosphere. The proportion of energy ultimately deposited in the atmosphere is difficult to assess with precision. Certainly in an explosion, a considerable percentage of the original energy ends up as blast wave. A figure of 10 per cent is adopted below.

Complicated though the atmospheric disturbances must be in the region of the crater, the situation will have simplified within a few crater diameters, a few minutes after the explosion. Beyond 1,000 km, say, from the epicentre, a shock wave will have formed and be moving rapidly outwards. The situation may be characterized by a cylindrical shock front behind which the atmosphere has piled up into a dense, high-pressure hot shell. The shell snowploughs into the as yet undisturbed atmosphere ahead of it, gathering it up. If say 10 per cent of the impact energy is deposited as blast motion into the atmosphere within 500 km of the epicentre, then at 2,000 km distance a wind velocity of 2,400 km/hr of characteristic duration 0.4 hr is expected. If there is no back pressure behind the blast, that is if it is impelled forwards simply by its own momentum, then at 5,000 km
the wind velocity has dropped to 400 km/hr, enduring for 0.8 hr, and at 10,000 km from the epicentre, that is 90° away, the wind speed is down to 100 km/hr and blows for 14 hr.

In addition to the dynamic pressure caused by the blast of air there is an instantaneous pressure and temperature rise due to the compression of gas immediately behind the shock front. The shock and blast inevitably deposit energy into the atmosphere, and this appears ultimately as heat. At 2,000 km the overpressure is 8.5 atmospheres and the air temperature is 480°C; at 5,000 km the figures are 0.6 atm and 60°C, dropping to 0.1 atm and 30°C at 10,000 km. This intense heating expands the atmosphere behind the front, which rises to create a hot, low-density regime: the blast wave is thus followed by a partial vacuum, a rarefaction wave, of somewhat longer duration.

If all the nominal 100 million megatons of energy deposited in the atmosphere were manifested as wind motions, a mean wind velocity of 1,500 km/hr would be expected globally. If deposited as heat, then a global rise in air temperature of 43°C would be expected (Figure 11).

The heat-deposition problem is somewhat complicated by the fact that vaporized and melted rock, hot ash and so on will be flung out of
Fig. 11 Rough calculations of wind speed and air temperature at various distances from the source of a billion-megaton event. The shaded areas indicate the distance out to which immediate destruction might be considered total: not only would all trees be uprooted and blown over, but the temperature would be lethal to living creatures.

the crater, the vapour and small particles especially streaming along with the current. This represents an additional source of heat, but the consequences are difficult to assess. Strewn fields of tektites (centimetre-sized pieces of fused rock which are most likely solidified ejecta from past cratering events) are found at several localities around the world. The Australites, for example, are found over the whole of southern Australia. Some tektite fields have been associated with known terrestrial craters. For example the Moldavites, found in Czechoslovakia, are associated with the Nordlinger Ries crater in Germany. The ages of both have been determined as 14.7 million years. The widespread occurrence of the tektites indicates that small ejecta may sometimes be thrown over great distances. However probably much more lethal are the ash and vapour borne along by the blast. An optically thick layer of such material, passing overhead at the condensation temperature of 2500°, would be quite lethal to anything below it. Öpik examined this effect and concluded that the lethality would extend over continental if not hemispheric dimensions.
About 100,000 cubic km of material is ejected by the impact, much of it in the form of fine dust which is carried along by the violent motions of the atmosphere. Even in an undisturbed stratosphere, fine dust quickly spreads globally: measurements of radioactive carbon deposition produced by past nuclear explosions show that there is a mixing of stratospheric material between northern and southern hemispheres on timescale of a few months.

The falling speed of a particle ten-millionths of a centimetre across in the normal, undisturbed atmosphere is about 1 mm/sec at 50 km altitude, about 0.1 mm/sec at 30 km, and about 0.01 mm/sec at 15 km. At the latter speed a falling time of five years is implied. Very roughly a particle a tenth as large has a tenth this falling speed and the converse. Sub-millimetre-sized particles would fall out within about a month.

The experience gained from volcanic explosions is invaluable here as showing the characteristic size of dust injected into the stratosphere from a great explosion to be about ten-millionths of a centimetre In the final report of the Krakatoa committee of the Royal Society (1884–1980) it is stated that particles of this size were suspended in the atmosphere for three years; this is broadly consistent with the theoretical figures above. Dust particles from the 1980 eruption of the Mt St Helens volcano in Washington State were similarly sized. Several eruptions of Mt Agung in Bali, the first on 17 March 1963, are of interest because a slight fading of starlight was detected at several observatories around the world. By about a month after the eruption, reddening of the sky at dusk was noticeable in Australia and South Africa. At the Cerro Tololo observatory in Chile, the normally small extinction in visible light (about 12 per cent) showed a sudden spike at the end of April followed by a gradual rise to about three times the normal value in September, followed by a slow decline. A similar phenomenon was noticed at the Radcliffe observatory in South Africa. By September or October 1963 the ash had diffused into the northern hemisphere and astronomers there were detecting absorption of starlight. This phenomenon was again characteristic of a few cubic kilometres of fine dust injected into the stratosphere.

In the case of the Krakatoa explosion, about 20 per cent of the ejected material was in the form of fine dust, amounting to about 6 cubic km (km³) in all. This was sufficient to reduce sunlight reaching the ground by about 10 per cent over a two- to three-year period, and this may have decreased the average global temperature by some
tenths of a degree. A similar proportion of 100,000 km\(^3\) would result in a blockage of sunlight with an 'overkill' factor of over 10,000! Thus, if this simple picture of dust suspension were valid, total blackness would be expected for two to three years after the impact, followed by a rather sudden clearing of the sky.

A drastic change in the chemistry of the atmosphere, probably of most consequence in the stratosphere, is also likely. Above about 2000° nitrogen and oxygen in the atmosphere combine to give nitric oxide. Each megaton injected into the atmosphere will produce between 1,000 and 5,000 tons of nitric oxide and this will be carried into the stratosphere. An injection of 100 million megatons therefore implies the creation of several hundred thousand million tons of NO. Between 15 and 40 km altitude, ozone (O\(_3\)) filters out biologically damaging ultraviolet solar radiation. The mass of ozone in the atmosphere is comparable with the injected mass of NO. The latter, however, destroys ozone by a catalytic reaction in which 1 g of NO removes 100–200 g of ozone. The result of the impact would therefore be a complete removal of the ozone. While this hardly matters when sunlight is blocked by dust in any case, the question would become important if, by the time the dust clears, the ozone were still depleted. The timescale for the replenishment of ozone is twenty to thirty years.

Apart from these atmospheric effects, mention should also be made of a ground effect which may be of consequence well beyond the crater. The energy carried by the shock, penetrating the ground, shatters and heats the rock, expelling some of it to form a crater. But a small residue of this energy will spread beyond the rock-fragmenting region: once the tensile strength of the rock is greater than the shock pressure, the rock no longer fragments and the energy is transported by vibration. Probably 1 per cent or so of the total energy is thus carried away by seismic waves. For the impact being discussed, about 10 million megatons will go into these vibrations much of it as surface waves earthquakes. The Rayleigh (corkscrew) and Love (to and fro) waves which comprise earthquake motions damp slowly with distance, the amplitude at 5,000 km still being a third of that near the epicentre; and at 90° from the impact point the energy/km\(^2\) in the ground motions will still exceed 10 per cent of that around the crater. A mean global value of about 0.01 megaton/km\(^2\) is implied. This is at the extreme top end of earthquake intensity scales, and corresponds to great catastrophe with for example earth layers being overturned, clefts appearing in the ground and free-standing objects and creatures being thrown in the air.
To sum up, the immediate global effects are a violent scorching wind, the ejection of incandescent material, severe earthquake, possibly a prolonged obscuration of sunlight, and exposure to ultraviolet radiation of germicidal intensity when the sky clears.

5.3 The effect of a large oceanic impact

Of course most impacting bodies will have crashed into seas or oceans. The consequences of ocean impact have been little studied and are not well understood, and in the description that follows one cannot even be sure that all the main features of the phenomenon have been included.

Experiments on crater formation in sand show that the sizes of craters in loosely bound material may be up to ten times those of the corresponding craters formed in rock. A very large, shallow crater, perhaps 500–1,000 km across, would be formed by the impact of a 10 km diameter asteroid, the crater 'walls' being formed of water. The whole structure, because of the great dimensions, would take over an hour to form. Of course the ocean whose depth will be less than the diameter of the asteroid, is quite unable to absorb the impact momentum and a true crater will be formed in the sea bed, breaking the crust and exposing the underlying hot mantle material. The shattering of the ocean bed material will not be greatly affected by the overlying water but its excavation will be: in effect some of the ballistic energy of excavation will be transferred into water wave motion. Lifting and displacement of the underlying rock may be a prime input to the oceanic disturbance.

The filling in of the water crater will create a rebounding column of water mixed with solids, the whole reaching several kilometres in height. Because in the latter stages the inrushing water is flowing over lava some energy transfer is expected. It might be considered that a square centimetre column of water several kilometres deep will not be significantly affected by heating through contact with lava at one end, however the possibility exists that some of the heat energy is expended in overturning the lava, in which case a rapid convective mixing of the lava is possible. The heating then becomes a volume rather than a surface phenomenon and may be quite significant. The energy contained in a 100-metre depth of lava at 2000°C, in a crater of radius 100 km, is about equal to the initial impact energy, and this must complicate the subsequent flow of the displaced water. We neglect the effect here.

The crater expert Gault and his colleagues carried out a calculation
in which a 1.4 km diameter asteroid struck the ocean at 25 km/sec. They found that 92 per cent of the impact energy went into splash, shock heating and wave formation. The ocean was evacuated to a depth of 6 km over a radial dimension of 15 km. Neglecting turbulent dissipation of the wave energy, they found that the ‘ripples’ spreading outwards had an amplitude of 1 km at 100 km distance from the epicentre, dropping off in proportion to distance so that, for example, the wave amplitude was 50 metres at a distance of 1,000 km.

Approaching a shoreline, a wave slows down and increases in amplitude as it enters shallow water. There is a piling up of water as the forward part of the wave slows down. An increase in wave height by a factor of ten as the coastline is reached is expected so that the 50-metre wave would become 0.5 km in height.

The important question however, is the stability of these impact-generated waves. Development of the wave structure is a complicated technical problem and work carried out by Streletz suggests that the waves may break up and dissipate in the ocean. The reason is that the waves are steep, not sinusoidal. Piling on to each other they evolve into a hydraulic bore—an almost vertical wall of water in an extreme case—which cannot maintain its shape and therefore breaks up in the open sea.

The steepness of the waves, in turn, comes from the small dimension over which the energy has been deposited: thus in the Gault calculation one has energy greater than that of any earthquake-induced tsunami dumped into a mere 200 km² of ocean. A normal tsunami may be induced by a sub-oceanic earthquake covering an area of 30,000 km². The waves generated are of great length and are very shallow: on a ship at sea one would scarcely notice the swell. These long wavelengths tend not to be destroyed by passage into shallow water and can therefore deposit their energy right on a coastline, with devastating effects. It is probably significant that an earthquake in Chile in 1960 produced damaging tsunamis at Hilo in Hawaii and on the Japanese coast, the latter 16,000 km away, whereas the catastrophic tsunami effects of the Krakatoa underwater explosion were felt somewhat locally. The implication, then, is that the huge waves generated by a modest Apollo asteroid may be safely dissipated in the ocean.

The situation may be quite different with an asteroid of 10 km diameter, for in that case the collision energy is a thousand times as great and the submarine crater has an area comparable to that covered by a large earthquake. Thus the ground motions which will
couple into the overlying water will generate waves of length comparable to that generated by a normal earthquake. Of course the energy transported implies a much greater wave amplitude: 1,000 km from the epicentre, the wave would be on the order of 0.5 km in height. For a wavelength of say 100 km this still represents quite a shallow wave: pending detailed calculations or observations in the field, it seems likely that this wave energy can be transported over global distances at least until it reaches a continental shelf or a coastline or a shallow sea, where it will rear up and transform into a breaker kilometres high. A run-up on to land would create a hydraulic bore of awesome dimensions, and a deep and catastrophic inundation of the land.

5.4 The fossil record: biological extinctions

In evaluating the significance of impacts, the approach we adopt here is essentially deductive. That is, it is taken as established from the astronomy that such impacts take place, and we enquire what the likely biological and geological consequences might be and whether evidence can be found in the geological and fossil record. For it would be extraordinary if events of this sort were to leave no trace. First we shall consider the biological effects.

It is the fate of most (or all) species to become extinct and the fossil record shows a continuing turnover of life forms from the earliest times. But from Cuvier onwards it has been known that the record reveals not a smooth proliferation of life from simple to complex as one might expect on a 'naive Darwinian' view. In fact, contrary to a widespread view, the fossil record is hardly Darwinian at all but rather seems to reveal an erratic process, in which evolution is punctuated by many episodes when great numbers of species, in all evolutionary stages, seem to have vanished more or less simultaneously. The palaeontologist Newell describes the situation thus:

'The stratigraphic record is punctuated not by orogenic rhythms but by numerous brief episodes of mass extinction of organisms followed by invasions of new forms into vacated ecological zones. These events vary from local to worldwide.... The most conspicuous palaeontological breaks lie at the top of the Devonian, Permian, Triassic and Cretaceous systems (see Table 4). These and many lesser palaeontological boundaries coincide with obscure paraconformities. This relationship suggests a universal physical control, such as eustatic changes in sea level.'
The situation is illustrated in Figure 12, due to Cutbill and Funnell. This represents the rate of turnover in numbers of taxa throughout the Phanerozoic (the period of multi-celled life) and was derived by assembling and correlating stratigraphic records throughout the world. The resulting data have been smoothed to bring out the main features. Evidently there have been many rapid extinctions of groups, the episodes varying from minor to catastrophic, followed by more or less rapid proliferation of species. Of course smoothing of data implies a loss of information and to determine whether, for example, an extinction episode was instantaneous as might be required by the big impact hypothesis one must look at the original information.

Unfortunately, the problem is complicated by the fact that correlation of stratigraphic sequences between different parts of the world is sometimes ambiguous and, indeed, no general consensus exists about stratigraphic classification at a detailed level. The time resolution of many of the extinctions is not therefore very precise.

Some of the lesser extinctions may have been caused by the removal of barriers between different fauna, resulting in competition...
eliminating species. The immediate cause of some others is apparently due to some prolonged environmental stress, however induced. At the end of the Ordovician, for example, 435 million years ago, when over 60 per cent of taxa became extinct, there was widespread continental glaciation, and the sea withdrew from vast reaches of the continental platforms. For other mass extinctions, however, including the greatest, it has been suspected that catastrophic circumstances must be invoked to explain their suddenness, ubiquity and intensity.

One of these is the late Devonian extinction of 355 million years ago, which was an extinction of the dominant creatures of that period, the bottom-dwellers of the shallow seas. These seas covered much of what is now the northern hemisphere, from Alaska to New York, thence to Europe, from south-west Spain and England across to Siberia, down to south-east Asia and across to western Australia and New Zealand. The extinctions likewise are recorded over this great area.

Many of the life forms which disappeared lived in reef environments, and included the corals: thus the fossil record is one of great coral reef development which came to an abrupt end. Other bottom-dwellers became extinct also, such as many groups of trilobites and filter-feeding brachiopods. Whatever caused the extinction left deeper corals unharmed; and molluscs and brachiopods adapted to rocky bottoms survived. Fish and plankton were unaffected, and there was no sudden change in land plants or animals. The chief characteristic of the event, then, is that there was a catastrophic extinction of animal life living on sandy bottoms of shallow seas which covered much of the globe. Other life was unaffected, including individuals of the same groups which happened to live at deeper levels.

Other marine extinctions of the same general character have occurred and may have the same explanation. Of these, the most dramatic was that at the end of the Permian, 230 million years ago, when probably 96 per cent of all marine species died out. Of the survivors, some lingered on and disappeared, others diversified. This diversification of the post-catastrophe species is consistent with chance effects, some less deserving groups faring well simply because more powerful competition had been eliminated. The creatures which were destroyed were at all stages of evolutionary development. For example the trilobites, which went back to the early Cambrian 570 million years ago and had already suffered in the late Devonian, were
already a declining group. On the other hand the brachiopods, found on all the continents, were at the peak of their development. Likewise the fusulinids (small, shell-bearing plankton) were a successful group, all 500 species of which disappeared. Most sponges and echinoderms (starfish, sea lilies, etc.) vanished also. The most spectacular extinctions were those of the corals. Thousands of species are found in the Permian but these simply disappeared at the end. Some must have survived as they begin to appear again 20–30 million years later.

Unlike the late Devonian catastrophe, that at the end of the Permian was not confined to the sea. Reptiles were the dominant animal life on land, and these suffered about 80 per cent extinction at the family level. Amphibians suffered likewise. However, other fauna seem to be continuous across the Permo-Triassic boundary, the flora were apparently unaffected, and rocks show a continuity of deposition. Throughout this period there was a steady regression of the sea and the emergence of continents.

The best-known catastrophic extinction took place 65 million years ago. This great event marks the end of the Cretaceous period and the Mesozoic era. After existing for about 170 million years, the dinosaurs and other large reptiles suddenly disappeared, other land and sea groups vanishing with them. The finer the taxonomic resolution, the more severe the disturbance is seen to be. For example no basic phyla became extinct, but according to Russell over 75 per cent of all species of organisms living at the end of the Cretaceous were gone at the beginning of the Tertiary. The dinosaur age produced such prodigies as diplodocus and brontosaurus attaining about 50 tons weight (and whose children were the size of African elephants), not to mention such interesting carnivores as the Jurassic allosaurus and Tyrannosaurus rex of the Cretaceous, whose skull was over a metre long. And yet, according to Russell, no land vertebrate over 25 kg weight is known to have survived into the Tertiary. However it should be noted that there were also in existence very small dinosaurs and these too died out. Also on land, the pterosaurs became extinct. Land survivors included the lizards, snakes, birds and of course mammals. The forests of those days were similar to those of present-day Malaysia. Tropical plant life was relatively unaffected by the event, but most species in Alaska, Canada and Siberia disappeared.

In the oceans the ammonites, with a history of about 400 million years and which had therefore survived such previous holocausts as the two already described, disappeared along with several carni-
vorous fish-like reptile groups, especially the successful ichthyosaurs and plesiosaurs. Tortoises and turtles survived. There is a pattern to ocean extinction, in the sense that more severe extinctions took place higher up in the food chain.

There is a good record of fossilized plankton, and for these the situation is somewhat complicated. Some types such as diatoms and radiolarians were unaffected but the position was different for other groups, especially the foraminifera. The foraminifera are shelled amoeba-like creatures of numerous types. The shells are calcareous and from them are built up massive limestone formations, often hundreds of metres thick, which cover an appreciable part of the Earth's crust. They arose in the Ordovician; reached their peak of development during the Cretaceous—the word Cretaceous means chalky—and yet were almost exterminated at the end of that period.

The end of the period was also the end of an era, the Mesozoic, which had endured for 160 million years. In fact the end of the era is its most remarkable geological feature (this might also be said of the Palaeozoic era which preceded it and was terminated by the Permian-Triassic event). From Mexico to Pakistan, from the Arctic to South America, there are abrupt and clear changes in the pattern of sedimentation of the rocks above the fossil boundary. Often there is an increase in the kinetic energy of the water from which the overlying Tertiary sediments were deposited, as well as colour changes which according to Russell suggest more intensive submarine erosion. If impacts were responsible for these vast extinctions, then they must also have somehow triggered climatic and other changes of very long duration.

5.5 Large impacts on land and the mechanics of extinction

There is no doubt about the fate of any living thing within a few thousand kilometres of a big land impact. The blast, overpressure and temperature separately make survival impossible, even underground creatures would be exterminated and seeds would be burned. It is doubtful if even deep roots would survive as the blast would uproot trees.

At say 5,000 km survival is becoming marginally possible for creatures in particular niches. The blast wave arrives instantaneously, that is for the impact studied, there is a sudden wind of 400 km/hr and temperature about 60°C which blows for characteristically an hour, and there is an overpressure of about 0.6 atm. The prospects of survival of creatures exposed to such a wind are a matter for some
speculation. But the high temperature would undoubtedly be lethal to all exposed animals. At a steady wind speed of 210–220 km/hr about 90 percent of modern trees are blown down, the remainder being denuded of branches and leaves. While roots and seeds would regenerate the denudation of the environment would itself be catastrophic.

At 10,000 km from the impact site the atmospheric effects no longer produce mass extinction. The direct effect of blast, then, is to produce mass extinction of life on a hemispherical scale. Whether this would destroy say 75 per cent of all species as in the Cretaceous–Tertiary event depends on accident of geography and impact location. For example an impact on the African continent at the present time would remove all large creatures, birds and so on over most of the land surface of the Earth. One would then have to envisage repopulation of the globe from underground and burrowing creatures, and from organisms in the Pacific islands and the polar regions. The scale of the extinction would therefore match that of the dinosaur event.

At the periphery of the zone of blast destruction cataclysmic earthquake will have shortly preceded the passage of the blast. This is liable to kill large creatures preferentially simply because of their lower strength to weight ratio: a small animal may survive being hurled into the air, a large one will not. More speculatively, the ecological upset may be biased against larger creatures. For in a devastated area, with much of the vegetation gone, there might be enough food/km² for some small creatures with small individual food requirements to survive, but not enough food/km² to maintain large eaters. At a sufficiently low population density the mean distance between surviving large creatures would interfere with mate-finding and continuation of the species.

It is evident from lunar craters such as Copernicus (Plate 11) and Tycho that a blanket of ejecta is formed lying several radii beyond the rim of a crater, at least in the absence of an atmosphere. Indeed the streaks which radiate from Tycho extend over most of the visible lunar hemisphere. On Earth, as we have seen, strewn fields of tektites are also found over great areas, the bediasites for example stretching from the Indian Ocean across the Pacific to the Caribbean. Ballistic studies of the formation of such ejecta blankets indicate that debris must be thrown out at appreciable angles to the horizontal. Now the terrestrial atmosphere is very thin in comparison with the dimensions of the crater being formed; hence the indication is that an appreciable
The proportion of this material will reach high altitudes, and some will be thrown into orbit. The asteroid will typically excavate a hundred to a thousand times its own volume of material, several per cent of which is thrown beyond the rim. The proportion of this material ending up as very fine particles with a settling time of years (that is with dimensions in the order of 0.01 per cent of a millimetre) is difficult to estimate. It will depend on the degree of shattering of the rock and this in turn depends critically on the speed of impact. Other factors, such as the recondensation of vapour into smoke, might be more important than shattering. Although this aspect of the argument is very qualitative, it seems very likely that adequate material will be injected to block out sunlight as only a few cubic kilometres of fine dust is required. Evidently the cutting off of photosynthesis for more than a year or two would have a devastating effect on food chains. In the event suspended dust particles might coagulate and fall out rapidly, and there would be only a few months of blackness; so whether food chains would collapse wholesale is not absolutely certain.

The effects of ozone depletion on modern organisms, let alone prehistoric life, are not well understood. Many modern species on land and in sea are already living close to their tolerance of ultraviolet radiation, so that even a small increase in exposure would be lethal. This might affect tropical plankton in particular, and it has been suggested that vitamin D production in exposed vertebrates might rise to toxic levels. Creatures which burrow, or can find shade, or living in polar zones, would not be affected. A great increase in the mutation rate of pathogenic viruses would be expected. It therefore seems likely that in the years following the clearing of the sky ultraviolet irradiation would be devastating.

The indications are, then, that widespread and immediate biological destruction will generally follow in the wake of a large impact. There may have been half a dozen or so such impacts over the last 600 million years occurring, not randomly, but within episodes of bombardment with a separation in time appropriate to galactic mechanisms. But over the same period there has been a similar number of global mass extinction events. It is tempting therefore to suggest that these events are the aftermath of impact; but it remains to be seen whether their pattern of destruction is compatible with such havoc from the sky.
Table 4. Geological ages

<table>
<thead>
<tr>
<th>Myr</th>
<th>Present</th>
<th>Myr</th>
<th>Myr</th>
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<tr>
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<td>PLEISTOCENE</td>
<td>Evolution of man</td>
</tr>
<tr>
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<td>CENOZOIC</td>
<td>Mammals dominant</td>
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<tr>
<td>2000</td>
<td>MIOCENE</td>
<td>Dinosaur extinction</td>
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</tr>
<tr>
<td>3000</td>
<td>PLIOGENE</td>
<td>First flowering plants</td>
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<tr>
<td>4000</td>
<td>PLEISTOCENE</td>
<td>Widespread seas</td>
<td></td>
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<tr>
<td>5000</td>
<td>EOCENE</td>
<td>Dinosaurs, First birds</td>
<td></td>
</tr>
<tr>
<td>6000</td>
<td>PALAEOCENE</td>
<td>Pangaea breaks up</td>
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<td>ARCHAEOZOIC</td>
<td>Therapsids dominant</td>
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<td>8000</td>
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<td>ORCHAEZOIC</td>
<td>Major marine extinc</td>
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<td>10000</td>
<td>ORCHAEZOIC</td>
<td>Appallachians formed</td>
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<td>ORCHAEZOIC</td>
<td>First reptiles</td>
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<td>ORCHAEZOIC</td>
<td>First amphibians</td>
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<td>ORCHAEZOIC</td>
<td>Caledonians formed</td>
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<tr>
<td>21000</td>
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Table of principal geological ages. Time before present is measured in units of a billion years in the left hand column, 100 million years in the centre column, and 10 million years in the right hand column. Assuming the boundaries in successive columns are due to extra-terrestrial impacts, bodies of say 30-50 km, 10-30 km, and 5-10 km diameter respectively may have been involved. (I = Ice ages)
5.6 The Cretaceous—Tertiary extinction

Of all the major and minor evolutionary hiatuses, that at the Cretaceous–Tertiary boundary has been the most widely studied. Criteria suggestive of impact—suddenness of onset, synchronicity of land and sea extinctions and so on—can thus be analysed in some detail for this event.

De Laubenfels in 1956 argued that just such creatures became extinct as one would expect from a brief, high-temperature episode. Vegetation would survive a brief incinerating rise in air temperature through regeneration of roots or seeds. Aquatic animals would likewise survive. Turtles can hold their breath for hours at a time under water, likewise possibly crocodiles, whereas the air-breathing plesiosaurs vanished. Pterosaurs and dinosaurs, presumably unable to shelter from great heat, perished. Pterosaurs, which had great wingspans and which were able to soar in a 25 km/hr breeze, would presumably in any case be destroyed by the huge wind speeds of the blast. Lizards survived, which de Laubenfels suggested was because they could crawl into cracks or fissures. Likewise the serpents, some of which were burrowing; others, boa-type, surviving in tree hollows—although as we have seen if the temperature is high enough to be lethal then the wind is strong enough to knock over trees. Birds and mammals survived, de Laubenfels ingeniously suggested, because they can live in snow-covered high latitudes. Thus, ‘Even boiling hot air, blowing over miles of snow, would cool down to a breathable degree.’ Certainly although there were apparently no polar caps 65 million years ago, there is fossil plankton evidence that northern seas froze over during the winter. Mobile creatures, tolerant to a wide range of environmental conditions and globally distributed, would inherit the Earth, and so in the Tertiary would follow the great expansion of birds and mammals into vacated ecological niches. Certainly also the archetypal ‘big impact’ we have studied would create lethal air temperatures over almost hemispheric dimensions, and for an equatorial collision cooling is likely to be more rapid with increasing latitude than with longitude. One can thus conceive of an impact large enough to destroy most life in equatorial and temperate zones, while preserving life at the antipodes or polar regions. Hence within the uncertainties the land extinctions might be due to the heat trailing in the wake of the blast wave. The blast wave itself, coupled with the earthquake, would produce land extinctions with the characteristics observed large creatures, if not directly killed by
incineration, blast or earthquake, would certainly die as a consequence of the stripping of leaves from trees and the subsequent collapse of the food chain, as we shall discuss. Aquatic, small and burrowing creatures would survive as before. The scale of extinction would again be hemispheric for the blast considered. It seems likely then that an impact can broadly account for the land extinctions and survivals at the end of the Cretaceous by blast and heat.

In the seas the extinctions are broadly consistent with a collapse of the food chain, whether caused by irradiation or darkness, although there are some puzzling features amongst some of the plankton. Some groups of these could survive a crisis by encysting, the dinoflagellates, for example, surviving for months or years on the sea bed at a few hundred metres depth before resurfacing. The geologist Hsü suggested that an active comet, falling in the ocean, might produce the extinctions through cyanide poisoning. Certainly there is enough hydrogen cyanide in a comet to do this, but the intense shock heating generated when a comet is brought to a halt would dissociate chemical compounds. It remains to be seen whether poisonous compounds might regenerate as the material expanded and cooled. Poisonous elements might exist, such as arsenic and zinc, which if concentrated in surface currents after an impact might be lethal to small organisms.

Twilight conditions are insufficient to produce the extinctions. However, a complete shut-off of sunlight for many months would kill plants, particularly trees and grasses which are fodder for large herbivores, which would die of starvation. The great carnivores would follow although no doubt smaller scavengers would do well at least for a few months. Small creatures such as mammals would be able to survive on seeds, nuts, roots, insects and so on for a year or so although in ever dwindling numbers. Freshwater fish and other creatures would continue to survive as the base of their food chain is decaying vegetation which would continue to be washed into streams and lakes. These fish would be fodder for turtles and crocodiles which can in any case hibernate for some months.

Plant life would probably continue across the boundary through the survival of roots and seeds. It is curious at first sight that tropical plant life was (or so it seems) relatively unaffected, as it is adapted to uniform conditions and is therefore least able to tolerate great environmental stress, whereas high-latitude plants and their seeds have dormancy mechanisms and could coast through months of cold or dark. The actual pattern of survival was the reverse. However the
clearing of dust from low latitudes would, if the present atmosphere is a guide, be quite rapid, the temperate and polar regions sustaining a dense blanket for longer periods. Depending on the season of impact, this might affect the pattern of survival. Clearly, however, it is dangerous to extrapolate from the undisturbed atmosphere now to a violently disturbed one 65 million years ago. O'Keefe has even thought that a temporary ring system (see Chapter 3) might form from debris hurled into orbit: this could create intolerably cold winters in temperate latitudes. The indications are that nothing in the plant record requires a catastrophic event, and in fact the plant extinctions seem to have been modest and to have followed some tens of thousands of years after the dinosaur extinction: the highest dinosaur bones are found in the ground metres below the level at which the plant changes occur.

A plausible case can be made, then, that the pattern of extinctions of animals is that of an immediate killing following a great impact. Incinerating heat and blast, the blockage of light or its excess in the ultraviolet, or even poisoning of the oceans, could in some combinations exact the toll of life implicit in the end Cretaceous fossil record. As we shall see, the possibilities of extinction through climatic and geological action are even wider. But the uncertainties are clear enough. We do not know the proportion of impact energy which actually goes into blast, or the site of the hypothesized impact. We do not know whether the atmospheric disturbance creates currents which quickly clear out dust particles from the stratosphere; the ecological effects of massive worldwide earthquake have not been studied; and so on.

The greatest uncertainty, from the palaeontological point of view, is whether the dinosaur extinctions were instantaneous at all. This has for some time been a controversial question amongst palaeontologists, the bias or consensus being distinctly uniformitarian. The uncertainty arises mainly from the fragmentary nature of the fossil record and the difficulty of precisely comparing geological times at different sites. Some authors have maintained that the giant reptiles were already in a declining phase, being gradually overrun by a mammalian community, and died out over perhaps a million years. Others such as Russell argue that, on the contrary, the dinosaurs comprised a thriving and complex community, that there is no evidence of a terminal Cretaceous decline, and that they must have been overwhelmed by a global catastrophe.

Strong evidence for a catastrophe has come from recent studies of
plankton fossils across the boundary at several localities. This can be illustrated by a section studied near Caravaca in south-east Spain. According to the geologists Smit and Hertogen there are marls here over 100 metres thick containing tropical fossilized plankton such as foraminifera, showing no significant change up to the last few millimetres: and then they disappear within 0–5 mm. The sedimentation rate is such that the extinction must have taken place within a few centuries and may have been instantaneous.

Overlying this extinction boundary is a layer of clay about 10 cm thick, and on top of this again the new Tertiary plankton suddenly appear, rapidly diversifying within the next half metre until a mature evolutionary state is reached, with only gradual evolutionary changes.

Smit and Hertogen carried out a trace element analysis on 100 samples of material around the extinction level. Approaching the level from below, no trends of any sort appear. But immediately above the level there are enormous overabundances of several elements, chief of which are iridium (450 times normal), osmium (250 times) and arsenic (110 times). These are measured in relation to the abundances usually found in the terrestrial crust. The significance of the iridium and osmium anomaly is that these elements are strongly depleted in the Earth’s crust, having been concentrated, probably, in the core. Such platinum, iridium and osmium as occur in the crust probably come from an extraterrestrial source such as comets, meteorites or meteorite dust. A chondritic meteorite may have 10,000 times the crustal concentration of these elements, an iron meteorite a

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Fig. 13 Concentration of iridium deposition in a clay layer at the Cretaceous–Tertiary boundary. The graph is derived from data due to Smit & Hertogen (1980). The iridium concentration is abnormal for terrestrial crustal material and may be indicative of an interplanetary or interstellar origin. It is inexplicable in terms of a past supernova in the vicinity of the solar system (if only because the isotope ratios do not fit), and is perhaps evidence of a major terrestrial impact 65 million years ago.
few times more again. The sudden spike (Figure 13), only a few centimetres deep, has therefore to be seen as strong evidence for an extra-terrestrial cause. Similar overabundances in iridium and osmium have now been detected at many sites around the world. The first of these anomalies was found by Alvarez and his colleagues near Gubbio in central Italy, where an overabundance of iridium by a factor of twenty-five was found in a clay seam sandwiched between limestones. This discovery was widely publicized as the first geological confirmation of the impact theory, but others regarded this as premature: a local clay seam may have a higher trace element content than surrounding limestones simply because clay is generally deposited more slowly and so contains a higher proportion of iridium-bearing meteoric dust. It is the accumulation of evidence that an iridium-rich layer is associated world-wide with the boundary that provides some of the best evidence for an extra-terrestrial event; and in any case the iridium concentration is so high at several localities that no ordinary deposition process is adequate.

The existence of zinc and arsenic at these levels may support the sea-poisoning mechanism suggested by Hsii as these elements are found in surprising abundance. They are scarce in ordinary meteorites and this suggests that, as anticipated from the astronomical scenario, a comet (active or degassed) was most likely involved, in which case we might expect an interstellar signature of some sort. However, the iridium and osmium isotope ratios measured at the boundary have values very close to those of solar system meteorites, and we need to ask whether the missile was nevertheless by chance a peculiar ‘local’ one. According to nuclear theory the creation of these elements took place in extremely dense environments at temperatures of up to 100 million °C. Where were these environments? Possibly these elements were created in the centres of supernovae or red giant stars before being flung into interstellar space. The missile might have condensed from an interstellar cloud contaminated by only a few such local factories, and if so, variations from star to star in element production would imply that some non-solar system isotope ratio would be brought in by the missile. But if the interstellar cloud incorporated the output of 100 million such factories, as is possible, local variations would be smoothed out and the isotope ratios should be constant everywhere in the Galaxy. These elements may even have formed in a pre-galactic phase, from supermassive bodies no longer in existence, so that the entire Galaxy would once again be a uniform mix. We are touching then on the mysterious realms discussed in
Chapter 1 and it would be unsafe as yet to draw positive conclusions on the origin of the missile from theoretical preconceptions about these nuclear furnaces. However, the magnitude of the geochemical anomalies is consistent with an interstellar missile of more than 10 km diameter excavating a few hundred times its own volume. A crater of 100–200 km diameter is implied; none such has been discovered as yet but it could exist, undiscovered, beneath the ocean. A few craters, from 3 to 65 km in diameter, have been discovered and dated at 65 million years. They are much too small to represent the missile we seek but may indicate that the body came in, not in isolation, but as part of a prolonged barrage.

These geochemical discoveries seem to indicate some connection between a cosmic missile and the dinosaur extinctions. But there are disconcerting features. One of these is the lack of controlling measurements at other levels. Thus from the astronomical point of view the Earth is continually bombarded by comets and asteroids of various sizes and one expects, not just a peak at a few great extinction boundaries, but a more continuous deposition varying at all levels. One is left wondering just how significant the signal is. It is also disconcerting that iridium levels have been found in similar concentrations in ocean-floor sediments 2.3 million years old in Antarctica, and yet there were no significant extinctions at that time. It is clear then that much more work needs to be done; a complete theory will require more geochemical information, more complete fossil data, much numerical work on the many consequences of impact, and a better knowledge of the chemistry of cosmic bodies and the interstellar medium, and of variations in the impact rates.

The Cretaceous–Tertiary boundary has evidently been rather thoroughly studied at several sites and it has therefore been possible for us to evaluate the impact hypothesis in some detail. Unfortunately data are not available to nearly the same extent for other extinction boundaries, impact criteria cannot be tested, and so a degree of speculativeness is inevitable at the moment. Nevertheless from the point of view of the astronomical model if not aesthetics one should look for a single underlying cause of extinctions rather than, as has been customary, attempt to explain the events by separate and unrelated phenomena. Regarding, for example, the late Devonian event, McLaren has made a very strong case that a world-wide catastrophic extinction affecting many marine groups took place, simultaneous to within current stratigraphic resolution, suddenly, and affecting successful and dying groups equally. He remarks that
'this is not merely a taxonomic extinction. It represents a disappearance of animals on a colossal scale.' We have seen that it was characterized by the disappearance of animals living on a sandy or muddy environment, or on or around reefs. Fresh or turbid waters are both fatal to the organisms which became extinct. There seems to be no mechanism whereby large volumes of fresh water could be simultaneously dumped into shallow seas around the world, and so McLaren was led to the suggestion that a 'giant meteorite' might have created turbidity in the seas. We have seen that the energy from a small Apollo asteroid will dissipate itself harmlessly in the open ocean, but that a very large impact, say from a 10 km diameter asteroid crashing into the ocean, would create precisely the intense turbidity in shallow connecting seas that McLaren requires. Since the Palaeozoic Pacific covered more than half the surface of the globe then on probability grounds an impact of the required type is expected. Thus two missing ingredients from the McLaren hypothesis have been supplied: the turbidity would probably occur, and the impact is a probable event. Although not a proof it seems at least plausible that this event and others like it should be seen in the catastrophism context. On this view for example the great Permo-Triassic event would be seen as a sea impact of such magnitude that blast and dust caused land extinctions in addition to the turbidity-induced sea extinction.

The dinosaur extinction has been a rich field for armchair speculation in the past. The main extra-terrestrial possibilities discussed have been that the Earth was irradiated by a nearby supernova, or that a giant solar flare coincided with a magnetic field reversal thereby exposing the Earth to cosmic rays. Internal mechanisms proposed have been generally gradualistic, such as changes in vegetation which dinosaurs could not adapt to. All such explanations are too specific, that is, they fail to account for all the major features; and in any case the internal explanations do not account for the wide range of evolutionary development of the creatures which became extinct. There is evidence that a major lowering of sea level took place from the late Cretaceous onwards, and this has been quoted as the cause. One can imagine this for a marine extinction but it is less easy to envisage a drop in sea level having a drastic effect on inland dinosaurs. In any case the increase of land area might have helped the propagation of dinosaurs; similar sea regressions are known to have taken place without mass extinction; and of course this would not account for the iridium and
other anomalies. Superimposed on this was a brief but dramatic drop in sea level of about 100 metres, occurring at the time of the extinction. We shall argue that such rapid regressions of the sea may be caused by impacts.

5.7 Lesser impacts and the evolution of life

We have so far argued that great collisions must have occurred several times within the Phanerozoic (we see the missiles in the sky and the holes in the ground); that the global consequences must be profound; and that on these grounds alone, quite independently of any geological evidence, one should expect mass extinctions to have occurred several times in the past. That the recorded extinctions have the qualitative characteristics of the expected type must be seen as a satisfactory confirmation of this catastrophist theory. But what of the much more numerous smaller impacts? Blast wave arguments of the sort already developed indicate that the immediately lethal area of a 7 million megaton land blast (expected on average once in 10 million years) extends for 600 km; but of course it is to be expected that great disruption, through hurling of ejecta and possibly through earthquake, will extend well beyond this.

The effect can be studied by first considering the diversification of a few species introduced into a favourable environment with no external forces causing extinction. The rate of creation of species will depend both on the evolutionary potential, that is the rate of creation of mutants, and on the environmental receptivity, that is the rate at which they are 'accepted' by the environment. The rate of creation of mutants is determined by the proportion of mutants created in a population, by the total population size and by the interval between generations).

In this perfect setting evolution would proceed rapidly at first and then, as the major ecological niches became filled, competition within these niches would become more severe and more refined evolution would take place: for survival, a finer adjustment would thus be required, species developing traits suited to specialized niches. Diversification would still occur but now more slowly: a mature population mix would arise with completion producing continuous marginal adjustments. The situation is analogous to research or discovery in a newly opened area; the initial advances are easily made but as more and more details are filled in it becomes more difficult to make big advances. The fossil evidence of the post-catastrophe periods of extinction shows a rapid diversification of species.
Crater to catastrophe: the aftermath of impact

entirely consistent with this picture of small groups of biota re-establishing a devastated world; and this evidence indicates that timescales of 10–30 million years have been involved in the recreation of a mature population.

But this timescale is comparable with the mean interval, allowing for sea impacts, between collisions of more than 5 or 10 million megatons which are devastating over continental areas. It will often happen that migration into a devastated zone from less affected areas

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Fig. 14. Diagram due to Russell (1976) illustrating the proliferation of the families of birds during the Cretaceous and Tertiary periods. Notice in particular the generally slow growth during most of the Cretaceous, contrasting with the sudden enhancement of rate after the event of 65 million years ago.
will follow but there will sometimes be zonal and sea barriers. For example if an impact destroyed much life in polar regions diffusion would have to come from temperate latitude creatures not yet adapted to colder climes.

It is of course the nature of the extermination that is important. Selective killing, whether between or within species, promotes evolution by eliminating the weak. Large impacts have probably also been an important factor in promoting evolution by sweeping aside bottlenecks (e.g. See Figure 14). Random killing by medium-sized impacts however seems to delay evolution by repeatedly setting the clock back and requiring a re-run of the struggle for existence. The overall result of mini-catastrophes is then to slow down the evolutionary process. The break-even point will occur when the recuperation and destruction times are comparable. On these arguments there ought to have been (or be) immature populations at certain latitudes or on certain isolated continents, with the fossil record showing an erratic evolution, and populations frequently in an immature state. These ‘local’ effects are over and above the global extinctions and immaturities induced by big impacts. Coincident with many of these smaller breaks in the record there should occur nonconformities, intrusions in the strata, corresponding simply to debris thrown beyond craters. One is reminded of Newell’s general description of the palaeontological record; in any case the hypothesis can in principle be tested via the fossil record.

Of course, direct correlation of a minor evolutionary hiatus with a medium or small crater will virtually be impossible over much of the Phanerozoic, due to the thoroughness with which such craters are eroded. However for the more recent past, with finer resolution of the fossil record, such a correlation may be possible; and it happens that this can be done.

The end of the Eocene 35 million years ago saw a drastic cooling of the Earth. Botanic evidence indicates that summer temperatures were unaffected but that winter temperatures became very severe, the mean temperature decreasing by about 20°C in comparison with previous winter temperatures. Close to or coincident with the end of the Eocene was the production of the bediasites (tektites distributed halfway round the Earth having ages of 34.7 ± 2 million years). The Popigai crater in the USSR is 100 km across and has an age of 38 ± 9 million years (Table 5). A 5 km diameter asteroid is implied; impacts of at least this magnitude should occur at a mean interval of 14 million years. It has been shown by Glass and Zwart from sea-bottom
Table 5. Recent terrestrial impact craters

<table>
<thead>
<tr>
<th>Biostratigraphic interval</th>
<th>Age at beginning (Myr)</th>
<th>Tekrite/Tektite crater age (Myr)</th>
<th>Tekrite/Crater</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pleistocene</td>
<td>1</td>
<td>$0.77 \pm 0.10$</td>
<td>Australites, Ivory Coast</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$0.88 \pm 0.13$</td>
<td></td>
</tr>
<tr>
<td>Pliocene</td>
<td>13</td>
<td>$14.7 \pm 0.7$</td>
<td>Moldavites</td>
</tr>
<tr>
<td>Miocene</td>
<td>25</td>
<td>$28.6 \pm 2$</td>
<td>Libyan desert glass</td>
</tr>
<tr>
<td>Oligocene</td>
<td>35</td>
<td>$34.7 \pm 2$, 38 $\pm 9$</td>
<td>Bediasites, Popigai, USSR (100 km)</td>
</tr>
<tr>
<td>Eocene</td>
<td>58</td>
<td>57</td>
<td>Kara, USSR (50 km)</td>
</tr>
<tr>
<td>Palaeocene</td>
<td>65</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Cretaceous</td>
<td>135</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Jurassic</td>
<td>181</td>
<td>183 $\pm 3$</td>
<td>Puchezh–Katunki, USSR (80 km)</td>
</tr>
<tr>
<td>Triassic</td>
<td>230</td>
<td>210 $\pm 4$</td>
<td>Manicougan, Canada (70 km)</td>
</tr>
<tr>
<td>Permian</td>
<td>280</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Carboniferous</td>
<td>345</td>
<td>365 $\pm 7$</td>
<td>Siljan, Sweden (52 km)</td>
</tr>
<tr>
<td>Devonian</td>
<td>405</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>

Ages of geological boundaries compared with those of tektites and all known Phanerozoic craters over 50 km in diameter.
cores that an extinction of radiolaria (plankton with shells composed of silicates) took place at virtually or exactly the time at which the tektites were laid down. About two-thirds of the radiolarian population disappeared. Figure 15 shows this phenomenon for a Caribbean core: the occurrence of microtektites and microfossils in the same core allows an accurate relative dating, and the coincidence is found to be within a few tens of thousands of years. We see evidence

Fig. 15. Concentration of microtektite particles corresponding to a biological hiatus at the close of the Eocene period 35 million years ago. Diagram derived from data due to Glass & Zwart (1977). The horizontal bars illustrate abundances of certain radiolarian species which clearly diminish simultaneously as the tektites are deposited. This is even more direct evidence than the iridium concentration of an association of extra-terrestrial bodies with events responsible for biological extinctions.

then that not only can a medium-sized impact produce an extinction, but also that somehow a climatic change lasting millions of years may be induced.

5.8 Geological evolution: sea-level variations, glaciation and plate tectonics

But not only were there rapid planktonic extinctions at the end of the Eocene along with the tektite deposition, there was, simultaneously, a rapid interchange of the north and south magnetic poles of the Earth, the turnover time being less than a thousand years. Somehow, it appears that whatever created the tektites and exterminated the plankton also reversed the direction of the Earth’s magnetic field and induced a prolonged climatic change. Other tektite falls have been found to be likewise correlated with rapid polarity reversals, to within the accuracy of measurement. Further, we have seen that not only was there a prolonged change in the sedimentation patterns of rock beginning 65 million years ago, there was a brief but rapid drop of about 100 metres in sea level. These extraordinary correlations lead inevitably to the question of the part played by impacts in the physics of the Earth.
Following the incident at the end of the Eocene the mean temperature of the Earth’s surface returned to its normal level—a level significantly higher than the one that we enjoy at present. Then, towards the close of the Tertiary, in the Miocene age, a more permanent climatic decline set in. This deterioration has continued into the Quaternary and the present era. During the last two million years in fact, there has been a rather well-documented cycle of glaciations with periodicities ranging between 10,000 and 100,000 years. There are corresponding variations in oxygen isotope measurements of deep-sea sediments reaching back to the Miocene; these measure ocean temperatures. The implied ice ages interspersed with interglacials, all comprising a major glaciation, are in part random with time. But some of the small changes in mean temperature also correlate rather well with terrestrial precession and variations in orbital eccentricity. The fluctuations in mean temperatures thus almost certainly reflect the Earth’s position and aspect relative to the Sun. The impression is of an atmosphere and ocean that have somehow achieved a mean temperature that is sensitive to the modulating effect of the Earth’s orbital behaviour. Certainly neither major glaciation nor variations of this kind seem to be present early in the Tertiary, but about 20 million years ago as the solar system came through the core of Gould’s Belt the climate seriously deteriorated. The supposition must be that there was some additional cause of the lowering of the temperature at around this time.

Could impacts achieve this? A good deal of theoretical work over the past few years has shown that the terrestrial climate is currently only marginally stable, and it is possible that a small perturbation could cause a drastic change. The so-called ice-albedo feedback in particular has the potential for strongly unstable behaviour. The theory is that if for some reason there was exceptional snow cover over a hemisphere, the enhanced reflectivity of the Earth would decrease solar heating, so leading to a further snow deposition, reflecting more sunlight and so on until a full-scale glaciation had taken hold. Obviously there must be some stability against such a disaster as otherwise any small effect would plunge us into an ice age. It has been suspected that a reduction of sunlight by more than about 3 per cent for a year or so would lead to an unstable growth of the ice caps. We have seen that the impact of a large body would produce enough dust in the stratosphere to block out sunlight several thousand times over. In fact the saturation point, at which the dust veil blocks out say over half the incident sunlight, is probably...
attained at intervals of less than a million years through impact of missiles of about a kilometre diameter. This is not a small disturbance. The growth time of large continental ice sheets has usually been taken as 1,000–10,000 years but there is recent evidence that this may not always be so. Strong and almost instantaneous ice growth took place in the northern hemisphere about 115,000 and 75,000 years ago. A possible reason for this lies in the mechanism proposed by Hoyle and his colleagues. During the weeks following obscuration of sunlight there would be a rapid fall in the temperature over land, but the sea, with its greater capacity for heat retention, would maintain a higher temperature. Strong landward gales would be driven by the difference and there would be large-scale precipitation of water vapour, mostly as snow. What is in effect an atmospheric heat engine would draw upon the heat reservoir of the oceans, sufficient to evaporate 1–10 trillion tons of sea water. This is enough to lower sea level by about 100 metres, in good agreement with the actual size of variations of sea level in the geological record. It is likely that by the time the dust has cleared from middle and high latitudes (say one to three years), a glaciation, all else being equal, would be under way.

But the very instability of the system might lead to the decline of the glaciation in no more than the time taken for an ice sheet in a mild atmosphere to melt, say in 1,000–10,000 years. However, the dust injected by an impact of a few thousand megatons energy may produce a climatic cooling of a few degrees and this, if such impacts occur in less than the melting time of an ice sheet, could maintain the glaciation. Generally this would be a marginal situation, but following a capture episode such an impact rate would be easily maintained. A glaciation, the magnitude of which would probably depend on astronomical and other factors, would be maintained indefinitely until by chance there was an absence of small impacts, the ice melted and the glaciation ended almost as suddenly as it had begun. Calculations show that a medium-sized impact of the type expected at 100,000-year intervals after a capture episode will induce glaciations which terminate randomly within 0.01–1 million years.

Geographical factors are likely to be important in creating the unstable climatic conditions necessary for such triggering to be effective. It is often supposed that a continent at one or other pole is required, so as to cool the oceans through iceberg calving and the like. Such conditions may be necessary but they seem not to be sufficient in themselves: North Africa was at high latitudes from about 530 to 480
Crater to catastrophe: the aftermath of impact 125

million years ago although there was no ice age; the glaciers vanished from Australia in the Permian period although the continent was then at a high latitude. It seems that some other factors are at work. If high impact rates are necessary to initiate and maintain a glaciation, then ice ages proper comprising a whole series, perhaps hundreds, of short-lived glaciations should occur at 100–200-million-year intervals corresponding to major capture events, and should endure for 30–100 million years corresponding to the retention time of the captured bodies. Considering the crudeness of the estimates these figures agree surprisingly well with the observed behaviour of ice ages (Table 1) and suggest that the impact mechanism, with galactic control, deserves to be taken seriously.

Corresponding to the rapid creation of thick continental ice sheets must be an equally rapid lowering of sea level. Geologists have now discovered that, throughout the 160 million years of the Mesozoic (including the Permo–Triassic and Cretaceous–Tertiary events which bound it) there was a stochastic sequence of ocean regressions and transgressions (five of each) involving _inter alia_ salinity crises and minor extinction events with an erratic time interval of the order of 15 million years. More recent data from 65 million years ago to the present are shown in Figure 16. One remarkable feature is the apparently increased frequency of sea-level drops over the past 30 million years. Another is the abruptness with which the sea level seems to drop. This is proving difficult to account for on conventional

![Figure 16. Global sea-level changes according to Vail and other researchers at the Exxon Research and Production Company.](image)

The large precipitous drops (50–100 metres) have been the subject of controversy largely because of the difficulty of finding a suitable mechanism. However, an ocean impact, cutting off sunlight and flooding land, might trigger a land sea heat engine which would very quickly transfer ocean water to the polar caps or high-altitude regions (see text).
scenarios, and it is very tempting to correlate the impact mechanism with these global variations, particularly as a major sea regression seems to have coincided with both the Permo-Triassic and dinosaur extinctions. A test for this model would be to see whether rapid glaciations coincide with such drops. The evidence of correlated glaciation is at the moment very sparse. One problem is that ice does not always leave a signature.

So far, we have examined only the energetic consequences of an impact. But perhaps even more profound than the input of energy is that of momentum. The energy of a collision dissipates itself largely in the surface layers of the Earth or the atmosphere above; there is virtually none available to affect the deep interior of the planet. Momentum, however, is distributed throughout. The magnetic field of the Earth is created in the liquid core of the planet, and any impact mechanism which can cause the field to reverse must somehow be based on the momentum of the collision.

The nature of the force powering the dynamo within the Earth is uncertain, long-term gravitational settling and heat convection being two proposals. Whatever mechanism operates, the geomagnetic dynamo is apparently very unstable and this is supposed to give rise to spontaneous field reversals. The liquid core has about half the dimensions of the Earth, and extremely slow circulation currents (about 10 metres/year) are required to generate the field, which is about 5 gauss at the surface of the core. Suppose now that the Earth were struck by a comet or asteroid, moving at some random angle, at say 25 km/sec. Because the crust and mantle are very rigid they will respond as a whole, and within the global travel time of earthquakes (say less than an hour) they will have acquired a new velocity and axis of rotation. The change in both will be minute: a 2-km asteroid, impacting once every 10 million years, will create a velocity change of only 0.0001 cm/sec, corresponding to 10 metres/year, at the core-mantle interface. However the core, being liquid, will at first carry on rotating in the old sense. This modest impact is therefore enough to spin the overlying mantle, creating friction at the boundary of core and mantle so forcing a completely new velocity pattern on to the circulation currents at the top of the core. The time taken for the core to accelerate to matching speed with the mantle is about the circulation time of its material, say about 1,000 years. There is therefore, over this period, a major redistribution of velocities within the core, and since as we have seen the geomagnetic dynamo is very unstable, one expects that the magnetic field will be strongly
perturbed and may rapidly flip over.

Thus even modest impacts occurring at intervals of 1–10 million years constitute a major perturbation of the velocity field of the core. The actual frequency of reversal is about 0.1–1 million years, and given the supposed sensitivity of the dynamo to disturbance it seems that impacts may be a prime cause, if not the cause, of the reversals. Certainly the observed coincidence of tektite falls with the reversals supports the hypothesis. It seems then that a record of past impacts, otherwise beyond detection, may exist frozen in the rocks in the form of field reversals. If this argument is correct then one can test the proposition that there have been episodes of high bombardment rate during passages through spiral arms: they should produce periods of high reversal rate, coincident with whatever other phenomena are induced by impacts. In fact such periods, the so-called mixed magnetic intervals, exist and recur at characteristic intervals of about 100 million years.

There are striking coincidences in time between these periods of high reversal frequency and tectonic episodes. Also, it is remarkable that the Permo-Triassic and Cretaceous-Tertiary extinctions of 225 and 65 million years ago occurred within mixed magnetic intervals 230-204 and 70-50 million years ago. In other words, on each occasion the Earth knew the big asteroid was coming! This is of course inexplicable in terms of random solar system impact and further indicates that an episode of bombardment was involved, with one or more large asteroids or comets coming in as part of a prolonged barrage.

Coincident with the dinosaur extinction was the greatest vulcanism in geological history. From 65 to 60 million years ago, lava flooded wide areas of the Arctic, Scotland and Ireland, and Southern India. The vulcanism in India created, over 5 million years, the Deccan traps, about a million square kilometres of basalt up to a thousand metres thick. Simultaneously there was a world-wide creation of hotspots generally regarded as created by plumes of molten material penetrating into the crust from the mantle below. A remarkable aspect of Earth history is that such plate tectonic events seem to occur in episodic bursts. Throughout the last 550 million years as well as pre-Cambrian times, brief and presumably violent periods of orogeny have taken place at intervals of around 50–100 million years. Even larger episodes involving vast outpourings of lava have taken place at perhaps 200–400-million-year intervals (Table 1).

Over the last fifteen years or so the theory of continental drift has
become well established, collisions of the plates on which the continents sit creating the forces necessary for such activity. The unification of geology and geophysics achieved by the theory of plate tectonics is impressive. But there is one area where plate tectonics has not so far succeeded, namely in accounting for the episodicity which is frequently claimed for the phenomena which it otherwise explains. The plates are driven by extremely slow currents within the mantle: it has taken 65 million years for the Atlantic to open from a rather narrow channel to its present width, a rate of less than 10 cm/year. The depth of these currents is controversial, some maintaining that only the hot, weak rock immediately under the crust is involved (that is the aesthenosphere), others that the whole mantle takes part in the circulation. It is likely that horizontal temperature gradients within the mantle or aesthenosphere drive these motions.

Now consider the momentum transferred by a body, not 1 or 2 km in diameter, but 10 or 20 km. The momentum is 1,000 times greater than we have so far considered and so are the velocities induced within the Earth. At the core/mantle interface these amount to 0.1-1 cm sec$^{-1}$, say 10,000 times the normal core circulation velocities and 10-100 million times the normal rate of continental drift. By the usual undisturbed standards, the mantle is set spinning at an enormous speed relative to the core, and correspondingly enormous stresses are involved within the mantle in accelerating the core to matching speed. The mantle, which behaves like a rigid body in response to a sharp blow, responds to a prolonged stress by flowing. The viscosity of flow is very large by ordinary standards and may vary by 100,000 to 1 from base to top, but it is this viscosity which permits continental drift to occur at all. The break-even point seems to be a few years, that is any stress of more than a few years duration will result in flow of the mantle material. Therefore if 1,000 years are involved in accelerating the core, flow velocities of say 1 cm sec$^{-1}$ will persist for that time, resulting in a relative drift of material at the base of mantle or aesthenosphere of thousands of kilometres, implying a complete redistribution of temperature inhomogeneities within the Earth. At the surface, extensive opening of lithospheric cracks by 10-100 km are expected within a few thousand years. The picture then is one of episodes of rapid continental drift, with all the associated worldwide sea-floor spreading, mountain building, vulcanism and so on, immediately after an impact, followed by a gradual decline of activity as the disturbed Earth settles into a new pattern of movement with more gradual splitting or colliding of continents.
If these ideas are correct, large impacts will thus set in motion a complex chain of interacting phenomena: sea-level changes, climatic excursions, violent tectonic episodes, magnetic-field reversals and, of course, mass extinctions. Some of these phenomena will appear suddenly, virtually as pulses in the record, and these will be superimposed on the same phenomena appearing as responses to longer acting forces. The evolution of land creatures, carried around on giant colliding rafts, may therefore be affected not just directly through impact, but also indirectly through more prolonged climatic effects and the opening or closing of sea barriers leading to mixing or isolation of populations. Catastrophism then merges into the widening horizons of biogeography and the general effects of plate tectonics on evolution. The distentangling of cause and effect in this complicated situation, at even one boundary, will be a long and arduous task, one which as astronomers we can leave with relief to our terrestrial colleagues. As Milankovitch, speaking of the cause of ice ages, said in 1941:

'These causes... lie far beyond the vision of the descriptive natural sciences. It is therefore the task of the exact natural sciences to outline this scheme, by means of its laws ruling the universe and by its developed mathematical tools. It is left, however, to the descriptive natural sciences to establish an agreement between this scheme and geological experience.'

We need for the present to go no further. Towards the end of the chapter we have ventured, very precariously, towards an overall view of geophysical science that involves conflict with the somewhat gentler prevailing scenarios. Our proposal is that the modern astronomical setting in which we now find ourselves may have profound consequences for our understanding of Earth history. Biological evolution must now proceed in an environment which suffers drastic, sudden and irreversible upheaval from time to time: in the fight for survival, adapting rapidly to each new set of conditions, it is probably reasonable to expect the existence of a species to be a series of 'punctuated equilibria'. It follows that the theory of discontinuous evolution by 'successive creations' espoused by Cuvier at the beginning of the last century, and the theory of gradual evolution advocated later by Darwin and Wallace, are but extreme versions of two processes that go on side by side. The idea that Earth history has been dominated only by familiar processes, directly experienced over the last few centuries, is then a fallacy. Such a timescale is wholly irrelevant to the scale of events.
in the astronomical setting.

Indeed, more than this, for if the Earth’s more remote past carries the record of a long series of huge impacts, we must also take account of the far more frequent encounters with smaller but nevertheless significant bodies in Earth-crossing orbits. Our interest is thus drawn towards bodies which are able to produce explosions of say 10,000 megatons or so, capable of devastating areas of about a million square kilometres. It is to impacts of this class in the recent history of the Earth that we now turn. Our starting point is not so much the barely visible Apollos, it is with those other tantalizing creatures, the short-period comets.
6 - The mystery of the short-period comets

Short-period comets have characteristic lifetimes of between a few hundred and a few thousand years. Not only do they break up, they also get driven away by planetary encounters. There are at present approximately one hundred times too many short-period comets relative to the rate at which long-period comets are captured by Jupiter and fed into the observed stock of Apollo asteroids. The present number is probably due to a burst of new short-period comets formed several thousand years ago as a result of a single large comet fragmenting during Jovian capture or perihelion passage.

6.1 The over-abundance of short-period comets

One of the vital links in the picture so far is the family of Apollo asteroids. In Chapter 4, we saw how there were likely to be over 1,000 of them with diameters greater than 1 km. Although their number is being slowly reduced by planetary collisions and hyperbolic ejections, the current stock is easily enough explained in terms of encounters of long-period comets with Jupiter during the last 30 million years or so. The idea is that these comets are deflected into orbits of considerably shorter period and then over a relatively short time, 1,000 years or so, the volatile elements boil away leaving the Apollos as defunct comets. The number of long-period comets we observe fits very well with this scheme and all would be well if we also observed an appropriate or corresponding number of short-period comets on their way to becoming Apollos. The process of transition from long to short periods takes place through the gravitational perturbations acting on the comets. Jupiter, much the most massive planet (over 300 Earth masses), is by far the dominant source of perturbation.

Everhart has used a high-speed computer to simulate the orbital evolution of comets fired into the inner regions of the solar system. Firing comets into the neighbourhood of Jupiter, from all angles, he found that 90 per cent of all ‘captures’ into short-period orbits took place from orbits with a narrow range of characteristics. These had inclinations less than 9°, perihelia between 4 and 6 a.u., that is straddling Jupiter’s distance of 5.2 a.u. from the Sun, and they moved in a direct sense. The implication is that for capture to be possible, there must be an overtaking of the planet, that is the comet must
The mystery of the short-period comets

approach from behind Jupiter and more or less parallel to its
direction of motion. Of course Jupiter may not be there when the comet
arrives at its perihelion, and Everhart found that only one in 130
comets with these parameters was actually captured into short-period
orbits. Capture tended not to take place in one dramatic orbit change,
but rather by the accumulation of many smaller perturbations.

Enormous variety was discovered, the process of capturing taking a
few dozen to over a thousand returns, the orbits themselves
fluctuating in period. Comets will not generally be discovered unless
their perihelia drop below about 3 a.u. and when that happens their
periods are usually short. The distribution of periods and the low
inclinations of Everhart’s theoretical comets agree with those of the
known short-period comets. These results are a strong indication that
the flattened, co-rotating system of short-period comets is derived by
selective capture from the randomly inclined intermediate or long-
period comets.

Kresak has studied the orbits of the known active comets with
periods more than 200 years and finds that over the inner few a.u. of
the solar system there is a constant number density of comets, that
is, a snapshot would reveal one such comet per 11 cubic a.u. The
extrapolation of this density out to Jupiter and beyond is admittedly
less certain, being based on the evidence of a few large comets.
Nevertheless with this figure and a random distribution of in-
clinations, one comet per eleven years would enter the capture zone
and so the number captured in a year would be only $\frac{1}{11} \times \frac{1}{130}$, or
one in 1,430 years. But with say 100 comets in short-period orbits,
each being visible for say 500 years, a comet would have to be fed into
the system every five years or so to keep the population stable.

We may also suspect that Apollo asteroids are being created more
rapidly than they are being depleted, perhaps once every few centuries
rather than the equilibrium rate of one in about 40,000 years. This
latter suspicion rests on the existence of a single active comet, Encke,
in an Apollo orbit: according to Sekanina, it will become an asteroid
of kilometre dimensions by around AD 2030. Already the comet is
telescopedally very faint. Both discrepancies lead to the same
conclusion: with the observational and celestial mechanical informa-
tion available, there is a current overabundance of short-period
comets by a factor of about 150.

There are indications that the short-term comets are smaller than
the average long-period comet— that is, the populations are not
strictly comparable—but there is no positive evidence that a significant
underestimate is being made of the low mass end of the long-period population. In any case, the smaller average size is precisely what one would expect with rapid evolution of the short-period comets.

6.2 Jovian encounter and tidal fragmentation

We have therefore arrived at a quandary. The overall picture, of a weeding out of long-period comets by Jupiter and throwing them into short-period orbits, of the spreading of some of these orbits into the space between the inner planets, of the decay of these comets into Apollo and Amor asteroids, and of their final impacting on to the planets, seems persuasively established by a whole range of numerical calculations and observational data, not to mention a lack of alternatives. But the transfer rates do not fit: there appear to be far too many short-period comets. There is obviously a mystery here requiring an explanation.

In 1826 a comet was discovered by Biela and found to have a period of 6.6 years. It was observed in 1832 and again in 1846, in which year it was seen to divide in two. In 1852, the components were again seen as two well-separated comets; they have not been observed since. Only about twenty comets have been observed to split since that time, the fragments becoming individual comets. The drift apart is gentle and is probably caused simply by differential solar gravity rather than any internal forces. There is a group of about a dozen comets, with periods ranging from about 500 to 1,000 years, but whose orbits are otherwise very similar, and which pass quite close to the surface of the Sun, some passing within 500,000 km of its surface. These are bright comets; some have even been visible in daylight close to the Sun. Tracing back these orbits, it appears that they were once a single gigantic object, 10 or 20,000 years ago, which underwent a hierarchy of disintegrations. There is little doubt that the tidal strain induced by the close passage to the Sun has split the parent comet into fragments. This is the key to the resolution of the paradox. If one bright comet can become a dozen (and indeed more since one of the fragments, Comet 1882 II, sub-fragmented into four more comets), what are the prospects that one large comet might become a hundred, or a thousand, smaller ones?

The process of converting a long-period comet into a short-period one involves successive passages within Jupiter's sphere of influence. During each passage there is a small but finite probability that the comet will pass close to the surface of the planet itself. The tidal force exerted on a Jupiter-grazing comet is similar to that on a Sun-grazing
The mystery of the short-period comets

Comet. Two comets, Lexell's comet of 1770 and Brook's comet of 1889, are known to have passed through the satellite systems of Jupiter, the latter comet almost grazing the planet's surface and subsequently splitting in two. The discovery probability of a small comet at Jupiter's distance is very small and so it is likely that such close passages occur frequently, perhaps annually, going undiscovered.

Fragmentation occurs when the solar or Jovian tidal force is greater than the internal cohesive strength of the cometary material. The tidal force is calculable, and it turns out that, for a given internal strength, there is a critical diameter above which the comet cannot hold itself together. The tensile strength of a comet can be estimated from the known force exerted on comet Brook, and from such events as the spontaneous splitting of comet West in 1975. The few examples available indicate tensile strengths of about 1-10 g wt/cm², that is, one square centimetre column of comet material could be pulled apart by a few grams weight of force - it is the weakest known solid material.

It can be shown that a comet 1 km or less in diameter might survive a close encounter with Jupiter: anything larger must split into fragments. But if, once a year say, a comet more than 1 km across has a close passage to Jupiter, then from the size distribution of comets inferred directly and indirectly, once every 1,000 years on average a comet more than 30 km diameter will pass close to Jupiter, and this will split into about 10,000 kilometre-sized fragments.

If one long-period comet enters the capture region in a decade, then only once in 100,000 years will such a comet have a close encounter in the above sense. But the process of capture into a short-period orbit involves, as the Everhart calculations show, hundreds of
The mystery of the short-period comets

thousands of passages near Jupiter. The comets which annually (we infer) have grazing encounters with Jupiter already belong to the short or intermediate period set. Thus the pre-encounter orbital periods of comets Lexell and Brook were respectively 11.4 years and 31.4 years.

The replenishment of the short-period population, rather than a smooth one-at-a-time process, is likely to be an affair of bursts, in which the occasional tidal disruption of a large comet, already on an intermediate or short-period orbit, showers the inner regions of the solar system with hundreds of thousands of fragments each of which is itself a comet. Such tidal disruption of a large comet will probably occur only once in several centuries, and injection of the debris into the inner solar system, where it would volatilize and become spectacularly visible, will probably occur only once in a few millennia.

But recorded history goes back 5,000 years, and the roots of mythology may extend even further back. Consider an event of this sort observed by men in, say pre-biblical times. In the weeks following the break-up of a 20 or 30 km diameter comet, the only change in the appearance of Jupiter would be a brightening of the planet. As the fragments streamed away, spreading outwards, they would reflect more and more solar radiation, the myriads of dust particles contributing the greater part of the reflected light. After a month or so, the brightness would resolve itself into a jet which night after night, would be seen to detach itself from the planet. The jet would grow and spread out, temporarily outshining Jupiter, itself a brilliant object in the night sky for much of the year. As the debris spread the display would fade from sight within a few weeks. But in the case of a major break-up some proportion of the debris could be thrown into unstable orbits taking the fragments into the inner regions of the planetary system. In that case, a few years after the shattering of a large comet the debris would begin to approach perihelion, outgas, and so become active comets. What would actually be observed depends on the characteristics of the break-up. Another possibility for example, if the fragmentation happens to occur during perihelion passage—not unlikely if the comet has been previously weakened during Jovian encounter—is that a vast meteor stream is created in orbit around the Sun. Not only then would the night sky be, for some centuries, spectacularly filled with comets ranging from the very faint to the brilliant, probably in their hundreds, but the ecliptic would become a vivid band of light, even visible perhaps around the Sun during twilight. This appearance would of course be only
temporary but even out of sight, the evidence would remain: thus there are today other quite striking indications of an exceptional recent comet history. There is an overabundance of fireballs impinging on the Earth and as Kresak has shown, the stock of interplanetary dust is ten to a hundred times what is expected with the currently observed flux of comets. The fact also that some 25 per cent of the known meteor streams are in relatively stable Apollo orbits is difficult to understand except in terms of recent activity. Whatever the exact course of recent events, the chance of a close encounter with the Earth will under these circumstances be significantly increased, and whatever the average rate of low-mass impacts implicit in the overall flux of long-period comets, this rate might temporarily rise to very high levels. We shall examine this problem further.
7 · Prehistoric encounters?

Not only were short-period comets on occasion very conspicuous in the prehistoric sky but one or two of them may periodically have come very close to the Earth. The effect would have been spectacular, and impacts from cometary and other debris have probably occurred from time to time with devastating consequences. The Halley and Encke comets in particular were very likely terrifying sights several thousand years ago.

7.1 The frequency of small-scale impacts

We have seen that the collision-hazard population of asteroids more than 1 km across may be close to 1,000 and that their numbers increase rapidly towards the lower masses. The smallest observed to date (and since lost) had a diameter of only 100 metres and, on collision, would have struck the Earth at 16 km sec. The impact energy would have been about 50 megatons and, assuming it was not broken up in the atmosphere, a land collision would have produced a crater about 2 km across. The calculated impact energy is for a rocky constitution. However, the missiles, as we have seen, are of several types and have compositions ranging from iron to ice, and this introduces a range of uncertainty into the calculated figures. It is likely that the Apollo asteroid mass distribution, which is seen to extend from 10 km to 1 or 2 km, may continue down to at least such 100-metre-sized objects. Extrapolating from the known Apollos, the implication is that about 100,000 bodies of this size or greater are potential collision hazards; with impacts down to the 50–500 megaton energy range. If the orbits of the known bodies are typical, impact rates and energies can be calculated as in Table 6. The collision velocities range upwards from 15 km/sec or thereabouts, and average 25 km/sec.

Table 6. Low energy impact rates

<table>
<thead>
<tr>
<th>( \delta t ) (years)</th>
<th>( E ) (megatons)</th>
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<tr>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>300</td>
<td>500</td>
</tr>
<tr>
<td>1900</td>
<td>5000</td>
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The typical interval \( \delta t \) between impacts of 'small' planetesimals of impact energy at least \( E \). Based on extrapolation of fireball data, with uncertainties as discussed in text.
17. The Tunguska explosion of 30 June 1908. A region of forest 8 km from the epicentre photographed many years later. Approximately 10,000 square km of forest were destroyed in this way.

But these calculations lead to an extraordinary conclusion. For we find that within the last 5,000 years, that is within a timescale of interest to the archaeologist, the historian and the mythologist, there must have been about fifty impacts in the energy range 1-100 megatons, about five in the range 100-1,000 megatons with an even chance that there has been an impact in the range 1,000-10,000 megatons. This conclusion is most secure at the highest energies where one is dealing with bodies of about 0.3 km diameter, close to the regime where telescopic discovery rates are well known, while the uncertainties become progressively larger towards smaller energies, say in the 10 megaton range.

It is true that about three-quarters of all impacts will occur over the oceans and go unrecorded, and that most of the land area of the Earth has been, and is, sparsely populated. But civilization originated some 5,000 years ago, with the union of the peoples of the Upper and Lower Nile. Cuneiform writing first appeared in 3000 BC in Sumeria, to be adopted by the Babylonians and the Assyrians. In India, a well-ordered government was established in the Indus valley before
2000 BC, while Chinese civilization was then spreading along the Yellow River valley. By 1500 BC or earlier, hieroglyphic writing on papyrus had been adopted in Egypt, a linear script had been invented and adopted by the Aegean civilization and the Chinese had developed a complicated character writing. There has therefore been a period of 4 or 5,000 years when several per cent of the surface area of the globe has been inhabited by peoples capable of recording events, and there is an expectation that several devastating impacts have occurred in inhabited areas.

To say that impacts in these energy ranges would be dramatic is not to do them justice; this may be illustrated by the case of the Tunguska meteorite. In the early morning of 30 June 1908, an object entered the atmosphere over western China, on a long sloping trajectory which took it to a remote part of the Siberian taiga, where it disintegrated, close to the Tunguska River. Partly because of the remoteness of the region it was not until 1927 that an expedition, under the Russian astronomer Kulik, reached the site. A picture of the impact has been built up from eyewitness accounts and on-site examination. Entering the atmosphere at 30 km/sec, the missile penetrated to a height of 6 km, being seen as a blinding ball of fire which darkened the Sun and trailed a thick cloud of dust. It was accompanied by intense thunderclaps which culminated in a stupendous bang: the noise was heard over 1,000 km away. A column of fire 1,500 metres wide appeared to rise from the ground to a height of 20 km and could be seen from 400 km. The blast flattened the forest around the epicentre out to 70 km, charring the barks of many trees on the inward-facing sides; singed the clothes of people out to a similar distance; knocked people unconscious at up to 100 km; blew over men and horses at distances of up to 250 km; and at a distance of 600 km an engine driver on the Trans-Siberian Railway was forced to halt his train because of the commotion. The fall was seen over a huge area, almost 1,500 km across, and ground tremors were felt over a similar area. A gigantic column of smoke remained suspended along the track, and throughout Asia and Europe in the days that followed the night sky was strangely bright. No crater has been found.

The Tunguska event may have been caused by a small fragment from a comet. From radiation and blast damage it appears that its impact energy was 40–100 megatons. During the present century, there is known at least one further impact of similar character. In this case however, it was on a lesser scale, that is, in the range of 1.5 megatons. This object, the Sikhote-Alin meteorite (Plate 18), also fell
on Russian soil and there have been physical studies of the spot where it landed as well as many eye-witness accounts. Where the Tunguska event is attributable to a cometary fragment exploding just before impact, the Sikhote-Alin event has more the character of a meteorite that broke up during its passage through the atmosphere.

A land impact of 100–10,000 megatons, in a civilized area, would of course completely overshadow these events, with severe blast and radiation damage occurring over an area up to almost a million square kilometres. The implications of these collisions are evidently so remarkable that it is as well to check the evidence from as many angles as possible. Thus the likelihood of such impacts can also be assessed by considering the smallest of missiles: we enter the realm of small meteorites, fireballs and shooting stars. Data from this regime are summarized in Figure 17 and a simple extrapolation of the meteorite distribution into the range of higher energies clearly leads to impact rates similar to those inferred from the Apollos, although again with similar uncertainties. Fortunately one meteorite event with an energy in the ‘gap’ has been dated and this provides a test of the extrapolated
Prehistoric encounters?
collision frequency. The Barringer crater at Canyon Diablo, Arizona, was caused by the impact of an iron body of perhaps 25 metres diameter and a mass of 100,000 tons, entering the atmosphere at about 15 km/sec. The impact energy was 4 or 5 megatons, and the crater is about 22,000 years old. About 5 per cent of meteorites are irons, and these are the only missiles in this energy range to produce a single explosion crater, stones normally breaking in flight to produce showers. Thus the totality of meteoritic land collisions in this energy range must be about one in 1,000 years. Inclusion of sea impacts gives a recurrence time of about 300 years, agreeing remarkably well with the expectations.

The data are much too uncertain to say whether the meteorites are a straightforward continuation of the Apollo asteroids. If the hypothesis developed in Chapter 4 is correct then a progressive decline in the proportion of interstellar bodies is expected towards the smaller masses, and because of these different modes of origin the
distributions need not match. Nevertheless it is again satisfactory that an extrapolation into the gap from the extreme low-energy end of the scale leads to impact rates similar to those already deduced. It seems that there may be several types of objects in Earth-crossing orbits capable of yielding multi-megaton impacts within historic timescales.

Finally, within the past few years sufficient data on small lunar and terrestrial craters have become available, and these directly bear on the energy gap. The situation is complicated for terrestrial craters by the shielding effect of the atmosphere and for lunar craters because of secondary cratering. The terrestrial crater data indicate that an impact in the range 10–1,000 megatons is expected once in 2,500 years, with a 25 per cent probability that the energy will exceed 100 megatons; but again 95 per cent of meteorite impacts in this range leave no craters at all, weaker missiles unloading their energy into the atmosphere. The lunar cratering data seem to indicate that, to within a factor of three or four, the Apollo impact rate holds down to the 10,000 megaton range or less. The cratering data of course refer to time averaged rather than to recent impact rates.

7.2 Fireballs

There is one further, and very significant, class of missile. Occasionally a meteor is so bright that it lights up the landscape. Most probably this will belong to the class of objects known as fireballs. A large body of data on these objects has been accumulated through research programs such as the Prairie, Canadian and European networks, using all-sky cameras to record meteoric events. Operation of these networks began around 1964 with a search area of about 2 million square km. From their atmospheric deceleration and fragmentation it is possible to deduce the physical properties of the fireballs, which normally have end heights of 50–60 km. It turns out that these objects are very fragile and of low density, indicative of cometary material. Some have had high entry velocities and appear to have come from beyond Jupiter or even to have been in retrograde orbits before collision. The largest Prairie Network fireball recorded had a mass of about 3.5 tons; the Šumava fireball recorded in December 1974 by the European Network had a mass of about 200 tons. Mass for mass, the arrival rate of fireballs is about a hundred times as great as that of meteorites (Figure 17). They are much too abundant to be a low-mass extension of the active comets in the Earth's neighbourhood.
The Earth is thus encountering a considerable population of interplanetary boulders, quite distinct from stony or iron bodies, and which cannot be directly related to the telescopic asteroids or comets. This population is dominant amongst the smaller projectiles entering the atmosphere, and the question arises: what is the frequency of larger masses amongst them? For somewhere in the range of 1 ton (from the larger Prairie Network fireballs) and 10 billion tons (from the telescopic missiles) there must occur a turnover in their mass distribution, as otherwise one would predict far more kilometre-sized bodies in circum-terrestrial space than are observed. Once again, information in the 'gap' is provided by a single exceptional collision.

The Tunguska object may have had a mass of 500,000–1,000,000 tons (diameter about 100 metres) and an impact speed of about 30 km/sec. These figures have been reconstructed from the topography of the flattened and burned forest, and from the accounts of dozens of eyewitnesses, most of whom were hundreds of kilometres from the impact site. The occurrence of this 40–100 megaton event as recently as 1908 is consistent neither with its being a small asteroid nor with its being a small active comet. Extrapolation of the known fireball mass distribution indicates that Tunguska-like land impacts should occur as often as once in fifty years, and this is entirely consistent with observation of one such event in the twentieth century. Indeed fireballs intermediate between Tunguska and the Prairie Network objects have been recorded. The Šumava fireball of 1974 has been mentioned. One over Holland in 1958, with an end height of 45 km, appeared almost as bright as the Sun. The Montana fireball of August 1972 grazed the Earth’s atmosphere and escaped into space again. The frequencies of these occasional events are consistent with an extension of the Prairie Network fireballs into the Tunguska range, and so the mass distribution appears to hold at least as far as million-ton objects. But somewhere between 0.1 km and 1 km diameter there must be a cut-off in these large numbers of fireballs. The corresponding uncertainty in impact energies is very large—somewhere between 100 and 100,000 megatons. In Figure 18 we have somewhat arbitrarily supposed that there is a cut-off at 4,000 megatons, erring probably on the conservative side. This figure illustrates a number of simulations in which collisions were randomly generated over 5,000-year intervals, extrapolating the meteorite, Apollo and fireball populations in accordance with our discussion.

To sum up, there are acts of faith involved in estimating impact rates in the 10–1,000 megaton range. The missiles are too small to be
directly seen in space; and the impacts are too rare for modern documentation to be possible. But all the lines of evidence—the impact rates extrapolated from both ends of the energy gap as well as the very fragmentary cratering data within it—point in the same direction: a few dozen sporadic impacts in the tens of megatons, and a few in the 100–1,000 megaton range, must have occurred within the past 5,000 years.

Fig. 18 Four simulations of a random impact history over a 5,000-year period, based on the data of Figure 17. Collisions have been placed at regular intervals for clarity, and impacts of less than 50 megatons or more than 4,000 megatons have been neglected. It can be seen that appreciably different histories are possible because of the random nature of the impacts. This and the previous figure are based on the probable current flux of near-Earth bodies; temporal fluctuations such as might arise from the break-up of a large comet or a temporarily large comet population have been neglected but they might very well be as important if not more so.

7.3 Meteor storms

But a smooth extrapolation from existing data is not the whole story: at best this describes averaged impact rates over some time interval or other. From the galactic scale downwards, the importance of fluctuations has become clear. Thus the erratic structure of the galactic gravitational field has a dominating effect on the dissipation and capture of an Oort cloud to the extent that the smoothed out field
usually employed gives a totally misleading answer. The supply of short-period comets is likely to have been very erratic over historic timescales, and for this reason the flux of comets into Earth-crossing orbits will be likewise erratic. As we have tried to show in the previous chapter, the recent incidence of short-period comets may have been vastly greater than average.

A collision with a comet is unlikely over the timescale under consideration, even if there were such a temporarily enhanced comet flux. The significant feature is not collision with comets themselves but with their debris. For comets spread dust and rocks along their orbits; and as we have seen already, they are often observed to split and sometimes disintegrate. We shall be led to propose that, over and above the sporadic impacts already discussed, there may have been brief periods, within historic times, of greatly increased Tunguska-like bombardment.

An enhanced impact rate might come about in two ways. Firstly, an increase in the comet flux of the sort described in Chapter 6 would correspondingly increase the amount of cometary debris in circum-terrestrial space. The existence of an abundant population of fireball-producing missiles is itself evidence that the missile supply is erratic. For the majority of fireballs have a cometary constitution and it is natural to see them as the disintegration products of comet nuclei. A second scenario arises from the expectation that on occasion the Earth will find itself in the wake of a large, active, disintegrating comet. With this picture the comet—or the comet and its dissociating fragments—would be spectacularly visible in the sky, and the connection between the comet and the concurrent fireballs would surely be obvious to an observer. We shall explore this interesting possibility with such data as are available, beginning with cometary dust.

The Earth, in its orbit, intersects over fifty meteor streams of which a dozen or so are strong. Passing through swarms of tiny particles, shooting stars seem to emanate from a small area of sky. The Geminids, for example, appear between 7 and 15 December each year, with a maximum hourly rate of one shooting star a minute on 14 December; the Leonids appear around 17 November with a maximum rate of appearance of only five shooting stars an hour, and so on. On rare occasions on the annual return of a shower, intense and short-lived bombardment has occurred, indicating a bunching of particles at one part of their track. About half of these meteor streams follow similar orbits to known comets. Evidently as a comet decays it
leaves solid bodies which, although initially bunched, gradually spread around the orbit. Eroding forces which act on fine dust particles in the inner solar system would destroy meteor streams within 1 or 2,000 years, unless they were replenished.

Storms of meteors have occurred a few times over the past two centuries. These have arrived more or less unexpectedly, recurrence cannot be reliably predicted, and most information on them has come from eyewitness accounts. One such storm occurred on 11 November 1799. From a description by the explorer von Humboldt it has been estimated that shooting stars appeared at a rate of about 300 per second, or close to a million an hour. On 12 November 1833 the shower was repeated with "meteors as thick as snowflakes" streaming from a point in the constellation Leo: it must have been an amazing sight. The connection of the Leonids with a comet was established in 1866, with the discovery of a faint comet by William Tempel and the realization that it had the same orbit as the Leonid swarm. The swarm was not seen again until 1966, Jovian perturbation having shifted the meteors from intersection with the Earth's orbit until recently.
Only three meteor swarms (two associated with Giacobini's comet) have been detected during the present century. In 1933 a swarm lasted for half an hour with a peak hourly rate of 19,000 or about five meteors a second. In 1946 the swarm again appeared and on this occasion cameras and radar were deployed to study it. Precise orbits were obtained and evidence was found of fine structure within the swarm. The whole swarm had a thickness of 9,000 km, less than the diameter of the Earth. Certain inferences can be drawn from meteor streams and swarms. More than one epoch of debris-creation seems to be involved. For example in addition to an even spread of meteors around the orbit of comet Tempel there is an intense concentration of particles, perhaps a million times as dense, just behind the comet.

These observations from the recent past are therefore an indication that in the wake of a comet there is a great deal of dust, erratically distributed, and that brief episodes of intense dust bombardment are not uncommon. The existence of fine structure within the Giacobini swarm and within other meteor streams such as the Taurids is an indication that not only may fragments break away from comets but also that there may be sub-fragmentation.

### 7.4 Fireball storms

These observations cannot tell us whether bodies larger than dust particles are found within a meteor stream. Fortunately there is another source of data, namely the seismic stations left at five sites on the Moon by the Apollo astronauts. One failed, but the remaining four have operated since April 1974, and can detect miniscule lunar surface vibrations. An impacting meteorite creates a distinctive signal, quite different from that of a moonquake, and boulders of a few kilograms can be detected landing anywhere on the Moon. The largest boulder so far may have had a mass of a few hundred kilograms. Unfortunately, in spite of efforts to calibrate using the precisely calculable impacts of Saturn 3 boosters, there is great uncertainty in going from amplitude of vibration to impact energy, and estimates of the absolute collision rate have varied by a factor of 100 over the past few years. Variations in the collision rates, however, can be found, and these are shown in Figure 19. The boulder impact rate is clearly non-random, and the seasonal peaks can be associated with known meteor streams. The outstanding peak occurs in June, when the Earth-Moon system runs through the $\beta$-Taurids, a meteor stream associated with comet Encke. There are boulders, therefore, along the track of a comet.
The association of the Leonids with Tempel has been mentioned. This body is about as inactive as it is possible to be and still be recognized as a comet, and yet we have seen that an immense meteor flux may occasionally happen when the Earth passes through its neighbourhood. The three-fold summer increase in boulder flux, clearly showing that large meteoroids or iceballs lie along the track, is likewise associated with Encke, a comet which is almost defunct. In fact all the current comets which can be associated with meteor streams are small and feeble objects.

![Fig. 19. Graph showing the smoothed flux of meteoroids on the lunar surface versus day of the year. The curve is derived from data due to Doumas et al., which are based on measurements obtained with three seismic sensors placed on the Moon. The most significant impacts are those associated with the β Taurid meteor stream which is in similar orbit to that of Encke’s comet. The size of this feature and its age of 5,000 years or so argue in favour of an exceptionally large progenitor](image)

If the picture of boulder ejection, possibly with a hierarchy of fragmentation, is correct, then one might expect that from time to time there have been fireball storms, analogous to the meteor storms. Modern records are all but non-existent, although one interesting event was recorded in 1913. A procession of bright fireballs passed slowly in a long arc over Canada and the United States, moving over New York and out to sea. Two marine observations extend the path to 9,000 km, or about a quarter of the circumference of the Earth. The fireballs passed over with a noise like thunder, and from eyewitness accounts along the track there was evidently a hierarchy of disintegrations taking place in the atmosphere.

Records of what appear to be fireball storms are to be found amongst ancient Chinese records of meteor showers. These have been compiled from many sources including local gazetteers by the Chinese astronomer Tian-shan, and amongst them are found some remarkable events. Out of 147 showers sufficiently unusual to have
been recorded, over a dozen seem to have been fireball storms. Five of
the showers, for example, were seen in daylight. Thus entry 39 in
Tian-shan's compilation reads:

‘Dynasty Han, Reign Yuan-yan, Year 1, Month 4, Day Ding-you [i.e.
22 May, 12 BC]. At the hour of rifu [3–5 p.m.], the sky was cloudless.
There was a rumbling like thunder. A meteor with a head as big as a
fou [an earthenware pot], and a length of some ten-odd zhang [a
zhang is 12 degrees] colour bright red and white, went southeastward
from below the Sun. In all directions, meteors, some as large as
basins, others as large as hens' eggs, brilliantly rained down. This
only ceased at evening twilight.’

Tian-shan considers that this event was associated with the present-
day Perseid meteor stream. If so, the parent body is again a faint
telescopic object, Comet 1862 III, whose aphelion is almost 50 a.u.
from the Sun, about the distance of Pluto. It is interesting that what
appear to be the Leonids are recorded as having fallen with noise, or
great noise, on several occasions. This is characteristic of fireballs, and
happened in 1798, 1666, 1602, 1566, 1533, and 1002. Reading these
early accounts, it is difficult to avoid the conclusion that in the past, the
known meteor streams were very much more spectacular, and have
been declining ever since.

7.5 Close encounters with active comets

The historic records then show that on occasion quite spectacular
celestial phenomena have followed from the interception of debris
from faint comets. But what is the probability that, within historic
times, the Earth has found itself in the wake of a young and active
comet, or even a giant one? And if so, what consequences might we
expect?

Because of the likely erratic nature of the comet supply statistical
predictions of the close encounter frequency are probably not
relevant. However meteor streams are fossil evidence of past
intersections with comet orbits and indicate that over the past
1,000–2,000 years, the typical lifetime of a stream, about fifty comets
have found themselves in roughly Earth-crossing orbits, usually
unstable ones.

Ancient Chinese and Korean records show that the major streams
are of great antiquity. The Leonids, Perseids, Geminids and
Andromedids are over 1,000 years old, the Orionids and Aquarids
over 1,500 years, and records of the Lyrids go back over 2,000 years.
There is therefore a concentration of ages of more than 1,000 years, all the more remarkable if the streams only last 1 or 2,000 years. This and the recorded history of the streams seems to confirm that the present meteor streams are the declining remnants of a burst of comets into circum-terrestrial space a few thousand years ago: at the very least it seems that a few hundred active comets have been in Earth-crossing orbits within the past 5,000 years. Random sampling then shows that a few Earth-crossers of say 5–10 km diameter are a reasonable expectation: the occasional close encounter with a large, active comet is therefore to be expected.

Direct evidence of past close encounters comes from a complex of debris which includes comet Encke, the Taurid meteor stream and probably the Apollo asteroid Hephaistos. There is a multiplicity of fine structure within the Taurid stream, as determined from detailed studies of individual meteor orbits. Some of these were studied by Whipple in 1940. One set of meteor orbits was indicative of a violent ejection of debris from comet Encke 4,700 years ago, another set seemed to arise by ejection from an undiscovered companion to comet Encke. The orbital elements of Encke, Hephaistos and the Taurid meteor stream are shown in Table 7.

From the close similarities of these elements it seems very likely that they are disintegration products of an erstwhile large comet, certainly in excess of 10 km diameter. This conclusion is strengthened by the boulder evidence within the Taurids, and by the fact that the Tunguska object had an orbit very similar to that of Encke and was probably therefore a fragment. The still active nature of Encke and the ephemeral nature of the Taurids indicates that the large body was probably active a few thousand years ago.

The small inclination of comet Encke, currently at 12°, enhances the probability of a close encounter, but slight perturbations by Jupiter cause the inclination to vary down to 6°. A more important effect is the slow 'wobble' of the orbital plane of Encke, analogous to the precession of a gyroscope. This has a period, according to Whipple, of 7,000 years, and would ensure a series of extremely close passages of Encke and the Earth at 3,500-year intervals. The actual encounter distance is probably unknowable because of the past action of non-gravitational forces but may be of the order of the Earth-Moon distance. The evidence thus seems to indicate that a remarkably large comet was injected into a low-inclination, short-period orbit within historic times and has been subject to a hierarchy of disintegrations since then. The size of the body, its low inclination
and short period, and the orbital precession ensure that at intervals a series of very impressive close encounters with the Earth must have taken place. The process of spiralling in of this body to a stable orbit may have taken some thousands of years during which time it would have been a spectacular object in the sky.

Comet Encke was discovered only in 1796. It was then just below naked-eye visibility and has been declining in brightness ever since. Why then has it not been a brilliant object in mediaeval or classical skies? The answer seems to be that a recent change in the axis of rotation has exposed fresh volatile material, so that the activity of the past two centuries is a temporary resurgence. It is likely that Encke was seen as a brilliant comet in remote antiquity, quite possibly during the time of the Chaldeans or Babylonians, and probably in prehistory.

As to the consequences of periodic close encounters with an object such as the Encke/Hephaistos/Taurid progenitor, this owes more to speculation than quantitative evidence. That disintegrations or ejections of large fragments from comets commonly take place seems well established. Plate 7 shows such a fragment in the act of detaching itself from Halley's comet during the 1910 apparition. Fragments of this sort pursue an independent existence for days or months before fading or passing beyond the observer's ken. They are expelled from the nucleus at speeds usually less than 2 m/sec, as if some internal force within the comet from time to time throws out chunks of material. Hydrodynamic calculations based on the Whipple icy nucleus model have been carried out and these suggest that outgassing of water vapour due to heating by sunlight may create the necessary acceleration, a throwing out from the nucleus of pieces as large as 0.1 km being possible. This is about the inferred size of these fragments and corresponds to an impact energy of the order of several hundred megatons.

Apart from the detaching of small fragments, we have seen also that a comet may split. The exceptionally large comet Wirtanen, discovered in 1957, split into two parts, the smaller piece having about 10 per cent of the mass of the primary. Each part, essentially a comet, was followed for over two years. The fate of comet West in 1975 is illustrated in Plate 16: it is shown in the act of disintegrating into four parts. One fragment faded from sight within a few weeks but the main comet and its surviving companions were followed for months thereafter.

A simple-minded model of a bombardment episode would then be
to imagine the Earth running into a swarm, say with the volume of the Giacobini meteor swarm, containing a mass equal to a 0.1 km diameter fragment and some plausible size distribution of boulders. Studies of fragments such as volcanic debris, cratering fragments,

Table 7. Orbital elements of Encke's Comet, Hephaistos and Taurids

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The 'elements' describe the present elliptical orbits of Encke's comet, the Apollo asteroid Hephaistos and the daytime Taurids (P=orbital period in years, a=semi-major axis in a.u., e=eccentricity, q=perihelion distance, in a.u., Ω=longitude of the ascending node, and i=inclination of orbit to the Earth's orbital plane). Note the general similarity of the orbital characteristics except for Ω. This latter measures the orientations of the orbits in space, and since the orbits 'wobble', small differences in the rate of wobble may accumulate to produce large differences in Ω. It is unlikely that the orbital similarities are coincidental, and so the break-up of a massive comet some millennia ago seems to be indicated.

broken rocks and so on have shown that in spite of the wide variety of circumstances of formation, the mass distribution of the debris does not vary greatly, being similar to that of say the Apollo asteroids. Then in the course of encountering a swarm of this sort, the Earth would, within half an hour, be subject to about thirty impacts in the range 10–100 megatons with perhaps one or two in excess of this!

7.6 Prehistoric encounters

The situations we have now described are: the short-period comet population is replenished erratically and there may have been intervals within historic or late prehistoric times when the sky was temporarily filled with comets: at least one exceptional, probably brilliant, disintegrating comet has been in an Earth-crossing orbit, and there have been epochs when a series of close encounters might have had dramatic consequences in the sky and on the ground in the form of impacts, and from time to time sporadic impacts in the Tunguska or super-Tunguska class are expected.

It is hard for us to imagine the effect such phenomena would have had on pre-scientific peoples not least because few modern people have seen the night sky as it was, say, to a desert dweller of 3,000 years ago. There are now very few places on the globe, none in Europe for example, which are free from light pollution or haze and it may be
difficult to appreciate what an awesome thing the night sky can be. But to our hypothetical desert dweller the panorama which appeared above him as the sun set was the home of the gods, and the signs and omens which appeared there were very relevant to life below.

The earliest recorded appearance of comet Halley is found in a Chinese military book and dates from the time when 'King Wu marched on Zhou of Yin', probably 1058 BC. The comet then had a magnitude —7.7 on the usual astronomical brightness scale (0 for the brightest stars, +5 for the faintest seen with the naked eye; Venus may attain magnitude —4.4, when it is an outstanding object in the evening or morning sky). Halley's comet was therefore then a dominant object in the night sky and undoubtedly plainly visible by day. From its rate of fading, it is likely that in 2000 BC it reached magnitude —10, about a hundred times the luminosity of Venus.

The progenitor of comet Encke and the Taurids, supposing it to have been about 20 km in diameter, would at its closest approaches to the Earth have attained a magnitude —12, approaching that of the Moon and sufficient to throw shadows at night. It would have appeared as an intense yellow spot of light surrounded by a circular coma probably larger than the full Moon, with a tail stretching across a large part of the sky at suitable configurations, graduating from bluish white near the nucleus to a deep red in colour, the whole being finely structured. If the disintegration history revealed by the current debris took place within the sight of men then there would have been occasions when subsidiary comets, perhaps even an array, would have been observed. For the few centuries during which precession caused the terrestrial and comet orbits to intersect, there would probably (as already discussed) have been greatly enhanced seasonal fireball activity, rising to enormous levels at periodic intervals corresponding to a strong commensurability between the orbital periods of Earth and Encke, and the risk of Tunguska-like impacts would then have been greatest. In a periodic orbit the close approaches would obviously have been predictable. Indeed if, at these close approaches, the Earth ran into debris of the sort we have discussed, prediction would have been a matter of urgency. We have to sympathize with our hypothetical desert dweller, trying to formulate a sensible view of the world, faced with this terrible phenomenon: we can be sure that it would have dominated his theorizing.

These conclusions cannot be regarded as proven; but they do seem to be reasonable expectations from the available data. However they
present us with a paradox. For if such overwhelming celestial events have taken place, where are they depicted in the artefacts or petroglyphs carved by neolithic man? And where are they in the ancient literatures or mythologies of the world? Where is the record of a brilliant comet undergoing a history of disintegrations in the sky? For turning to the literature and mythology of antiquity, one is struck by the quite extraordinary absence of the comets described as such:

20. Illustrations from twenty-nine comet charts among silk paintings very recently unearthed from the Han tomb No. 3, dated 168 BC, at Mawangtui, Changsha. Although comets were regarded as grounds for prophecy and divination in ancient times, the charts show that the Chinese people also had rather scientific concepts of them. Thus, the paintings clearly display both tails and heads, some of them even with smaller dots and circles indicating that nuclei could be detected in the comas. Several of them also indicate some degree of inspiration by likenesses to antlers, trees, beetles or candelabra, and it seems associations of this kind could well have been suggested by comets over two thousand years ago.
there are very few in Egyptian and Babylonian records. And yet such comparatively mundane objects as planets came to have deities associated with them.

Some hint of the resolution of this paradox comes from two biblical passages which seem to describe comets. The author of Genesis (15:17) wrote: 'When the sun went down, and it was dark, behold a smoking furnace, and a burning lamp.' The description appears to be that of a comet; but its representation is that of a vision of God to Abraham. Or again, in I Chronicles (21:16): 'And David lifted up his eyes, and saw the angel of the Lord standing between the earth and the heaven, having a drawn sword in his hand stretched out over Jerusalem. Then David and the elders of Israel, who were clothed in sackcloth, fell upon their faces.' Once more the object is seen as a divine being, an 'angel of the Lord', and a religious interpretation is placed on a natural phenomenon.

Another hint is provided by the ubiquity of Flood myths amongst ancient legends. For if there existed a dense meteor stream of the kind we have discussed, a passage one year through the wake of the progenitor comet could well have been a devastating event precipitating both rain and flood on such a disastrous scale that it would not have been forgotten. Indeed, if such were to have happened, the fear of repetition would have been natural and man would have been especially fearful of those later passages when the approaching comet, the source of the stream, was so placed as to darken the Sun. Our ancestors are known to have been peculiarly fearful of eclipses, the work of dragons and devils, and it might be that they established a perfectly logical association with comets.

We are thus led to the possibility that, indeed, the comets are there in the record, not in the objective, materialistic form appropriate to a scientific age, but as divine creatures of the sky. It is to this question that we now turn.
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The ancient religions of prehistoric man were unmistakably polytheistic and astronomical in character. This raises questions concerning the basic nature of the gods that were worshipped. If comets were included among the principal deities, their erratic motion and changing appearance could well have inspired a ready acceptance of the fickle character of ancient gods. In this chapter, we begin by looking back through mediaeval times to the classical period and note that many Greek and Roman philosophers were, amongst other things, greatly concerned to explain comets in materialistic terms and rid them of any supernatural qualities. In as much as the heads and tails of comets appeared often to take on a human form or that of animals, the aim seems to have been to prove that these were illusions created by perfectly natural causes. By such means it may be they expected to divest comets of their supernatural qualities. In practice, however, belief in the gods was so entrenched that the arguments seem merely to have served to convince that the gods were invisible. To illustrate some of these developments, we give particular attention to the writings of the poet Lucretius. According to our hypothesis, the rise of materialism in classical times came with the passing away of some very important prehistoric gods which were comets in the sky. Many of the legends of mythology can thus be interpreted as highly embellished accounts of the evolution of one, or perhaps a few, very large comets during the last 2,000 years of prehistory.

The subject matter of this and the following chapters has at the outset to be recognized as a simple attempt to see our past through different eyes. On its own, ancient textual evidence does not constitute proof: we deal therefore with the compatibility of ideas and measure their strength when woven together by the extent to which they follow the predictions of the earlier chapters.

8.1 Theories about comets: how they have evolved

Unlike previous returns of Halley's comet, that of 1758 was predicted. There is nothing like a successful prediction to convert non-believers, and in this case, the occasion was greatly to favour Newton's law of gravitation. The law has of course continued to dominate our understanding of the universe, and it is all too easy for us now to see the event of 1758 as relevant only to this new-found
mastery over nature's secrets. We tend perhaps to overlook the transformation which the event also produced in popular attitudes to comets had seemed to be guided solely by caprice.
where previously there was none. Until Newton's time, the mysterious comets had seemed to be guided solely by caprice.

Then as now, comets appeared in the heavens in the most diverse forms. There was no part of the sky, no constellation or region which was not liable to occasional visits. There was no season of the year, no hour of the day or night when comets might not be seen above the horizon. In like manner, the size and aspect of the comets were of every character, from the dim spot just visible to the eye perhaps fortified by the telescope, up to a gigantic brilliant object, with a tail stretching across the heavens from horizon to zenith. So also the direction of the tail of the comet seemed at first to admit of every possible position: it might stand straight up in the sky as if the comet were about to plunge below the horizon; it might stream down from the head of the comet as if the body had been shot up from below; it might slope to the right or to the left. It is no wonder that very little order was at first to be detected among the comets. We need only remind ourselves they were once thought more worthy of the Earth's changing atmosphere than of the orderly heavens. Whereas the stars generally inspired a sense of constancy and permanence, the comets appeared to be the jokers in the pack. Comets and chaos went hand in hand. So, if anything, it was the complete unpredictability of comets rather than the reverse that impressed itself upon the average viewer.

A viewer can of course contemplate unpredictability in a butterfly with rather greater equanimity than in an elephant on the rampage. The latter undoubtedly provides the better parallel in this case. Right up to mediaeval times, comets were a source not just of confusion but of terror. They seem to have engendered a feeling of virtual helplessness as if in the presence of superhuman forces. Indeed, they were widely regarded as omens of quite terrible import: wars, earthquakes, epidemics and the like were all among their forebodings. It is likely that more direct assaults, straightforward impacts on the Earth were also anticipated Newton himself was well aware of this possibility. The appearance of Halley's comet in AD 66 for example was a warning to the Jews of the coming destruction of Jerusalem, and when it appeared in 1066, it presaged the conquest of England by the Normans. The apparition of 1453 was associated in the popular mind with the fall of Constantinople. The effects, imagined or otherwise, were, to say the least, on a very generous scale.
21. Multiple-tailed comet of 1744 announced on a broadsheet printed in Augsburg. Such announcements were commonplace in mediaeval times and bear witness to the great concern such spectacles aroused.

Now, we may have come to see in this dread of comets the unreasoning response of elementary and superstitious minds: we may have assumed that people were forever imagining unproven associations between the heavens above and the Earth below; and we may see in our knowledge of their attitudes proof of an ancient belief in the power of magical forces. But the logic supporting this viewpoint does leave a little to be desired. True, it is possible that in seeking the causes for certain effects, there may have been an element of fantasy in our ancestors' explanations. But that does not mean we should always credit them with inventing puerile connections. The widespread belief that comets portended disaster (literally, "evil star") is in truth just as likely to have its origin in real evidence that a comet actually did cause disaster as in any wild imaginings of men in the remote past. That being the case, any possible evidence of this kind probably would have involved disaster and catastrophe on a scale not normally conceived since the memory of it, however mutilated by the ravages of time, succeeded in surviving in the popular mind down through many centuries. But the choice between the alternatives, real or
imagined catastrophes, is no longer purely a matter of guesswork. As we have seen in the previous chapters, comet-induced catastrophes within near historic times are a reasonable possibility. It seems that if we know what we are looking for, the positive evidence in historical records may be there to be found.

As good a starting point as any for a search is the superb history of the 1577 comet by Hellman. This is a most thorough and useful enquiry into the evolution of ideas about comets during the Renaissance period. The ferment of theories was obviously considerable. But the development was not haphazard. Each step in understanding, forward or back, had its basis in rational thought, and Hellman brings out particularly well the way in which the ideas of the mediaeval philosophers developed naturally from those of their classical counterparts. Indeed, only a very casual reading of the classical authors is required to reveal that they also were very greatly occupied with providing rational explanations for the behaviour of comets. If we were not already aware of the fear comets generated, we might well wonder what it was in these objects that so captured their imagination. Were the natural philosophers of ancient Greece and Rome perhaps a little closer in time to a comet-induced catastrophe? Were they perhaps trying to persuade readers that comets were not divine or satanic beings given to hurling thunderbolts at a wayward mankind? We might expect to test such a speculation by paying close attention to the detail of their arguments.

One of the earliest philosophers of whom we have knowledge was Thales of Miletus 625–545 BC. It is thought that he was a merchant who travelled to Egypt where he obtained an understanding of geometry, and to Mesopotamia where he studied astronomy. He is said to have predicted a solar eclipse, possibly that of 585 BC, using the Babylonian saronic cycle. Thales doubtless came across the creation stories of the Babylonians and the Egyptians, in both of which water featured as part of the primaeval chaos, for he supposed that all things came from water at the beginning. The Earth, he thought, was a disc with waters below, on which it floated, and with waters above from which the rains came. By reason of these inheritances of Sumerian doctrine, we tend to see Thales primarily as a link in a chain of diffusion of knowledge from the east, but this is probably an oversimplification. There is an equally ancient and independent mythology and cosmology in Greek history. No doubt Thales was able to reflect on the similarities and differences in formulating his philosophy. For the first time perhaps, we detect the
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signs of a dialectical mode of thought, a distillation of something new from the comparison of conflicting theories.

In Thales' philosophy and that of the Ionian Greeks generally, nature did indeed become for the first time very much more impersonal than it was in all the Bronze Age cosmologies. It seems the pre-Socratic Greek philosophers were concerned above all to banish the gods from nature. They supposed in particular that the heavenly bodies were solid material objects, not powerful personalized beings. The Latin word for stars (sidera) and the Greek word for iron (sideros) have a common root, so the new view must have been pressed with some success. But one wonders whether the later interpreters have fully appreciated the significance of this radical step? It is obviously a little too glib to credit the Greeks with a far-seeing knowledge of the constitution of the stars and planets. As it has turned out, they were not wrong in their supposition, but the association then can only have been a guess and would have been quite unconvincing unless the material attributes were for the Greeks linked in some very direct way with heavenly objects. As we are now well aware, the association of iron is most naturally with meteoritic phenomena, and there is no reason why falls should not have been known to the early classical philosophers. Indeed, they bracketed together a whole range of things like comets, shooting stars, thunderbolts, meteorites and the like. The idea that they all originate in some way from the home of stars, the aether above, is hardly a discordant one. It is safe to assume these early thinkers knew from experience, or at least thought they knew, that comets had material attributes.

We can easily overlook this fact however because later classical philosophers developed new conceptions of the universe which were subsequently taken up and greatly elaborated by mediaeval astronomers. According to them, the moving planets were supported in the heavens by invisible crystal spheres. This later theory made it quite reasonable to cast doubt on comets as part of the astronomical framework. How was it possible for solid objects to penetrate the heavenly spheres? It is interesting to reflect on the consequences of this logic. Aristotle, 384-322 BC, had provided one of the best early theories of the origin of comets: he supposed fiery phenomena were generated in the interface between the air and the aethereal zone beyond. As the latter rotated, friction between it and the stationary air produced 'sparks'. Although Aristotle may originally have envisaged some of these sparks being the cause of stars, it seems the
existence of crystal spheres would eventually have argued against the notion. So it was inevitable that comets should be treated merely as meteorological phenomena, thereby separating them from the celestial sphere containing the stars. Whatever eminence the comets may have enjoyed originally as part of the astronomical scene, academic logic appeared to make them no more important than clouds or lightning. Admittedly they could still be frightening but no more so, it might have been reasoned, than a violent thunderstorm. It is no wonder that later interpreters completely lost sight of the significance of comets to those early philosophers who presumably saw in their material attributes the proof that heavenly bodies were not heavenly: a proof, we must remember, that was so convincing to at least the more rational contemporaries that materialism took root in Greek philosophy and became the foundation of scientific thought. We are so conditioned nowadays by the comparative unimportance of comets that it may come as a surprise to realize that comets could have been among those heavenly bodies or powerful personalized beings that these early philosophers were seeking to treat like ordinary objects. But if this were so comets could have been among the principal deities of pre-classical times. The significance of this interesting possibility has not previously been appreciated as far as we are aware, and it is evidently of crucial importance.

8.2 Pre-classical association with deities in the sky

Although the word comet is derived from the Greek Kometes (‘hairy one’), it was almost certainly the Egyptians who first used the description ‘a hairy star’. The Egyptians are reported alluding to the analogy of long female tresses in connection with the appearance of a spectacular comet. There has also been a tentative identification of the hieroglyph for a comet with a nameless hieroglyph ideogram which was many years ago vaguely interpreted as ‘woman with dishevelled hair’. This hieroglyph is almost a replica of the well-known Sky goddess Nut, except for the addition of the long-flowing hair tresses. That comets were exalted as gods may therefore be susceptible to direct proof—in the meantime, we review some of the circumstantial evidence pointing this way.

One of our later informants concerning classical theories of the nature of comets is Seneca (4 BC AD 65). It is known that he conducted an unsuccessful search for early physical theories of their origin amongst Egyptian and Babylonian records. This failure coupled with the trend towards seeing comets as atmospheric rather than
astronomical phenomena may well have led later students to conclude comets must have been so unimpressive as to be of little importance to these earlier civilizations. Thus could seemingly impeccable logic lead to a conclusion diametrically opposed to reality as it must have been—the reality we have uncovered in previous chapters. If comets were among the gods of pre-classical times, the fact that the Egyptian and Babylonian astronomers had no theory of comets may be because a presumption of divinity stifled any speculation as to their physical origin. It is remarkable indeed how few are the recognizable references to comets as such in Babylonian and Egyptian records. This cannot be because they did not exist, so it must be because they were generally described as something else. If we accept this picture of comets as divine figures in the sky, we are obliged to see them as being among the most important and fundamental elements of the ancient sky. We need hardly emphasize how natural this picture would have been if the sky contained short-period comets perhaps with one or more sometimes an outstanding celestial spectacle during close passages. The Hellenic philosophers were thus responsible for a really quite major revolution in human thought: they were the first to describe comets in particular much as they appear to us, the first to make rational attempts to explain their origin in terms that we recognize as scientific.

The fact that these attempts eventually led the Greeks to treat comets as atmospheric can mislead us into thinking this was the view of their predecessors also. However there can be little doubt that the Babylonians before them considered comets to be astronomical in character, wanderers amongst the stars. Both the fixed stars and the comets were together associated with omens: omens that were not in the early days however concerned with the fate of individuals. The records show that it was the well-being of the country that was at stake—weather and harvest, drought and famine, war and peace, and the fate of kings. Typical of these is an omen which, according to Schaumberger, may well go back to the Dynasty of Akkad (circa 2300 BC): 'If Ishtar appears in the East in the month of Airu and the Great and Small Twins surround her, all four of them, and she is dark, then will the king of Elam fall sick and not remain alive.'

The experts have not yet provided an explanation of the frequently referred to Twins but Ishtar was one of the great trilogy of Babylonian gods which included Shamash (the Sun) and Sin (the Moon). There are obvious reasons why the latter two should be regarded as influencing affairs on Earth but the grounds for such
associations with the planet Venus, with which the goddess Ishtar was later identified, remain obscure. Indeed, if the association is correct, the phrase 'she is dark' is curious, to say the least. As it happens, there are several indications of a transference of name in the past, for example, in middle Persian texts, this member of the trilogy is known as Anahit, also later identified with Venus, and is, according to Nyberg, best likened to a river and interpreted as the Milky Way. At the same time, he describes the great celestial god as one that might 'leave the region of the stars' and approach the Earth. Mighty and splendid are the epithets employed with descriptions on a scale difficult to associate with a point of light, for example, the phrase: 'a height of a thousand men'. It has been suggested that these descriptions do not fit the Milky Way but that they will serve for Venus. Neither in fact is all that convincing but it could be argued that, as descriptions of a vast meteor stream, they serve rather well. The possible implication is that the god Ishtar may in the past have been associated with one particularly conspicuous periodic comet in Earth-crossing orbit. The reasons for associating it with omens to do with survival of the state thus become rather obvious.

Some words by an expert in comparative religion concerning the beings harboured by the ancient heavens, but with no conception of the association we are now discussing, might serve to illustrate something of the situation as it was:

'Anyone who has visited (let us say) the British Museum, or the archaeological galleries of the Louvre, or the Musée Guimet cannot fail to be impressed by the ease with which the great nations of antiquity accepted the supposition that the world in which they lived was dominated by a plurality of beings of human or even bestial character, framed on a scale larger than normal. ... Why was it that ancient Sumerians for example could credit the existence of deities who, though terrifying, were yet human beings writ large? How could Egyptians for a period equal in length to that which separates us from the reign of Alexander the Great (nearly 2,500 years) have been to all intents and purposes perfectly satisfied with a view of the universe which made it rather like a colossal game of chess, with no players, but only pieces of varying magnitudes, moving about of their own initiative, and treating humanity as pawns?'

We have to ask what conceivable objects could have given rise to such ideas. Possibly the Sun and Moon might just have been credited
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with great size, or the stars with sufficient numbers but the bestial character and disposition to disorderly motion hardly ring true. Comets on the other hand do seem to fit the bill more satisfactorily. Admittedly, we cannot claim it yet as an established fact but we believe there are grounds for supposing comets really were among the principal deities of primitive man.

It may be no coincidence that just at the time the Greeks were learning to dissociate comets from gods, so their contemporaries Amos the Hebrew, Zoroaster the Persian and Buddha the Indian all separated their gods from nature. These religious reformers all minimized the roles assigned to the gods in earlier civilizations such as rainmaking and providing a good harvest, such as producing plagues and causing thunderbolts. To what common factor could these reformers perhaps appeal that would allow them then successfully to persuade some of their listeners of the correctness of their radical views? If, as previous chapters have shown, the stock of short-period comets was rapidly dwindling, the terror they evoked would have been correspondingly diminished. Perhaps some time soon after the start of the first millennium BC, some particularly significant comet or god got diverted out of the solar system never to be seen again? Or perhaps the fuel for its tail simply came to an end? Only when comets had sufficiently died away and man was learning not necessarily to associate terrestrial effects with celestial causes, could he begin to contemplate other kinds of supernatural influence. Nowadays, we may be taught to believe that a manifold of gods is a natural product of primitive minds and that the advance towards a single less tangible god a natural consequence of inevitable anthropological forces. But we need not subscribe totally to such a theory here. The pagan beliefs were very plausibly supported by an appeal to quite visible celestial forces. As the sky cleared of comets then, so the old gods became more abstract and less real, and the world of the ancients became more impersonal and material. Thus, we might suppose, were made the first tentative steps towards modern science and modern religion. At the root of both apparently lies the understanding that comets were truly of material origin. The supreme irony is that religion in throwing away its multiplicity of gods may have caused astronomy to lose sight of its multiplicity of comets.

8.3 Illustration of classical ideas through the works of Lucretius

Historical analysis is fraught with difficulties and conclusions are liable to be sterile if not adequately supported by reference to original
sources. In this case, it is not to be expected that we shall easily find direct proof among such sources of the decline in the significance of comets. After all, the works in question have been raked over by analysts and translators right up to modern times, and throughout this process they have increasingly adopted a view of the world in which comets did not have a major role. A present-day analyst for example would until now have been considered irrational to extract from his translation anything but a twentieth-century picture of comets as they now appear. It is to be expected then that the translation and the logic of the past philosopher's case will be broadly consistent with a picture in which comets were not of major importance to classical man. If this were not the case, modern scholarship would already have foundered. So, even if evidence of the kind we are seeking were there in the first place, it will of necessity have been submerged and distorted by the passage of time. The best we can hope for in a cursory analysis are ambiguities in the evidence or revelations of a contrary argument consistent with the picture we are now describing.

With this in mind, it may be that a look at some extracts from the writings of one of the greatest of Roman philosophers, Lucretius, will serve to illustrate the thesis we are developing. To justify this choice of authority, we will not write our own eulogy on Lucretius: we will turn to a modern translator, Latham. Lucretius was in fact a representative of the Epicurean school, but apart from his great poem 'The Nature of the Universe', he is scarcely more than a name. He must have been born soon after 100 BC on the eve of the murderous civil war between the autocrat Sulla and the popular leader Marius. He was probably already dead when his poem was given to the world around 55 BC during that uneasy lull that preceded the recrudescence of civil war under Pompey and Caesar. He thus lived at a time when Greek and Roman thought had already evolved through 500 years or so. Suppose we simply discount the European dark ages, and consider Lucretius as part of the Renaissance springboard, which indeed he was, then he is a philosopher who sits conveniently halfway between modern science and early classical thinking. His arguments are thus rather well placed for a judgement of the starting point from which modern science has evolved.

Latham says:
‘under the Roman Empire there were many avowed Epicureans: but they were [mostly] interested in the Master’s tolerant and easy-going morality rather than in its scientific and philosophic
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foundations. To the Christians the whole system was of course anathema, though some of the Fathers found Lucretius a useful arsenal of ammunition against the Pagan gods. From the collapse of Classical civilization only one battered manuscript of [his] poem was preserved to form the basis of all existing copies. In the Renaissance Lucretius was rediscovered as a poet; but it is only since the seventeenth century, when the rationalizing French priest Gassendi advanced an atomic theory based on his teaching, that Epicureanism has been treated with respect as a serious attempt to explain the physical universe. Today, for better or for worse, the atom has been well and truly split, and it looks as though much of the mechanical materialism of the eighteenth and nineteenth centuries has been shattered with it. But this change, which may not be permanent, in the content of current scientific theories does not lessen the value of Lucretius' poem as a poet's exposition of the scientific outlook or at least of an outlook which has inspired much of the most fruitful work in the field of the natural sciences. Lucretius was one of the relatively small number who have accepted the evidence of the senses at its face value—have dismissed metaphysical abstractions, Divine Providence and the immortal soul as vain illusions—and at the same time have found ample grounds for wonder and joy in the perceptible universe and the omnipotent and omnipresent working of natural law.

In essence Epicureanism is the simplest of all philosophies—so simple that it is hard to find words for it in a language that teems with names for objects which Epicurus believed to be non-existent. He believed that all knowledge is derived from the senses. Things are exactly as they appear to be to our senses, or rather as they would appear to be if our senses were slightly more acute. Material objects are perceived. Therefore they exist. When the wind blows through the tree tops, we perceive that the branches toss; but the wind itself is not perceived. Must we then suppose that it is something different in kind from the things we do perceive? Not at all. We can imagine it [i.e. form an image of it] as a stream of material particles, like motes in a sunbeam but even smaller, knocking against the boughs. By similar reasoning, Epicurus sought to explain everything we perceive without positing the existence of anything other than material objects and the space in which they move. . . . We are all wrong when we delude ourselves with dreams, or torment ourselves with nightmares, of invisible powers interfering to upset the regular and determinate working of
Most of the Epicurean dogmas, however startling they may appear at first sight, can be readily grasped as attempts to apply this central principle in the absence of microscopes or other aids to sense-perception and of any technique for testing hypotheses by practical experiment. As expounded by Lucretius, they fit easily into place with no more explanation than he himself supplies. Of course every dogma has a history. The historically minded reader will be intrigued to catch the echoes of forgotten controversies. He will trace the debt of Epicurus to the fifth-century atomists, Leucippus and Democritus, and speculate how far these in their turn were trying to reconcile the individualist tendencies of the Ionians with the totalitarianism of the Western Greeks. But it is possible to know nothing of these things and still to understand and enjoy Lucretius. For these problems lie below the surface, and Epicurus was consistently and deliberately superficial. He believed that truth was not at the bottom of a well, but near to the surface, scarcely veiled in the outward appearance of things. For this reason his language was pictorial, and in the hands of a poet easily became picturesque. For the same reason he was remarkably free from the tyranny of words and the disguised assumptions implied in them. He was less inclined than most philosophers to regard the common beliefs of his contemporaries as universal truths. Plato and Aristotle were doubtless far more profound thinkers; but they were unmistakably dated as fourth-century Greeks, thinking in terms of Hellene and Barbarian, citizen and alien, free man and slave. For Epicurus, these distinctions which eluded the senses were not part of the essence of man, but mere accidents.

But Latham tells us that in one notable particular, Epicurus failed to escape the limitations of his age

He accepted the word 'god' in the Classical, not the Christian, sense as the name of an object. He could not believe that those stately figures that caught his eye at every street corner, that were stamped on every coin and painted on every jar, were images that had formed themselves in the mind atoms of the original artists without pressure from without. They must correspond to some external object. So he found a home for the blessed Olympians far away from human affairs in the interspaces between the worlds, and worshipped them as models of felicity in the happy assurance that they were impotent as they were indifferent.' [Our italics.]
In the hands of Lucretius, quite determinedly materialist and seeking to explain all action in terms of substance and motion, these ideas had clearly developed to the stage where the gods were outwith the visible world and nothing more than the invention of men in whom ‘the balance of their minds is upset by fear’. Invisible gods that were neither in the world nor taking part in it would hardly appear to have been a necessary part of Lucretian philosophy we must suppose they were retained because it would have gone too far against the spirit of the times to reject them altogether. Lucretius was thus writing for an age that was adapting to the idea that gods were only in the mind. Two hundred years earlier, such ideas would have been unacceptable, the gods were still much more real. Indeed, it is not credible that contemporary admirers of Epicurean philosophy and all that it stood for could have tolerated implications that the gods were intangible or invisible. Certainly it was not part of the materialist view of Epicurus that his sky-gods should have been exercising remote control over the minds and lives of men. But inescapably, Epicurus would have been dealing with what were imagined by him and his readers to be real objects. Whether we refer to the early Romans and Greeks themselves, or look further afield to the Indians, the Sumerians or the Celts, they all were basically agreed that many of the gods were in some sense located in the sky. Today, it might seem the gods must have been aethereal beings or, like constellations, merely patterns among the stars, but this could not have served at all for Epicurus and his contemporaries. His philosophy was unmistakably at one with the presence of real material bodies in the sky which the community saw as gods. By the time we come to Lucretius however, the gods are being banished from the thinking man’s visible world and we are left with a purely materialistic vision of how it all works. Where and when exactly the shift of paradigm took place need not concern us; almost certainly it was a drawn-out process and had already occurred in previous generations. All that matters for our present purpose is our confidence in Lucretius as an apostle of materialistic doctrine, one who was given to seeking explanations of phenomena in terms which we would now recognize as scientific.

The climate of opinion in which Lucretius spoke forth was however still one in which the gods were material bodies and endowed with considerable powers. By providing ordinary mechanistic explanations of various natural phenomena often attributed to the gods, Lucretius reckoned on the one hand to dissuade readers of the need for divine powers. On the other hand, he was at pains to demonstrate that
divine existence was but an illusion read into material bodies. In an important passage that illustrates this, Lucretius insisted that his readers abandon the idea that astronomical and earthly bodies were thinking or purposeful gods. His case was based on an earlier demonstration that the capacity for thought could arise only in living things. Astronomical bodies were obviously without sinews and blood and therefore possessed no life. And among the astronomical bodies, he seemed without doubt to include comets. Maybe we should let the words of Lucretius convey something of this line of argument:

"Before I attempt to utter oracles on this theme, with more sanctity and far surer reason than those the Delphic prophetess pronounces, drugged by the laurel fumes from Apollo’s tripod, I will first set your mind at rest with words of wisdom. Do not imagine, under the spell of superstition, that lands and sun and sky, sea, stars and moon, must endure for ever because they are endowed with a divine body. Do not for that reason think it right that punishment appropriate to a monstrous crime should be imposed, as on the rebellious Titans, on all those who by their reasoning [i.e. according to the Epicurean’s reasoning] breach the ramparts of the world and seek to darken heaven’s brightest luminary, the sun, belittling with mortal speech immortal beings. In fact, these objects are so far from divinity, so unworthy of a place among the gods, that they may rather serve to impress upon us the type of the lifeless and the insensible. Obviously, it is only with certain bodies that mind and intelligence can coexist. A tree cannot exist in the ether, or clouds in the salt sea, as fishes cannot live in the fields or blood flow in wood or sap in stones. There is a determined and allotted place for the growth and presence of everything. So mind cannot rise alone without body or apart from sinews and blood. If it could do this, then surely it could much more readily function in head or shoulders or the tips of heels or be born in any other part, so long as it was held in the same container, that is to say, in the same man. Since, however, even in the human body we see a determined and allotted place set aside for the growth and presence of spirit and mind, we have even stronger grounds for denying that they can survive apart from all body or animal form in the crumbling clods of earth or the fire of the sun or in water or on the high borderland of ether. These objects, therefore, are not endowed with divine consciousness, since they cannot even possess living spirits."
In this paragraph, Lucretius evidently decries any idea that parts of the universe possess divine power. He ridicules the habit of visiting human practices on lifeless beings as if they had minds: thus it is wrong to suppose punishment is imposed on objects like Titans for breaking through the celestial framework and obscuring the Sun. But to what objects does he refer? The references can but put one in mind of the much-favoured cometary theory of Aristotle. This, as we have seen, had these objects formed in the borderland between air and aether, then breaking away into the air below or the aether above. It seems that Lucretius' argument can make reasonable sense only if comets were among the gods and the Titans were a special group of comets which could somehow, on occasion, dim the Sun.

For this to be thought possible the knowledge that some very large comet indeed had at some time appeared must have been available. In recent centuries, no such large comet capable of dimming the Sun has ever been observed. However this cannot be raised against the possibility as an exceptional comet strongly outgassing, with its tail along the line of sight to the Sun, could perceptibly dim sunlight during transit. In like manner, one cannot casually reject the claim by Diodorus of Sicily that the Chaldeans for example knew about the regular return of periodic comets, a fact of present-day knowledge that we now presume originated only with Halley. Such claims were even linked with the occurrence of solar eclipses. The picturesque association of eclipses with an act of swallowing by a dragon is a very common theme in the ancient world, and such a description might easily be associated also with huge visible comets.

Moreover, that the comets were not simply benign visions in the sky was also well known to Lucretius. Later on in his poem, he tells of historical events which could easily relate to an encounter of a comet with Earth. He is expounding his view, a popular one in classical philosophy, that life on Earth comes in cycles: 'this world is newly made; its origin is a recent event, not one of remote antiquity.' The theory is one of balance most of the time between opposing forces, fire and water, either of which can gain the upper hand and bring an age to a close. Lucretius begins with a reference to 'maxima mundi membra', an interesting phrase which has often been taken to mean the four basic elements of the world—earth, water, air and fire. The interpretation due to Giussani may not be entirely correct however, especially as Lucretius did not subscribe to Empedocles' basic elements. Perhaps the phrase relates to those mighty gods battling it out in the sky. Latham's translation appears to catch the flavour.
'Since civil strife rages among the world's warring elements on so vast a scale, it may be that their long battle will some day be decided. Perhaps the sun and heat will overpower the rivers and drink their waters dry. They are struggling to do this now, but have not yet accomplished their aim: the rivers maintain such ample resources and threaten on their side to deluge everything from the deep reservoir of the ocean. They, too, are thwarted their ranks are thinned by the ocean-scouring winds and the fiery sun's dissolvent rays, confident of their power to dry up every drop before the water can achieve the goal of its enterprise. So these opposing forces maintain their heated conflict, contending on equal terms for gigantic issues. But legend tells of one occasion when fire got the upper hand and once when water lorded it over the land.

'The victory of fire, when earth felt its withering blast, occurred when the galloping steeds that draw the chariot of the sun swept Phaethon from the true course, right out of the zone of ether and far over all the lands. Then the Father Almighty, in a fierce gust of anger, struck down the aspiring Phaethon with a sudden stroke of his thunderbolt, down out of the chariot to the earth. But the sun intercepted the everlasting torch of the firmament in its fall, brought the trembling steeds back to the yoke from their stampede and, guiding them along their proper course, restored the universe to order. Such is the story as recited by the ancient bards of Greece, a story utterly rejected by true doctrine. What may really lead to the triumph of fire is an increase in the accumulation of its particles out of infinite space. Then comes the crisis: either its forces for some reason suffer a setback, or the world shrivels in its parching blasts and comes to an end.

'Another legend tells how water likewise once massed its forces and began to prevail, till many cities of men were drowned beneath its floods. Then, when there came some diversion and withdrawal of the reinforcements mustered out of the infinite, the rains halted and the rivers checked their flow.'

The elements of the Phaethon tale are taken up in the next chapter, but note how the object is described as 'the everlasting torch of the firmament' and how it is guided on its proper course by the Sun. The phrase 'aeternam . . . lampada mundi' juxtaposes a sense of perpetuity with a word that was commonly used to describe a meteor resembling a flaming torch: only a regularly recurring comet meets such a
description. There are further grounds, as we shall see, for supposing the head of the comet is the Father Almighty and Phaethon a fragment in its tail, but the claim that their actions are inspired by divine intent is renounced or 'utterly rejected by true doctrine' since Lucretius attributes them all to 'an increase in the accumulation of its particles out of infinite space', precisely the mechanism Aristotle invented to explain comets. If Lucretius is the objective analyst modern opinion claims him to be, accepting the world around him more or less at face value, then there is no escape. The Earth was indeed reputed to have been struck in earlier times, presumably more than once, by fragments of an 'everlasting' comet. On one or more occasions, a large piece impacting on the sea may have been sufficient also to cause a general flood. Surprisingly, however, the 'ocean' is probably not the sea but the meteor stream in the sky.

One other aspect of the climate of opinion in which Lucretius was seeking to establish his ideas deserves attention: we consider meteorological phenomena. In earlier classical times, phenomena like lightning and thunderbolts, the most powerful effects of 'meteorology', were, as the very name implies, quite confidently held to originate in forces in the aether above. Thunderbolts or -stones were unmistakably thought to be real physical objects (see Plates 23 and 24) and were often attributed to gods who hurled them from the sky. As we have seen already, any appreciation of the material aspects of the stars themselves must have originated in such knowledge. Such ideas were evidently still at large in the popular mind at the time of Lucretius, but he also belonged to a generation of philosophers who were now inclining to the view that thunderbolts were nothing more than the visible consequences of lightning. There are indeed sufficient similarities in his descriptions of both lightning and thunderbolts, such as the massing of clouds, their tendency towards seasonal occurrence and their capacity to liquefy metals, for later interpreters to see in them but different aspects of the same phenomenon, namely lightning. In subsequent times, of course, the view gained ground that lightning was a truly atmospheric phenomenon and, armed with arguments of the kind used by Lucretius, men would naturally have become convinced that thunderbolts never originated beyond the atmosphere: indeed, as missiles of the gods, they were figments of the imagination. So it came about that men of learning, versed in classical knowledge, were absolutely certain that stones never fell from the sky. It is hard for us now to envisage the extraordinary depth of this conviction which, until just short of only 200 years ago, led the
learned to dismiss such ideas as complete and utter nonsense. But dismiss them they did and one can only suppose that prior to the modern facts asserting themselves, the late classical arguments must have carried far greater weight than they deserved—or deserve! It behoves us therefore to be very cautious considering Lucretius' arguments on these questions. Indeed, there are fairly strong indications that Lucretius' thunderbolts do not always have the character of lightning that a modern observer would be inclined to describe. Thus, although he claims 'such is the ominous night of cloud-rack that gathers overhead, out of whose gloom the visage of black dread looms down upon us, when the storm is making ready to launch its bolts...' he continues: 'With the thunderbolt’s [sic] heavy freight of fire and wind, it trails in its wake a murky tempest big with levin-bolt and blast.' He goes on to describe a fiery object piercing its way through the sky, shedding lumps as it goes: 'it is in much the same way that a leaden sling-bolt often grows hot in its flight through dropping many petrificative particles and picking up fire in the air.'

The picture Lucretius describes, not unlike a meteorite fall, seems to be one of a barrage of rocket-like missiles, each carrying in its wake a huge murky vapour trail, each perhaps miniature versions of the Sikhote-Alin spectacle (see Plate 18). 'There follows that shattering roar that sounds as though the celestial vault had burst asunder and were crashing down upon our heads. A tremor lays violent hold upon the earth, and tumult rumbles through the depth of heaven...'

Now, one cannot prove an extra-terrestrial origin of thunderbolts from this ambiguous account, but one should nevertheless be aware of events like the giant meteorite of 1296 described as a ‘stony swarm’ falling on the forests near Velikii Usting in Russia: '...there appeared over the town a dark cloud, and it was dark as the night. ...lightning kept flashing ceaselessly. And it thundered over the town so strongly and horribly that it was impossible to hear people talk. Even the ground seemed to shake and sway continuously as if terrified by the horror. And clouds of fire arose and collided with one another, great heat coming from the lightning and thunder.' Grounds evidently exist for questioning the hypothesis that Lucretius describes mere lightning. Lucretius argues for a non-astronomical origin however and makes a great deal out of the seasonal character of the phenomenon, claiming it to occur mostly in autumn and to some extent in spring, the times of conflict between warm and cold air, the source of clouds. But some doubt hangs over this logic. Certainly thunderbolts were not so common as to make the regularity obvious,
and Seneca reporting this same phenomenon was inclined to place it in midsummer, not the most common time for thunderstorms in the Mediterranean area. Indeed both Seneca and Pliny, slightly later than Lucretius, were convinced there were two kinds of thunderbolt, one atmospheric, the other astronomical. Lucretius' meteorological mechanism though plausible is thus not totally convincing. If there were a disintegrating comet in eccentric Earth-crossing orbit, barely visible in the first millennium BC, part of a then declining meteor stream, the annual or biannual events which the classical authors describe are just those one would expect. The Taurids are intercepted twice a year, once in midsummer and once in the autumn. It is evidently possible that Lucretius was recording for us the past behaviour of an object whose only remnant of distinction could now be Encke's comet. That Lucretius was attempting to press his theory against an established view of a contrary kind can hardly be doubted:

"it is a fruitless task to unroll the Tuscan scrolls, seeking some revelation of the gods' hidden purpose. That is no way to study from which quarter the darting fire has come or into which other it has passed... If it is really Jupiter and the other gods who rock the flashing frame of heaven with this appalling din and hurl their fire whenever they have a mind, why do they not see to it that those who have perpetrated some abominable outrage are struck by lightning and exhale its flames from a breast transfixed, for a dire warning to mortals? Why, instead, is some man with a conscience clear of any sin shrouded unmeriting in a sheet of flame, trapped and tangled without warning in the fiery storm from heaven? Why do the throwers waste their strength on deserts?... Why does he launch them into the sea?... Lastly, why does he demolish the holy shrines of the gods and his own splendid abodes with a devastating bolt?"

There is logic enough here for Lucretius to hoist his contemporary opposition by its own petard. But that is no reason for it now to mislead us. We have seen that there is very real doubt that Lucretius' thunderbolts were atmospheric, so the prevailing wisdom that they were astronomical and linked with the god was probably correct. It would not be the first time a theorist has unwittingly used false logic to deny a phenomenon that seems to undermine his cause.

Thus, although the force of Lucretius' argument may have persuaded his followers towards the currently accepted interpretation, the then prevailing climate of opinion was evidently one
that tended to see a natural link between stars, comets and thunderbolts. Indeed, the association must presumably have been the very one that earlier convinced the majority that the stars and the gods had material attributes.

A very recent survey of classical and mediaeval literature by dall'Olmo came up with a huge list of the different terms and expressions which have been used in the past to describe comets, meteors and meteor showers. This illustrates perfectly the very real difficulties modern compilers have had in their attempts to identify cometary events and determine their nature. The problems for the analyst are therefore undoubtedly present and we would not expect
It is interesting to note the short narrow tails and round heads so characteristic of the Neolithic carvings (see Plate 30) to see the thesis of this chapter established without a good deal more work. Nevertheless, the hints that modern interpreters may have missed the significance of parts of pre-Socratic thinking are strong enough to suggest the viewpoint expressed here may not be far from the truth. It is interesting that dall'Olmo finds that many of the verbal expressions used to describe comets that were used in classical times do not appear at all in the mediaeval documentation. It is as if the real phenomena of classical times did not really impinge upon the consciousness of the later writers in quite the same way. In the classical era for example, the word *signum* was commonly used by writers and historians when speaking of different kinds of light in the sky, mostly
comets and sporadic meteors. The term included *trabes* (boards), *globi* (globes), *faces* (torches) and *ardores* (blazes), all apparently describing different tail structures. The study of these phenomena was justified by Seneca who saw, with others, the need to establish whether there is a fixed succession for all events, that is whether 'what has happened before is a cause or an indicator [*signum*] of what follows. We will see whether human affairs are any concern to the gods; whether the sequence of events tells by definite concrete signs what is going to happen.'

By the time of the Middle Ages however, this rather open-minded approach had deteriorated significantly. The Christian writers maintained and emphasized all the most portentous connotations of *signa*, imagined or otherwise. People either invented fanciful connections with human affairs or lost sight of rational links altogether. It seems the Renaissance may have again set us on the road to modern science, but only by turning a blind eye towards the comets, the gods they inspired and the missiles they hurled.

### 8.4 Mythology as a history of comets

In giving special attention to some writings of Lucretius, we reiterate that it is not our intention to suggest any very special status for Lucretius in the history of human thought. His is simply a reasonably transparent philosophy which is conveniently well placed in time. If, as we suggest, his writings truly reveal signs of these arguments that eventually led man to think of gods as invisible beings where before they had been active, visible creatures in the sky, then our analysis must be seen as bringing the gods of mythology to life. For the first time, we begin to see the rationale behind many of their characteristics, the celestial environment of their adventures for example. We may also see their many animal forms as merged and stylized representations of the heads and tails of comets. In fact animal forms were still explicitly used to describe comets in classical times, the *hippeus* (horse-star) and *hurci* (goat-comets) being mentioned by dall'Olmo. It is interesting that the sixth-century Byzantine astrologer Lydus also includes in his classification of comets a type which is god-like. Thus in his *De Ostentis* he states: 'There is also a shining white comet with silver 'hair', shining in such a way that it can scarcely be looked at, and of human appearance, showing in itself the form of a god.'

Of course, if the gods were comets, it is not to be expected that many comets could have been continuously followed down the years. Almost certainly, if the theory is to be believed, we need only suppose
there were a few specially conspicuous comets in regular recognizable orbits. It is these objects that would have become the principal gods. Now, for the first time perhaps, we can begin to understand the meaning behind their genealogy. It is in essence a record of fragmentation and fading: a breaking-up that sometimes seems to be unattended by any visible agency, variously described as virgin birth or as children devouring a parent. In different countries, we can trace back through a number of generations to their principal progenitor: Zeus or Kronos in Greek mythology, Tiamat in Babylonian, and Atum or Ptah in Egyptian. A time was certainly envisaged when the founder was alone in the cosmos, sometimes in the form of a ‘cosmic egg’ but then there emerged offspring which themselves were the source of further offspring and so on. With the passing of the years, different versions of the tale were merged and there is a tendency in unravelling the tale for generations to become overlaid, giving rise to some quite natural confusion. Certainly one should not look for a precise history in the accounts. But the main features are nevertheless fairly clear.

The Egyptians in particular were inclined to simplify and formalize the pattern and reduce each generation to a single pair. They did in fact perceive a kind of duality in phenomena generally, but no doubt this is partly rationalization that came along with the establishment of national gods. Thus, where there was at first a plurality of gods, and many local cults devoted to the worship of particular objects, unification of the state brought with it a tendency to combine in single gods the functions of the different local divinities. The supreme primaeval figure, represented by the Djed Column, comprised both a lotus tree and a cosmic serpent, symbol of light and motion. It both blossomed in sunlight and, as Apepi, sought to darken the sun! According to the Memphis tradition the cosmic god Ptah spewed from his mouth the two deities Nunet and Nun. A similar tradition in the Hermopolitan story had Atum giving rise to corresponding figures, Shu and Tefenet. These were the principal gods of the Old Kingdom, Nunet having particular associations with the air or sky, while Nun was identified with water and primaeval flood. There are close similarities here to Noah’s flood, but Nun was generally understood to be a beneficent god who guarded and kept in check the demonic power of chaos represented by many giant dragon-snakes.

In some accounts, Nun was also the progenitor of Atum, who emerged standing upon a hill. This primaeval hill had a variety of forms and was no doubt associated with the Egyptian glorification of
pyramids. We can see in this common identity of Atum with a person arising from the flood on a hill and a god in the sky, the very earliest association between Egyptian kings and supernatural powers from heaven.

A variation on the same theme had Shu produce Nut and Geb but in the later cosmology things became more elaborate. Nut gave birth to Osiris and Isis, Seth and Nephthys all of whom together became important deities in the Egyptian pantheon. Osiris was a supreme and majestically portrayed sky-god, seemingly dominant throughout the Old and Middle Kingdoms, and bearing many similarities to the Zeus and Jupiter of Greek and Roman mythologies. Isis was both sister and wife to Osiris and bore him a son, Horus, the counterpart of Apollo in classical mythology. Horus, it seems, reigned in his father's place after the beginning of the New Kingdom period when Osiris descended to the underworld to become judge of the dead. The long reign of Osiris was not without incident however: for the most part, events were governed by ma'at, a kind of guiding principle maintaining harmony in the heavens, but the Egyptians also recognized propensities for chaos and the whole of their religion reduced ritual and prayer ('hike') to a kind of magic, aimed at combatting threats from above that were exceedingly real. These threats were mostly personified by Osiris' wicked brother Seth who twice succeeded in killing Osiris. On the first occasion, Osiris drifted out of sight but was brought back to life by Isis; on the second occasion, significantly, parts of Osiris' body were broken off and deposited in the ground in different places all over Egypt. Once again, Isis brought Osiris back to life but subsequently he lost his former glory becoming more and more a god of death. It was left to Horus, now grown up, to avenge his father's death by defeating Seth in a further mighty battle. The subduing of Seth (or Satan), the god of storms, was an important achievement and from henceforth, disgraced, the Egyptian mythology placed him on the prow of the solar barque, watching out for that other great enemy of Ra, the Sun-god, namely Apepi, the god of darkness. Apepi was not apparently of Nut's family but was pictured independently as a snake or dragon, one of its roles being to eclipse the Sun. However he did this, he does not seem to have been related to the moon-god, Thoth.

We might venture to paraphrase the mythology as follows. first of all, there is Ptah, perhaps either the planet Jupiter spewing forth comets as a result of a close encounter, or simply a large comet splitting in two; then there is the universal flood followed by a period
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dominated by the sky-god Nunet, this god either produces or is
identical to the god Osiris. The genealogy makes reasonable sense if
the events describe successive phases in the life of a huge comet in
periodic Earth-crossing orbit, but after further break-up and decay,
the main component ceases to be visible and presumably becomes an
Apollo asteroid. Although not part of the principal family of gods,
Apepi may have been another mighty comet periodically dominating
the sky: we can only speculate here but it is not impossible that Halley’s
comet may have been recognized (see later).

An important underlying theme of Egyptian cosmology is belief in
the actual presence of gods’ representatives on earth: thus the
pharaoh seems to have been identified with Horus during the New
Kingdom period. Such beliefs were part of the very fabric of society
itself. In fact, this idea was so much an integral part of the centralized
state control that it survived for such an enormous timespan that we
can safely assume that it was accepted with a conviction tantamount
to certainty. We need have no doubt therefore that minds would have
been turned away completely from any kind of rational explanation
of the sky-gods. The Greek civilization on the other hand was not
subdued to the same degree, at least as far as one can tell. It was still
fearful of gods and very conscious of disasters, but the Greeks
behaved more like disinterested observers of a heavenly pageant
unfolding before their eyes. The situation was to them more like one
in which the earth, an innocent bystander, sometimes takes a badly
aimed custard pie full in the face as a result of overenthusiastic
horseplay amongst the gods. Their mythology has become part of the
common heritage of western civilization, and is amongst the best
known. It is highly complex and has been subjected to any amount of
analysis and critical interpretation on psychological and sociological
lines both in modern times and in the days of classical antiquity. With
so many alternative explanations available, no unique astronomical
interpretation can possibly be claimed. Nevertheless it is possible to
discern some underlying patterns that are not at all unlike those
recorded by the Egyptians.

Among the principal sources of Greek mythology are the Iliad and
the Odyssey by Homer, circa 800 BC. Of the same period, there are
writings by Hesiod and his school, and then in the fifth century BC,
Pindar is another source. The Greeks themselves also systematized a
mass of local and particular mythology that had developed
independently in communities isolated by geography, to form a
mythological prehistory leading up to the large-scale Dorian invasion
and settlement of the Peloponnese around 1000 BC, the time also of
the return of the Heraclids to Mycenae. It is now known that the
latter once was the home of a mature civilization during the preceding
millenium and it reached some kind of high spot in Crete before
disaster overtook it around 1400 BC (see Chapter 10). Prior to this
time, the Greeks saw back to a Golden Age when man was basically
at peace in a bountiful world. This was then followed by a Silver Age,
described at first as a time of immense hardships when man was
obliged to construct houses and work hard, when he became
degenerate, mentally weak and impious. In the period that followed,
the Bronze Age, men became stronger but were apparently bent on
mutual destruction; thus we arrive at a time of strife and violence in
prehistory that eventually merged with the events of history.

All the while as life proceeded on Earth, the cosmic gods were
fighting it out in the heavens. It seems that Cronus and Gaea presided
over the Golden Age, but in due course they gave birth to an
abundant new dynasty of gods: the Cyclopes and the Titans are
particularly memorable. The youngest of the Titans was named Zeus.
The names Jupiter and Zeus are identical, being cognate with the
Sanskrit dyāus-piter meaning sky-father, but it may be in keeping
with the ideas we have developed if we think of Zeus as of Jovian
descent. He is one of the common stock of Indo-European gods since
Greek, Latin and Sanskrit are descended from a common Indo-
European language; thus although the earliest literary references to
Zeus are found in Homer, the god is of much greater antiquity. Both
Jupiter and Zeus were worshipped on the summits of hills or
mountains. Jupiter was associated with a sacred tree on the
Capitoline Hill; and there are many myths of the bestial transfor-
mation of Zeus, the use of aegis, the goatskin, as a battle-charm
deriving from this. However, there is no question that Zeus became
the principal figure of the Silver Age. He appears to have had a
retinue of hangers-on, Hera and Lcto for example to name but two,
and had strong links with gods of the sea and the underworld,
Poseidon and Hades respectively. All of this is in keeping with a sky-
god, attended by two principal companions, who regularly disapp-
peared over the maritime horizon and re-emerged the next night after
traversing the underworld. While Zeus in particular commanded the
skies, the Titans were producing an immense offspring of separate
gods, many of whom were eventually confined to Tartarus, the lower
depths of the underworld. Zeus himself was also the bearer of
considerable progeny but, according to the principal sources of
information, it was Leto amongst his hangers-on who gave birth to Apollo and Artemis. This is not quite the same as the Phaethon tale which has, in one interpretation, Phaethon coming from Apollo who was himself the offspring of Zeus, but the underlying themes are not dissimilar once they are recognized as derived from different eyewitness accounts of a comet breaking up. Whatever the detail, Apollo seems to have supplanted Zeus and become a major new figure in the family of gods.

In Hesiod’s *Theogony*, written around 800 BC, is a quite marvellous account of the evolution of the gods in their heavenly setting. He speaks of Olympus, the home of the gods, and Zeus, one of the sons of Cronus who also gave birth to the Titans. Seen at first through approving eyes, Olympus had assembled around it the nine daughters of Zeus, one may envisage a huge disintegrating comet attended by so many subsidiary ones.

‘And at their birth they went with Olympus, exulting in their beautiful voice, in their immortal song, and around them, as they sang, dark earth was re-echoing, and a winsome sound arose from their feet as they went. But he [Jove or Zeus] reigns in Olympus, having at his own disposal the thunder and the glowing bolt, since he had conquered by force his father Cronus.

We seem to be picturing Olympus in motion, the home of the gods with Zeus at the head. In due course however, the clash in the heavens gave rise to a more fearful view of the gods:

‘On that day all of them, male and female, the Titan gods and all who were born of Cronus and those terrible mighty ones with their insolent strength whom Zeus brought up to the light from beneath the ground from Erebus, stirred up the sad battle. A hundred hands shot from the shoulders of all of them alike and fifty heads on stout limbs grew on the shoulders of each one of them: Then with high rocks in their stout hands they fought against the Titans in a mournful battle. On the other side the Titans strengthened their ranks zealously and both sides simultaneously displayed the works of hands and strength [i.e. their strong hands]. The boundless sea rang terribly around, the earth crashed loudly, broad heaven quaked and groaned, and high Olympus shook from its base... The heavy shaking, the noise on high of feet in ceaseless pursuit and of mighty blows reached murky Tartarus; so then they threw at each other their grievous bolts.’
The picture of a huge body disintegrating into a vast shower of comets, with the Earth sometimes running into a stream of debris, seems to suggest itself. As time went on, the meteor stream, 'Ocean' as it was called, gave rise to even more spectacular events:

‘Then Zeus no longer held back his ferocity but now immediately his mind was filled with fury and he showed forth all his strength; at the same time, continually hurling his lightning, he came from heaven and Olympus. Thick and fast, the thunderbolts, with thunder and lightning, flew from his stout hand and they made a holy flame roll along, as they came in quick succession. The life-giving earth blazed and crashed all around, and all around immense woods crackled loudly in the fire. The whole land, Ocean’s streams, and the unfruitful sea seethed; the hot blast surrounded the earthborn Titans and an immense flame reached the shining upper air. The gleaming brilliance of the thunderbolt and lightning blinded their eyes, strong though they were. An awful heat seized Chaos; to look at it straight on with the eyes or hear the sound of it with the ears, it seemed just as if earth and broad heaven threatened to meet above us; and so great was the din which arose from the former collapsing in ruins and from the latter dashing her down from above; so great was the din when the gods met in conflict. Together with this the winds stirred up earthquakes, dust, thunder, lightning and smoky thunderbolts, the arrows of great Zeus, and carried shouts and war-cries into the midst of both sides. . . .

But this is not the end of the tale: years pass by until ‘when Zeus had driven the Titans from heaven the huge Earth gave birth to her youngest child, Typhoeus, by intercourse with Tartarus.’ We may picture them one night, Zeus and his new offspring, rising up over the horizon presumably trailing its huge tail. This combination then threatened the Earth perhaps for many years, until there came yet another assault:

‘But he thundered harshly and strongly, and all around the earth, the broad heaven above, the sea, Ocean’s streams and the lowest parts of the Earth resounded terribly. . . . Through the two of them, heat seized the purple sea, from the thunder and lightning, the fire from the monster, the hurricane winds and the blazing thunderbolts. The whole earth, sky and sea seethed; and moreover long waves raged around and around about the shores. . . . So when
Zeus had raised up his strength, he chose his weapons, thunder, lightning and the smoky thunderbolt. He leapt from Olympus and struck him and burned about the awful heads of the terrible monster. But when he had tamed him and lashed him with blows, he was thrown down lame and the huge earth groaned. The flame from the thunderstruck lord shot out in the unseen rocky glens of the mountains, when he was struck. Much of the vast earth caught fire as a result of the awful blast and melted just as tin melts. . . . Grieving at heart, he cast him down into broad Tartarus.

Hesiod’s war of the gods, then, is between two factions in the sky, in the course of which one group is dashed down from above. The description seems to be that of a shower of comets emerging to do battle with pre-existing ones, with the Earth sometimes running into a stream of debris, the events culminating in the close passage of a late fragment, Typhoeus, with destructive consequences. Some aspects of the account bear a striking resemblance both to that of the Tunguska event and the Velikii Usting fall of AD 1296. It is notable that the thunderbolts of Zeus are clearly distinguished from thunder and lightning, that they rained down thick and fast, were blinding in their intensity, setting the Earth alight, while blast, heat, earthquake and tremendous noise accompanied the battle and an immense flame reached the upper atmosphere. It seems therefore that Hesiod’s account is a rather literal description, based on sources now lost, of a series of impact events which may be recognized as associated with comet disintegration; indeed, as we shall see, there are other grounds for associating Typhoeus or Typhon with a comet. But we need take this discussion of Hesiod no further; enough has been said to show that both Greek and Egyptian mythology contain important elements which are at least consistent with a course of events like that implied by the present distribution of short-period comets in the inner solar system.

According to our theory then, comets were not known as such before this time because people saw them as something else, as greater than life, as supernatural beings. Sometimes the comets stayed aloft and seemed relatively benign: perhaps these were the angels. Others however came down to threaten life on earth: these were gods of a more belligerent kind, qualifying as dragons in the sky or as devils. As we shall see in the next chapter, references to fire-breathing dragons careening across the sky were widespread in the prehistoric world, and it is remarkable that Chinese legends handed down to us
what seems a perfect reflection of the development of comets in short-period orbits. According to these legends, dragons usually hatched out in the form of small water-snakes or lizards, but rapidly and visibly began to grow towards maturity. Although the speed of growth was marked, the process of evolution took time: 'A water-snake after five hundred years changes into a kiao, a kiao after a thousand years into a lung, a lung after five hundred years into kioh-lung (horned dragon) and after a further thousand years into yuing-lung (winged dragon).' If, as it seems, the dragons were short-period comets, the Chinese must have pondered then with extraordinary care.

Turning to the myths and gods of northern Europe, the earliest recorded legends belong mostly to the second millennium AD and are heavily overlaid with fanciful embellishment, but somehow there nevertheless emerges a definite cosmological framework. The dominant concept of Norse cosmology is the World Tree, Yggdrasil. It was said to spread its limbs over every land and was visualized as a kind of ladder stretching up to heaven and downwards to the underworld. The World Tree marked the centre of the universe and was a symbol of the constant regeneration of its parts. The Tree was the realm of the gods and from which they seemed to grow and spread throughout the world. No such analogy has previously been drawn but it is not at all unreasonable to see Yggdrasil as a giant comet, the dragon of other mythologies, to which the rest of the world is subordinate. In several myths the dragon of chaos is also represented by or associated with a World Tree or Tree of Life: this is seen for instance in Genesis 1 where serpent and dragon are identical. This dragon/Tree equation is rather strange on its own but makes sense if both were descriptions, ultimately merged, of a comet. In classical times Seneca used the term cyparissia (cypress tree) to describe comets.

So huge was the Norse World Tree that its branches stretched out over heaven and earth. It apparently had three main roots and daily reappeared with all the other gods, galloping over the Bifrost that some have identified as the Milky Way, a rainbow bridge that glowed with fire. We wonder whether it was really a meteor stream in the ecliptic. As it grew and flourished, the tree was continually threatened by the living creatures that preyed upon it. On the topmost branch sat an eagle of whom it is said the flapping of its wings caused the winds in the world of men. At the root of the tree lay a great serpent with many scores of lesser snakes and these gnawed continuously at Yggdrasil. The serpent was at war with the eagle and a squirrel ran up and down the tree,
carrying insults from the branches and tender shoots of the tree, leaping at it from every side. We cannot prove this magnificent imagery refers to comets, but the celestial aspect, e.g. the diurnal reappearance, is clear, and the vision of a vast ever-changing complex of cometary bodies hurtling together around the sky seems to emerge without much difficulty. Once again, we detect a hierarchy of genealogy among the gods: first the Tree of Life gives birth to Loki who may be the same as the wolf Fenrir. This interesting character has jaws which brush heaven and earth, while fire spurts from eyes and nostrils. The counterpart in Greek myth is apparently Olympus, the home of the gods, with Zeus emerging as the head of the family. Loki (Zeus?) seems in due course to be the progenitor of Surt, who may also be Balder due one day to return from the dead. Surt is thus the Apollo of Greek mythology and Thoth (later Osiris) of Egyptian mythology. Ellis Davidson has given a superb account of the northern myths and we refer the reader to her book for details. Perhaps the following extract dealing with Ragnarok, the end of the world, reveals clearly enough the history of comets as we now understand it.

‘There Loki must lie until Ragnarok, the time of the destruction of the gods. This fearful time will be ushered in by many portents. First there will be great wars through the world, and a time of strife and hatred between men. The bonds of kinship will hold them no longer, and they will commit appalling deeds of murder and incest. There will also be a period of bitter cold, when a terrible pursuing wolf catches the sun and devours her. The moon too is swallowed up, and the stars will fall from the sky. The mountains will crash into fragments as the whole earth shakes and trembles, and the World Tree quivers in the tumult. Now all fettered monsters break loose. The wolf Fenrir advances, his great gaping jaws filling the gap between earth and sky, while the serpent emerges from the sea, blowing out poison. The sea rises to engulf the land, and on the flood the ship Naglfar is launched, a vessel made from the nails of dead men. It carries a crew of giants, with Loki as their steersman. From the fiery realm of Muspell [the south?], Surt and his following ride out with shining swords, and the bridge Bifrost is shattered beneath their weight. His forces join the frost-giants on the plain of Vigrid, and there the last battle will be fought between this mighty host and the gods.

‘... Thor meets the World Serpent, and Freyr fights against Surt... All the gods must fall, and the monsters be destroyed with
themselves. Thor kills the serpent, and then falls dead overcome by its venom. . . . Only Surt remains to the last, to fling fire over the whole world, so that the race of men perishes with the gods, and all are finally engulfed in the overwhelming sea;

The sun becomes dark, Earth sinks in the sea
The shining stars slip out of the sky
Vapour and fire rage fiercely together,
Till the leaping flame licks heaven itself.

Yet this is not the end. Earth will rise again from the waves, fertile, green, and fair as never before, cleansed of all its sufferings and evil. 'The sons of the great gods still remain alive, and Balder will return from the dead to reign with them. They will rule a new universe, cleansed and, regenerated, while two living creatures who have sheltered from destruction in the World Tree will come out to repopulate the world with men and women. A new sun, outshining her mother in beauty, will journey across the heavens.'

It is impossible here, in dealing with this vast domain, to go through the myths of the world in a systematic way indicating the associations with the comet scenarios already developed. Suffice to say, the theme that we have developed is commonplace. A more or less random example from the New World, for example, is the return of Quetzalcoatl, the 'feathered serpent', which was probably presaged by the great comet of 1490. Only a short time later, the Aztecs took Cortez and his brigands as a sign that the legendary rain-spirit god from across the ocean had returned. Quetzalcoatl, a complex and ambiguous figure of great age, sometimes represents the Sun and sometimes, with his twin Xolotl, the planet Venus. But it seems also that Quetzalcoatl, a white and bearded god, symbolized by the plumed serpent, was, in the eyes of the pre-Columbus central American ethnic groups, very often associated with apparitions of spectacular comets in the morning sky.

The mythologist Fauconnet, in his study of the mythology of the two Americas, makes the point that there are many similarities between these myths and classic mythology, as well as with Hebrew tradition. He asks:

'Does this mean that Humanity was once upon a time reduced to a little group of individuals who later spread over the earth, bringing with them their legends which they altered through the centuries in
accordance with new climates and new habits? Or, as seems more probable, are all these legends a confused account of great events on a planetary scale which were beheld in terror simultaneously by the men scattered everywhere over the world?"

Coming from a mythologist with no inkling of the astronomical picture we have developed, this is a remarkably perceptive comment. The picture then, is of a prehistoric sky which on occasion was filled with comets. Very probably, at least one of them was an exceptionally large, active and disintegrating body, in an orbit which at certain epochs resulted in a series of close passages to the Earth. In the present chapter we have revealed that much of the imagery of many world myths corresponds to such phenomena. We have also pointed out what appears to have been a shift of paradigm during the classical era as the sky cleared and the danger passed. Our comments in this chapter should of course be seen as indicative rather than definitive but there can be little doubt that, for all the multiple interpretations and layers of symbolism which have already been read into myth, a major re-analysis is called for. The conclusion, then, is that comets were originally amongst man’s principal deities. And of these, there lingers the memory of two which surpassed them all: Zeus and Typhon.
Several myths of the world are interpreted as allegorical descriptions of the break-up of a large comet in an Earth-intersecting orbit. Some fragments struck the Earth during the second and third millennia BC. A number of biblical episodes, in particular the Exodus event and the Flood, describe the consequences of one or more powerful impacts.

9.1 Mythology: fairy tale or history?

Any attempt to look for real astronomical events described in mythical form presupposes that myth can be evaluated as a source of historical information. Such a concept of myth would have been largely denied in the last century. The myth, it was considered, was mere fairy tale, the product of irrational and superstitious primitive minds which had not yet aspired to the philosophical and thence scholastic planes. This somewhat ingenuous thinking seems to have been essentially a product of Comte's positivism, a refusal to look beyond the immediately verifiable or measurable. There were occasional dissenters. Von Schelling in 1856, for example, considered that some myths relate to actual experience, that is historical events and real-life forces, concealed in allegorical form and poetic language. It is now appreciated that myths have many facets. They have what Grimal calls a 'spiritual quality', that is they provide a moral framework governing the day-to-day attitudes and actions of the believer. They have the purpose also of influencing the world, through personification of inanimate things such as wind and trees, sun and stars, opening the door to persuasion by prayer. And they give a description and explanation of the world, the view pioneered by von Schelling and vindicated in modern times by for example Walter Otto. It is this latter attribute, that historical truths may exist concealed in mythical language, that enables us to look for the real objects and events behind the gods and their adventures.

Here we may be helped rather than hindered by the existence of several versions of the same story, because the invariant component in these stories will represent the underlying event, the varying component, representing a superstructure of personification and moral, being the additions of individual poets. For Greek myth especially confirmations of the historical basis of many legends have
come from archaeological excavations. The foundations of Troy and Mycenae were unearthed by Schliemann on the basis of passages in Homer; and excavations of the palace of Knossos by Evans showed that many Cretan legends likewise had a historical basis.

It would not be the first time that astronomy and the literature of
antiquity have benefited from mutual illumination. In the early
nineteenth century for example Chladni assembled reports dating
from the remote past of stones falling from the sky, found that the
descriptions were consistent with one another and deduced in the face
of great scepticism that real events—meteorite falls—were being
recorded.

Having said all this one should be aware of the dangers of over-
interpretation, and of reading too much into the accounts. One must
proceed with sensible caution. Roman ‘historic’ myths, for example,
which mostly come from the Augustan period (first century BC), are
to some extent myths taken from elsewhere and presented in pseudo-
historic form. We shall not be concerned with Roman mythology.

This concept of myth, as being rooted in reality, is consistent with
and reinforces our proposal that the sky deities represented real
things in the sky, and hence comets. The question arises: Can we
establish among the myths of the world astronomical connections of
the sort we have discussed?

The earliest recorded myths are those of combat, between a god or
hero and a dragon. The dragon was a familiar figure in Greece, Egypt,
Mesopotamia, Babylon, India, China, North America, and else-
where. Usually, he has the form of a winged serpent. He is a gigantic
monster; he spouts fire and smoke; bellows and hisses; he throws
rocks, and is the creator of terrible destruction; and his home is in the
sky. The dragon or winged serpent seems as good a starting point as
any in our study of myth.

9.2 Combat myths: Zeus and Typhon

There were two main combat myths in ancient Greece, that of Apollo
vs Python and that of Typhon vs Zeus. The earliest known record of
Apollo’s combat with a dragon is contained in the Homeric Hymn to
Apollo. The story therefore dates at least as far back as 1200–850 BC.
Soon after his birth, Apollo crossed the sea and travelled over the
mainland of Greece in search of a place to establish a temple. On
Parnassos, on the site of Delphi, he laid the foundations of his
oracular shrine, and on these foundations the temple was laid by
tribes of men. In the course of this work, or just after its completion,
he encountered a she-dragon. The dragoness was huge, savage and
violent against men and their flocks; it was a devastating creature and
to meet it meant death. Homer tells us that nevertheless the creature
was killed by an arrow from Apollo’s bow. Apollo goes on his way
and his further exploits need not concern us for the moment. Plainly in this story, Apollo was the survivor. The question we raise is whether he was the surviving fragment of a disintegrating comet; whether on one passage or other as he rose over the maritime horizon and travelled over Greece, he was observed to shed a stone which became the foundation of the Delphic temple. Is a bow, one wonders, the natural image conjured up by the crescent head of a huge comet? Were the intoxicating vapours provided by the Delphic ‘priests’ regarded as essential for adding verisimilitude to their pronouncements because the foundation stone from heaven was originally recognized as a source of noxious fumes?

Homer supplies us with an interesting genealogy for the dragoness. She had been the nurse of Typhon, the child of Hera, the Queen of Heaven. Typhon itself was a monstrous creature, unlike god or man. Hera had produced the child in anger at her husband Zeus, because he had given birth to a daughter Athena, without involving Hera, by producing the child from his head (see Plate 7). In the tale as recounted by Simonides, the dragoness had become male and acquired a name Python. In this version, which seems to have become more popular after about 300 BC, Apollo comes to Delphi while Ge still rules the shrine. Python opposes Apollo, there is a battle, and the dragon is finally killed by many arrows from Apollo’s bow. Python seems again to have been a terrifying creature in this second version; Ovid, in his Metamorphoses, states that ‘populisque novis terror eras’—you were a terror to new peoples. It was its huge size that struck terror into men.
The monstrous size of the creature is mentioned by Lucan (maxima serpens—an enormous snake), by Hyginus (draco ingens—a huge dragon) and many others. Ovid also refers to pestifero ventre, which may imply an ill-smelling or noxious interior, although pestifer more generally means 'that bringing destruction'.

There are later versions. Hera sends the dragon against the pregnant Leto (wife of Ge, the god of the Earth) in order to kill her children. When the twins are nevertheless born, Python attacks them but is killed by the infant Apollo. Plate 24 shows one such representation, found in Neapolis-Samaria in Palestine, in which Leto holds the infants Apollo and Artemis in her arms while Python, in the form of a snake, attacks. There are other minor stories in which Apollo fights and overcomes enemies. He had to overcome a giant, Tityos, a brigand Phorbas, and Phlegyas, and the Phlegyans. Apollo destroyed the latter with many thunderbolts and mighty earthquakes, finishing the job by sending plague on the survivors. Fontenrose has carried out a rigorous study of these and other Delphic myths and has shown that they ultimately derive from a common source, the snake-like nature of the creature Python and its huge size being common to many of the tales. There can be no doubt that Python, as a winged serpent, is a larger-than-life, terrifying character. But as a dragoness or Queen of Heaven in the earliest version he was, we have seen, also nurse or foster mother to another fearful creature, Typhon. Typhon appears again in Greek mythology as a principal character in the other combat theme, Zeus vs Typhon (Plate 25), in which he displays some revealing characteristics. To what extent we deal with the same story or a separate one may be rather difficult to tell but versions of this combat are given, inter alia, by Hesiod and Apollodorus.

Hesiod's version is given in his Theogony, written around 800 BC, and was referred to in the previous chapter. Typhon was the youngest son of Ge and Tartarus. He was a huge monster, whose head reached the stars; in place of fingers he had a hundred serpents' heads, while from the waist down he was nothing but vipers; and fire flashed from his eyes. When he threatened Olympus, the home of the gods, hurling flaming stones and belching fire from his mouth, the gods fled to Egypt disguised as animals. Zeus alone remained, first throwing thunderbolts from heaven, and then coming to Earth to strike the creature. The Apollodorus version is more complex and involves the near-defeat of Zeus, but the end result in any case is the destruction of Typhon, who fell aflame in mountain glens and was hurled down to Tartaros, under Etna. The burying of Typhon under Etna might be
seen as indicating that Typhon is an underworld creature, a personification of vulcanism. However it is much more likely that the Etna connection is no more than a local addition to a much older myth occurring over much of the Old World, from Greece at least as far east as India (and possibly further), south to Egypt, and possibly north to Scandinavia. In the version given by Pindar, Typhon’s body is buried under a mountain in Boeotia, from which there were exhalations of fire. There are no volcanoes in Boeotia. There is, however, a mountain there which in classical times was known as Typhaonion. Boeotia was the country of the Phlegyans, whom Apollo fought.

One could, at this stage of discussion, take a ‘fairy tale’ view of these myths. However, as we have seen, there are significant hints of a cosmic connection. Typhon after all, spans the sky, hurls rocks, spouts fire and smoke, makes a terrible hissing and roaring, and after defeat crashes in flames into mountain glens. The whole thing is reminiscent of a large meteorite fall. Even more suggestive is the serpentine nature of the dragons. For the trail of dust left by an impacting fireball, after it has become windblown, takes on just such an appearance (Plate 13) and is often so described, especially in the mediaeval literature. Dall’Olmo has investigated Latin terminology relating to astronomical phenomena (see also Chapter 8), and finds that terms like *serpens* and *draco* are frequently used to describe meteor falls. He remarks that ‘the smoky remnants of a big sporadic
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meteor may take the twisted shape of a snake or of a dragon, due to the currents in the upper atmosphere. (In 1956 I observed such an event which lasted about half an hour. The meteor crossed the whole sky and lighted everything as if it were daytime, and even the luminous fragmented particles which fell vertically left behind smoke and some vapour, and the whole figure was in the shape of an immense monster.) Or again, from the monastic chronicles of Helinandus of December AD 999, referred to by dall'Olmo: 'a comet appeared on 13 December at about 3 p.m. splitting the sky as if it were a fiery torch. It fell on the ground after a long trajectory. Its splendour was so great that not only the people working on the fields, but even the people in the houses were struck by its light. While the split in the sky was gradually vanishing, its shape became the figure of the head of a snake with deep-blue feet' (see Plate 23). Krinov quotes from the Lavrent'evka chronicles referring to an event in AD 1091: 'Vsevolod . . . saw a large serpent falling from the sky. All this time the earth was rattling.'

There is etymological evidence also to support an astronomical association for Typhon. This can be seen first by noting that meteoritic iron has been in use from the earliest times and that a celestial connection was recognized. The Sumerian name for iron was an-bar, meaning 'fire from heaven'; the Hittite ku-an meant the same. In Egypt the name was bia-en-pet. According to Rickard, bia probably means thunderbolt, and pet stands for heaven. It has already been mentioned that the Greek word for iron sideros is genetically connected to the Latin sidus. Precisely such a connection can be made for Typhon; it is found in Plutarch’s Isis and Osiris. Plutarch, who once visited Egypt, probably derived the material for his treatises from books and priests, and is an important secondary Egyptological source. On Typhon, he remarks: ‘Moreover, they call the lodestone the bone of Horus, and iron the bone of Typhon, as Manetho records.’ It has been suggested that the word ‘Typhon’ may derive from the Egyptian tephit meaning ‘cave’ or ‘hole in the ground’. At any rate the duality between Typhon as a sky creature and Typhon as an underworld creature has been met already in Hesiod’s Theogony and is characteristic of the dragon in mythology. Incidentally the Hebrew for iron ore, nechoshet, literally means ‘the droppings of the serpent’ Given the above iron/meteorite association, this unmistakably means a cosmic serpent.

But Typhon is also one of the gods. With the arguments already deployed this implies that we should think of him as a comet. These
arguments, connected up, make sense if the fireball was associated with the comet, perhaps, indeed, if the two were not distinguished. This, of course, is likely only if the comet were large and active and perhaps disintegrating. These deductions could be considered tendentious were it not that there did exist a comet called Typhon. Typhon, in Liddell and Scott’s Greek Lexicon, has three meanings: it is the monster we have already met; it is ‘a kind of comet’, and it is a donkey. The best evidence that Typhon was something remarkable in the sky comes from authors such as Pliny. In his Natural History he states: ‘A terrible comet was seen by the people of Ethiopia and Egypt, to which Typhon, the king of that period, gave his name; it had a fiery appearance and was twisted like a coil, and it was very grim to behold: it was not really a star so much as what might be called a ball of fire.’ Lydus, in the astrological treatise De Ostentis, states that:

‘They say that the sixth comet is called ‘Typhon’ after the name of king Typhon, seeing that it was once seen in Egypt and which is said to be not of a fiery but a blood-red colour. Its globe is said to be modest and swollen and it is said that its ‘hair’ appears with a thin light and is said to have been for some time in the north. The Ethiopians and Persians are said to have seen this and to have endured the necessities of all evils and famine.

Elsewhere Lydus, classifying comets, introduces a Typhon type, stating that:

‘This happens as a result of a reverberation of the air: it is sickle-shaped, white, smoky, and sullen. Wherever it looks, there are general evils. Grave foreign and civil wars, public disturbances and lack of necessities. Glorious leaders will be taken away in wars and especially if it appears for three or four days. If it appears for more, it threatens the destruction and overthrow of everything and no end to evils anywhere’.

In summary then, it looks as if the Zeus vs Typhon and Python vs Apollo myths could be describing successive stages in the break-up of a huge comet, Zeus. Of course, one cannot expect a precise historical account and it is possible the myths are basically the same tale. So whether a single episode lies at the root of these myths or whether fragments of Typhon struck the Earth as he battled with Zeus, and a subsequent fragmentation left us with Python challenging Apollo is not easily discerned. Moreover, the meteoritic and cometary elements
are so merged in these stories that they may be for ever inseparable. Nevertheless, we conclude that Typhon was a major participant in a conflict relating to the break-up of a huge comet, and that the name Apollon, adopted for the family of Earth-crossing asteroids, seems now in retrospect to have been a peculiarly happy choice.

9.3 The dragon pair

Enough has perhaps been said to indicate that, at least as a working hypothesis, the dragon of the combat myths can be seen as a description of a comet which, in a near-Earth orbit, produced impacts or fireballs. The literal interpretation of the dragons as comets seems to have been made at least once before, in mediaeval times. Bellamy quotes the Italian astronomer Donolo (AD 940), drawing on mythological sources now lost, as saying: 'when God created the two lights, the five stars, and the twelve signs, he also created the fiery dragon, that it might connect them all together, moving about like a weaver with his shuttle.' Certainly this view of the combat stories fits well with modern belief that myth is rooted in reality, that the early stories were descriptions of real things. But it also accounts for the fact that the stories were world-wide and endured for centuries. Fontenrose, for example, states that 'If it is true that a particular myth pattern was diffused over a great part of the Old World, from Greece to India and south to Egypt, if not farther, and manifested in many national variants, then it must have had an unusual significance to the peoples who told it and adopted it.' He contends: 'No doubt the combat theme was suggested by actual struggles that men, as herdsmen or as hunters, had with ferocious beasts and dreadful reptiles and sea creatures.' Perhaps; but this 'local' theory does not explain why there is a common pattern of myth rather than an uncountable number of disconnected themes, nor does it explain their persistence nor their unusual significance. Fauconnet's comments on 'a confused account of great events on a planetary scale' are apposite here. Given the celestial framework of these tales and the astronomical scenarios we have developed, catastrophic events induced by the god in the sky are surely a more plausible explanation.

With the insights we have gained into the nature of the dragons, we can now look again at the Delphic combat stories. It will be sufficient to summarize those conclusions reached by Fontenrose which may have astronomical connotations:
The champion fought not a single enemy, as we assumed at the outset but two great enemies, male and female, of whom the latter was even more terrible.

Later in the Homeric Hymn, for example, Apollo settles an account with a deceitful spring nymph Telphusa by burying her spring under a shower of stones. Tracing the connection of Telphusa with other myths, Fontenrose is able to conclude that she is herself a representation of the dragoness of the Hymn, part snake or horse, and that the Hymn is a fusion of two local myths of Apollo’s encounter with a dragon pair.

Dragon pairs occur explicitly in many other combat stories. In Babylonian mythology Marduk has to overcome first Apsu and then Tiamat; in Indian mythology, Indra has to fight Vritra and then Danu; in Germanic mythology, Beowulf is in conflict with Grendel and his mother. Frequently the monsters are of vast size, fiery and snake-like. Further they are often related, mother and son or child and nurse. In Mordecai’s dream (additions to the Book of Esther, 6:3 and 5): ‘There was noise and turmoil, thunder, earthquake, and terror on Earth. And, lo, two great dragons appeared, either ready to give battle, and they made a great noise. . . . It was a day of darkness and of gloom, of trouble, oppression, distress, and terror on Earth.’

A detailed study suggests the duality has its origins in the fragmentation of a primary body which produces a meteor stream and a huge comet, the latter circulating around the former. These elements are treated as male and female respectively. But in due course, the great comet breaks up further: one of its components, Marduk of Babylonian mythology or Zeus of Greek mythology, engages in battle with its principal progenitors and emerges the dominant figure. However, in the earliest versions, the conflict is not simply between a god (Zeus or an analogue) and a dragon pair. The theme is actually one of celestial war, in which the monsters were accompanied by hosts of lesser demons. Tiamat, the chaos demoness found in the Babylonian creation epic Enuma Elish, heads an alliance of the rebellious gods and a fearful assortment of snakes, vipers, scorpion men, storm demons and so on. This is a not unexpected consequence of the astronomical model. The fireball seasonality of the near-defunct Encke has been remarked on (Figure 19). A large, active cometary fragment would very likely be accompanied by swarms of minor icy boulders which, on passing by the Earth, would create intense fireball storms—or demons.
The combat myth is a myth of beginnings, a tale of conflict between order and disorder, chaos and cosmos. It is also a myth of the recurring attacks of the forces of chaos upon the forces of order.

This view of recurring attacks on the forces of order fits well with the idea of a periodicity of passage of a comet. That is, we see the comet as a short-period one in an Apollo-type orbit, as indeed we would expect. Coupled with the duality of the dragons, a literal interpretation of the combat myth is that a large comet in an Earth-crossing orbit fragmented and that the two fragments were recurrently responsible for catastrophes on Earth below. Although one might suppose fairly frequent and regular interaction as the Earth passed through the debris stream, a close encounter with the comet heads would have been much less likely. Presumably the latter would have been linked only with the major catastrophes out of which a new world was to emerge. Overall, the picture is of a peaceful period—the Golden Age—which succumbed to chaos. But in due course, order was imposed on this chaos the Silver Age with Zeus recognized as the one in control.

The gigantomachies and theomachies of Greek and oriental mythologies belong to the combat myth.

Mother Earth (Gaea) and Father Heaven (Uranus) were monsters, 'somewhat like men and yet unhuman' to quote the mythologist Edith Hamilton. They produced three huge strange beasts each with a hundred hands and fifty heads, three Cyclopes, each with an eye as big as a wheel, and a dozen Titans (Hamilton makes the interesting comment: 'But it is extremely odd that they [the offspring] were also the children of Heaven. However, that is what the Greeks said...'). Zeus, son of one of the Titans, rebelled against his father Cronus: the battle was in fact between Zeus and his five brothers and sisters on the one hand, and Cronus and the Titans on the other. Zeus won, with the help of the hundred-handed monsters, but his victory was not yet complete. Earth gave birth to her last and most frightful offspring, Typhon. But by now Zeus had possession of thunderbolts, forged for him by the Cyclopes, and we have seen the results of this new weaponry. (The forging itself indicates that iron thunderbolts are referred to by the poet and is further evidence that the conflict between the gods is a description of some astronomical cataclysm.) This theme is broadly consistent with the picture of comet Typhon as a late remnant of the sort of progressive disintegration of a great comet.
26. Marduk attacking his mother Tiamat, with thunderbolts and sickle. According to the Babylonian creation epic, Apsu was the universal god representing order and goodness, Tiamat was a dragon-god representing chaos. Their union gave rise to the first gods of the universe but Apsu found them disrespectful and ordered Tiamat to get rid of them; anticipating the plan, the gods overpowered and murdered Apsu. Tiamat, determined to avenge her husband's death, now gave birth to a brood of monsters: giant serpents, roaring dragons, lion-demons and the like. They challenge the gods to battle, but instead, Marduk comes to face Tiamat in single combat. After an epic struggle, Tiamat is slain and Marduk becomes supreme lord of the universe. He raises dry land above water, puts the other gods in their place and appoints the Moon keeper of time.

In a near Earth-crossing orbit that we consider has probably occurred.

Our brief examination of the Delphic dragon stories is leading towards a surprisingly specific astronomical model. An exceptionally large and active comet entered an Apollo orbit. At some stage orbital precession took the comet into an orbit which involved a series of relatively close passages to the Earth. The comet split, and there was perhaps a hierarchy of subsequent disintegration. As the fragments moved along their respective orbits, and merged, it may be they appeared to be in conflict, one with another. Passing through the neighbourhood of the debris, there were intervals of incredibly
intense meteoric and fireball bombardment. In places these episodes included impacts near ground level, and a few of these might have been Tunguska-like or greater. The span of time need not have been long but the events must have been profoundly impressive, sufficient to trigger the ubiquitous and enduring myths. As time passed the comets decayed and faded from memory. The sky gods became abstractions and the significance of their celestial adventures became lost. That there is good evidence in the twentieth-century sky (Chapter 7) of the past existence of an exceptional body, in the orbit and with the disintegration history required, must be seen as strongly supporting this astronomical interpretation.

9.4 The cosmic serpent: further insights

The hypothesis can be further examined by looking more widely at the properties of the dragons and their combats. The nature of the combat, for example, is often one in which the Sun is obscured. Thus in the Egyptian combat myth between Horus and Seth, Horus loses an eye identified as the Sun. By the fifth century or earlier, the Greeks had identified Horus with Apollo, and Seth with Typhon. Horus, Lord of the Sky, was by this time often associated with and even identified as the Sun. In the Edfu Text (discussed by Fairman) Ra and Horus were sailing in Ra’s boat when they caught sight of Ra’s enemies in the form of crocodiles and hippopotami who opened their mouths to attack the boat. Horus flew up into the sky in the form of a great winged disc and attacked the enemy (the celestial combat theme). Later, the enemy reappeared (the recurrence theme) under the leadership of Seth, and Horus, in Ra’s boat, had to meet them in several places and inflict defeat on them. At one point in the combat Seth took the form of a roaring snake and disappeared into the ground. Around this central combat their respective companions also battled. In one scene Seth’s companions are represented, predictably by now, as snakes.

Seth was identified with several animals and could take the form of any at will. It was in the form of a black pig that he threw a jet of fire on to Horus, making him lose an eye. The conflict in this case, then, would be between the dragon and the Sun, and the dragon is attempting to block the Sun out. The giant snake Vritra of the Hindu pantheon attempts to swallow the Sun, as Chinese dragons do during an eclipse. It will be recalled that the Titans were described by Lucretius as gods which obscured the Sun; and Typhon is described by Plutarch in Isis and Osiris, not only as a comet, but also as a demon of
According to an Egyptian legend, the Sun-god Ra sails daily across the sky from east to west. Ra as periodically threatened by the mighty dragon Apepi who attempted to eclipse it. The defender of Ra was another fearsome monster, the enigmatic god Seth. Eventually, in one devastating encounter, Seth attacked and dismembered Apepi but then himself became the very incarnation of evil. As god of storms, of thunder, of earthquakes and of death, he continued to terrify mankind. The practice of representing gods in human form has of course persisted into modern times.

Eclipses. Normal eclipses are not being described here. In order to dim sunlight appreciably over a large area, one possibility is the interposition of a great, dense comet tail between Sun and Earth. Another is the injection of dust or water into the air by an impact at least in the Tunguska class. Note however that the Sun is not involved in the Zeus/Typhon conflict, and indeed it is debatable whether Apollo represented the Sun as early as the date of the Homeric Hymn. But a blinding light, a fiery serpent crossing the sky, and the sound of hissing and thunder followed by a bang, may be simply described as a god hurling thunderbolts at a serpent, which crashes to its death.

The use of a sickle as a weapon is a very widespread theme in these combat myths. The anthropologist Huxley, in interpreting the conflict between Cronus and his Father, notes that the sickle was a weapon and remarks that 'we can conclude that he [Cronus] is the new moon, for there is no other sickle-shaped body visible in the sky to make this legend comprehensible'. But either the windswept head or outflung tail of a comet may be sickle-shaped, Lydus, as men-
tioned already, describes comets of Typhon type as 'sickle-shaped, white, smoky, and sullen'.

More generally the numerous forms taken by the gods (or even their changing form, their occasional absence of form, or their multiple-headedness) are suggestive of comet shapes much more often than one would expect by chance. This can be seen, for example, in the alliance of snakes, vipers and scorpion men of the Babylonian Enuma Elish. The reference to snakes is understandable in the light of the above discussion. 'Scorpion men' may refer to the tail of a small fragment before entry into the atmosphere, which would appear as a faint comet. In one of the few descriptions of a comet per se found in Babylonian records, one dated 1140 BC reads ‘... a comet arose whose body was bright like the day, while from its luminous body a tail extended, like the sting of a scorpion’. We have seen that animal forms were recognized in comets in classical times, amongst them the horse and the goat. According to Fontenrose, 'Seth as donkey recalls the horse-shaped demons of night, sleep and death.' We recall that donkey was the third meaning assigned to Typhon: and our word 'nightmare' is no doubt a faint echo of these same horse-shaped demons of night. Amongst the numerous donkeys, scarabs, scorpions, lions, hippopotami and so on which appear on the heads...
of Egyptian divinities, there is a strange dragonish beast representative of Seth which cannot be identified and is often called the 'Typhonian animal'.

Comet morphology can be seen rather more clearly amongst the dragons of the East. Unlike Western dragons, these are generally more benevolent creatures. The Chinese dragon holds a pearl under its chin, and there has been much discussion of the meaning of this gem. It has been seen as a symbol of thunder, of the Sun, of the Moon and even of an egg, as well as other stranger objects. It may be red, gold or bluish-white. It is often associated with lightning-like symbols. Nearly always it has a tail-like appendage. The colours are those of great comets. For example Tycho, describing the great comet of 1577, states that this was 'a comet with a very long tail and a head of white light not like that of a fixed star but somewhat darkish, much like Saturn. The tail was very long, somewhat bent in the middle, of a burning dark red colour, like a flame penetrating through smoke.' Whatever his form, the Egyptian Seth was nearly always depicted as red. Close to the head of a comet the colour is bluish white: and the golden colour of some comets is illustrated for example in Gill's description of the comet of 1882 (Chapter 2). The lightning-like symbols and tail-like extension are almost self-explanatory, and the fact that Chinese dragons are afraid of iron might possibly be connected with the fact that Typhon was destroyed by the iron thunderbolts of Zeus.

A striking and universal property of the dragons of mythology is their connection with both underworld and water. With the cosmologies extant in the distant past, such associations seem also to be astronomically inspired. Again and again, the marauders would have been seen plunging 'into the sea' on their way to the underworld. What happened there would have been a rich field for speculation. It has been mentioned that Seth as a roaring snake disappeared into the ground during his conflict with Horus. Likewise Strabo's Typhon ploughed the channel of the river Orontes with his coils as he desperately sought to escape underground from the thunderbolts of Zeus; indeed the Syrian Typhon became the source of the Orontes. This duality of sky and underworld is ubiquitous in mythology and dates back to the earliest times. It can be seen clearly, for example, in the great Hurrite myth Royalty in the Skies. The fragmentary texts of which seem to date from about 1300 BC. In this myth there were the ancient gods who were dethroned from the sky once the younger gods had appeared, and were cast into the underworld. Thus, although
again it should be emphasized that we are dealing with compatibility rather than proof, the astronomical hypothesis seems to provide a surprisingly clear framework for the interpretation of many aspects of myth.

Because the dragon holds back the water lying beyond the celestial sphere again a water connection it has to be propitiated lest it sends, not rain, but a flood; even the friendly Chinese dragon has this quality. One is thus irresistibly drawn from the general to the specific, that is from a flood to the Flood. Flood myths are found world-wide, and in many of them can be detected evidence of a cosmic connection. We shall illustrate this by studying the Phaethon myth.

9.5 The Phaethon myth

The story of Phaethon, son of Helios, who fell from the sky, does not appear in the earliest records of Greek mythology. It was discussed by Hesiod but only fragments of his work have been found. Two extensive and incompatible fragments of the story are found in the Fabulae of Hyginus of the second century AD, but Euripides' Phaethon is better preserved and has recently been studied by Diggle. There are accounts in the poems of Ovid and, 450 years later, Nonnos (fourth century AD).

What happened to Phaethon took place in the domain of the stars; his name means 'the shining one', and he was the son of the Sun-god Helios. He was therefore one of the gods. There are other Greek cults and myths containing figures called Phaethon and also belonging to the stars. Hence the Phaethon story is about a divine being who belonged to the stars and whose adventures, as we shall see, affected the Earth. This event was incorporated into the already existing world of Greek myth. That Phaethon's fall may describe some exceptional event was recognized by Goethe in 1821 and Kugler in 1927. The meteorite hypothesis proposed by these investigators has been revived and extended recently by the meteorite expert Engelhardt and we follow his interpretation closely. He uses the 'invariant component' view already expressed here to discard the poetic additions and get at the core. He takes the features common to Ovid and Nonnos. This basic core is described below.

The story begins with Phaethon climbing into the Sun-chariot belonging to his father and starting to cross the sky in its daily course. At first the Sun rises as usual, but soon Phaethon loses control of the four horses drawing the chariot. According to Ovid this is because the horses sense the lesser weight of the charioteer, the
chariot leaps into the air, the horses abandon their usual track. Phaethon becomes disoriented not knowing where to direct the horses. Then he is seized with horror as he sees, at the highest point of the track, the countries of the Earth lying far below him. He finds himself surrounded by the giant animals of the constellations, particularly the scorpion with its tail and pincers, and he lets go of the reins in senseless fear. In Nonnos' version the journey starts well, and Phaethon is seized not by fear but by arrogance. Under the goad of their cruel driver the horses run out over the limits of their usual course. So far off is the Sun-chariot driven that it approaches the Earth closely, causing fires to break out, and then climbs high again. The greatest disorder reigns in the heavens and on Earth, the axis of the celestial sphere being tilted in the process.

Ovid goes into detail over the fires and drought of Earth:

'Then Phaethon sees the Earth in flames on all sides, and he cannot stand such great heat. He breathes in with his mouth glowing air as from a deep furnace and he feels his chariot begin to glow. Soon he cannot bear the ashes and glowing dust that are thrown out and he is enveloped on all sides in hot smoke. Where he is going or where he is, he does not know, he is covered in pitch-black darkness and is born along on the caprice of the flying horses'.

So far the catastrophes—confusion in heaven and devastating fire and heat on Earth—have been caused by the wandering of Phaethon in the sky. And now he falls to Earth. According to Ovid, Tellus the Earth goddess turns to Zeus to complain, whereupon Zeus destroys Phaethon with a thunderbolt:

'He thunders and sends from his right ear a shaft of lightning on to the charioteer. He thrusts him out of life down from the chariot and tames the raging fire with raging fires. The horses become dismayed and leaping backwards tear their necks out of the yoke, releasing the torn reins. Here the bridle lies, there the axle torn from the shaft and yonder the spokes of the broken wheels. The remains of the ruined chariot are scattered far and wide'.

Zeus' thunderbolt is definitely cosmic here, and the destruction of Phaethon is reminiscent of that of Typhon by the thunderbolts of Zeus. Phaethon fell into the mouth of the river Eridanus. Apollon Rhodios reports that as a consequence the waters of the estuary 'emit strong oppressive fumes from the burnt wound'.

In the *Mirabilia* ascribed to Aristotle there is a description of a lake
Zeus and Typhon

near the river Eridanus 'with warm water that exuded a heavy, unbearable smell that no animal could drink from it. Not even a bird could fly over it as it would otherwise fall down and die. The lake had a circumference of 200 Stadia [37 km]. The inhabitants recounted the legend that Phaethon, when struck by the lightning, had fallen into this lake.' One is reminded of the pestifero ventre of Python.

The locality of the fall has been mentioned as Ethiopia but most sources give the mouth of the Eridanus. Aeschylus places the Eridanus in Spain, but all later authors identify it with the present river Po which flows into the Adriatic. Engelhardt favours the latter but this is speculative. Because the myth was probably mentioned by Hesiod it must at least go back to the eighth century BC, but how much further is again a matter for speculation.

Of the post-fall events, the restoration of order in the sky and the flood which follows are significant. Ovid reports: 'For in pitiable mourning his father hides his covered face and if we believe what is told, a day went by without a sun. Fires bestowed light and thus some good came from this mischief.' Moreover there was a flood, which was brief but devastating according to Lucretius (cf. p. 172): 'The water, as the legend goes, started to rise above every mountain when it had covered many cities of man. When then for some reason the might of the water that had suddenly burst forth had receded, the torrential rain stopped and the rivers diminished their strength.' In Ovid's version Jupiter intends first to destroy man through lightning, but then decides on a deluge, as he fears that all the heavens could catch fire. Nonnus had Zeus bring about a world conflagration through the lightning which is being hurled at the Titans, and the flood known as the Flood of Deucalion follows.

It seems very unlikely that this story is based on nothing. When the 'poetic' component is discarded the core of the myth is essentially the same for all authors, and is a clear description of an impact. Certainly the shifting of the stars in their courses is unlikely to be physical and represents an attempt to explain simply chaos in heaven. But the other physical aspects are real. The Tunguska meteorite appeared brighter than the Sun to eyewitnesses; a larger one would be quite blinding and might be seen by survivors as the Sun-chariot crashing to Earth. The thunderous noise of a meteorite fall over a very wide area has been remarked on.

The features which make the Phaethon impact something extraordinary, however, and quite likely in the super-Tunguska class, are the partial obscuration of the Sun, the ravages of fire, and,
perhaps, the flood which follows Engelhardt gives strong reasons for supposing that these are again references to reality. For dramatic reasons Helios should have vanished and logically the world should have been plunged into Stygian darkness, especially as the Sun-chariot lay wrecked on the ground; but Helios merely had a veil drawn over his face, and had a dirty appearance (Ovid). A day later the Sun appeared as normal, Jupiter finding that all is as it was before.

The linking of the world conflagration and the deluge has proven particularly vexatious for the classicists because it makes no dramatic sense and they have seen no causal connection between the phenomena. The mythologist Knaack supposed that the linking of the two motifs must have been the invention of a later compiler, and remarked that ‘Mention of the rivers that Zeus unleashed gave the later reviser the idea of the deluge. . . .’ However, quite different sources adhere to this sequence of events, and in fact the association of fire and flood is a very old one. Englehardt comments that:

‘The very fact that several sources report on a link between Phaethon’s destruction and the deucalian flood, or more generally, between catastrophes of fire and water, in spite of difficulty in rational explanation, favours the fact that it is not a matter of later constructions but that here, via mythological hypotheses, a part of stubborn reality comes to light from under a veil. Therefore we shall have to conclude from the sources that the fiery catastrophe that was interpreted as Phaethon’s fall was really followed by a short-lived but extensive inundation which ended the lives of so many men that one could talk of a destruction of mankind’.

The impact, then, is related to the myth of a catastrophic flood, the flood of Deucalion.

9.6 The Flood

Not far below the level of the first royal tombs at Ur, probably constructed around 2500 BC, archaeologists have discovered material evidence for a vast flood. It has been confirmed that there exists throughout the extent of the Tigris-Euphrates valley, a clay deposit several metres thick. Though it is not proven, it has long been suspected that the event giving rise to this feature was the source of local flood myths. The relationship between the Bible flood story and those of Babylonia, Assyria and Sumer is an unsettled question
There seem to have been many very ancient flood myths in the near East region (and indeed world-wide) and the stories were persistent and often apparently independent. It seems probable that one or more real events were being described; indeed the description of the event on the eleventh tablet of the Epic of Gilgamesh appears quite unembellished and straightforward. For example: "When the seventh day dawned the storm from the south subsided, the sea grew calm, the flood was stilled; I looked at the face of the world and there was silence, all mankind was turned to clay. The surface of the sea stretched as flat as a roof-top. . . ."

The prior weather conditions described are characteristic of an unusual atmospheric disturbance. The appearance of black clouds and a roaring noise, sudden darkness in broad daylight, the howling of the southern gale as it drives the water in front of it, all have the making of a vast hurricane. Equally they are not unlike the vivid accounts we have from Lucretius of the violence and turbulence in the sky as thunderbolts strike.

Prior to the flood, the Anunnaki, the judges of the underworld, raised their torches, either lighting the land or setting it ablaze depending on the translator. This has been seen as a description of lightning. But the Anunnaki, the noisy descendants of Anu the god of heaven, were like the Titans once heavenly creatures prior to their banishment underground. Anything bright, making a noise, and passing from Heaven to Earth would fit, and without further information one could not discriminate between lightning and a storm of fireballs. However the biblical account gives some indication that an unusual cosmic phenomenon, prior to the Flood, may have been involved. There is a tantalizingly brief statement (Genesis 6:4) that the Nephilim were on Earth at that time and even afterwards these were seen as semi-divine creatures and correspond to the Titans. The pre-Flood disturbance is also described in Psalms 18:7-15:

‘Then the Earth shook and trembled, the foundations also of the hills moved and were shaken, because he was wroth. There went up a smoke out of his nostrils, and fire out of his mouth devoured coals were kindled by it. . . . And he rode upon a cherub, and did fly: yea, he did fly upon the wings of the wind. He made darkness his secret place; his pavilion round about him were dark waters and thick clouds of the skies. At the brightness that was before him his thick clouds passed, hail stones and coals of fire. . . . Then the channels of
waters were seen, and the foundations of the world were discovered at the rebuke, O Lord, at the blast of the breath of thy nostrils.

Thus although the tangible evidence for the Flood is often presumed to be due to an excessive cyclone in the Persian Gulf, these accounts of the event have cosmic overtones, and it remains a unique stratigraphic feature. This area did undoubtedly suffer a quite exceptionally huge inundation from the ocean, and since flood myths are not peculiar to this part of the world, the possibility of a fairly world-wide phenomenon certainly cannot be ruled out, particularly if a possible cause with world-wide consequences can be identified. As well as the written record and the physical evidence on the ground, there are also certain indications of a deterioration in general climatic conditions around 2500 BC. So, with the benefit of hindsight and modern astronomical knowledge, it seems that we might reasonably propose one or more cometary fragments impinging on the ocean at this epoch. It is possible also that encounter with a very dense meteor stream is a direct and immediate cause of large-scale precipitation: excessive rainfall is frequently mentioned. The very nature of the flood myths, involving as they do the construction of boats and the seeking of raised ground, would if taken literally indicate that there was clear warning of the impending disaster and its nature. Once again there is at least consistency with our conclusion that a mighty comet in an Earth-crossing orbit did indeed break into smaller pieces that filled the sky for centuries after, each leading the life of a decaying comet. One of these fragments, all the while disintegrating, ran perilously close to the Earth, sufficient to preserve our ancestors in a state of constant fear, and near enough to cause at least two large-scale catastrophes, one in the third millennium BC and the other perhaps 1,000 years later (see Chapter 10).

The question of the universality and chronology of the biblical Flood (or floods) is one for the archaeologist and prehistorian rather than the astronomer, and our objectives at this point are limited. These are firstly to recognize that there do exist astronomical mechanisms, eg sea impact, whereby massive floods might be generated, especially in the Near East where almost closed seas do not allow dissipation of wave energy into the open oceans; secondly to show that there are cosmic overtones to the myths which are suggestive of impact; and thirdly to show the Phaethon myth especially provides a link between a large impact, and a great conflagration followed by a great flood.
9.7 The apocalyptic literature of the Bible

To what extent the Bible can be used as a source of history has been a subject of controversy for over a century, and scholarly opinion is still divided, particularly among the literary analysts. At one extreme is the view, taken for example by Noth in his *History of Israel*, that the early Old Testament events are based on tradition and that whatever historical basis these traditions may have cannot be found out from the literary accounts. On the other hand Bright in his *History of Israel* a few years later, concluded that the events of the early Old Testament were an accurate reflection of historical occurrences. It has been suggested that these differences arise from specialization. Literary analysis of biblical narrative has led some to the conclusion that so long has been the span of time between the handing down of oral or written traditions, with presumably a random walk of elimination or insertion *en route*, any historical content can no longer be extracted. Others have been struck by the parallels which have accumulated between extra-biblical and biblical documents. According to Freedman, for example, 'archaeology has tended to support the historical validity of the biblical narrative. The broad chronological outline from the patriarchs to New Testament times correlates with archaeological data. Allowing for occasional anachronisms and other lapses, the biblical writers correctly describe the cultural patterns and mores of the period to which they refer.'

The apocalyptic literature of the Bible stands on its own. It is highly symbolic, every detail having a meaning. Translating the symbols into the reality or the concept is not always a unique procedure, if only because a symbol may have more than one association, and of course the game is a treacherous one to play. Nevertheless this sort of literature is rich in allusions to what we can only see as astronomical events of the sort we have described.

This type of writing became popular in the two centuries before Christ. It represents a rejection of history as the medium in which religious truth found its expression. History was seen by the Jews merely as a vehicle to convey religious ideas. The descent into Egypt, the Exodus, the wanderings in the desert, the conquest and so on were interpreted as interventions of Yahweh in the affairs of the tribes. For example Frost has seen in the conflicts between Yahweh and the enemies of Israel (such as Egypt, subjected to ten plagues) an expression of the idea of combat of Marduk and Tiamat. But when this divine intervention view became hard to believe, as a con-
sequence in part of the Babylonian attack on Israel in the sixth century BC, the apocalyptic movement returned to myth as a vehicle for the expression of religious thought. There was a tendency, as Frost has said, ‘on the one hand to historicize myth and on the other to mythologize history’. So if there are important myths with a real astronomical foundation we might expect to see the astronomy in the apocalyptic literature.

The Revelations of St John the Divine are not therefore another confirmatory tradition providing independent evidence on our theme. By the time they were written, Greek culture pervaded Palestine and any fairly literate person would have known the myths. An important component of Christianity is that it borrowed from existing religions and cults in the Roman Empire to make itself more acceptable. Changing water into wine and virgin birth, for example, are both found in Mithraism: it was in Zoroastrianism that it was asked ‘Lord, why hast thou forsaken me?’ So, in considering the following extracts from Revelations 8–12, we are not so much appealing to independent evidence as remarking on the clarity of the astronomical associations.

Chapter 8: The seventh seal
The Lamb then broke the seventh seal, and there was silence in heaven for about half an hour.

The prayers of the saints bring the coming of the Great Day nearer.

Next I saw seven trumpets being given to the seven angels who stand in the presence of God. Another angel, who had a golden censer, came and stood at the altar. A large quantity of incense was given to him to offer with the prayers of all the saints on the golden altar that stood in front of the throne; and so from the angel’s hand the smoke of the incense went up in the presence of God and with it the prayers of the saints. Then the angel took the censer and filled it with fire from the altar, which he then threw down on to the earth, immediately there came peals of thunder and flashes of lightning and the earth shook.

The first four trumpets
The seven angels that had the seven trumpets now made ready to sound them. The first blew his trumpet and, with that, hail and fire, mixed up with blood, were dropped on the earth: a third of the earth was burnt up, and a third of all trees, and every blade of grass
was burnt. The second angel blew his trumpet, and it was as though a great mountain, all on fire had been dropped into the sea: a third of the sea turned into blood, a third of all the living things in the sea were killed, and a third of all ships were destroyed. The third angel blew his trumpet, and a huge star fell from the sky, burning like a ball of fire, and it fell on a third of all rivers and springs; this was the star called Wormwood, and a third of all water turned to bitter wormwood, so that many people died from drinking it. The fourth angel blew his trumpet, and a third of the sun and a third of the moon and a third of the stars were blasted, so that the light went out of a third of them and for a third of the day there was no illumination and the same with the night.

In my vision, I heard an eagle, calling aloud as it flew high overhead 'Trouble, trouble, trouble, for all the people on earth at the sound of the other three trumpets which the three angels are going to blow.'

Chapter 9: The fifth trumpet

Then the fifth angel blew his trumpet, and I saw a star that had fallen from heaven on to the earth, and he was given the key to the shaft leading down to the Abyss. When he unlocked the shaft of the Abyss, smoke poured up out of the Abyss like the smoke from a huge furnace so that the sun and the sky were darkened by it. And out of the smoke dropped locusts which were given the powers that scorpions have on the earth: they were forbidden to harm any fields or trees and told only to attack any men who were without God's seal on their foreheads. They were not to kill them, but to give them pain for five months, and the pain was to be the pain of a scorpion's sting. When this happens, men will long for death and not find it anywhere; they will want to die and death will evade them.

To look at, these locusts were like horses armoured for battle; they had things that looked like gold crowns on their heads, and faces that seemed human, and hair like women's hair, and teeth like lions' teeth. They had body-armour like iron breastplates, and the noise of their wings sounded like a great charge of horses and chariots into battle. Their tails were like scorpions', with stings and it was with them that they were able to injure people for five months. As their leader they had their emperor, the angel of the Abyss, whose name in Hebrew is Abaddon, or Apollyon in Greek.

That was the first of the troubles; there are still two more to come.
The sixth trumpet

The sixth angel blew his trumpet, and I heard a voice come out of the four horns of the golden altar in front of God. It spoke to the sixth angel with the trumpet, and said, 'Release the four angels that are chained up at the great river Euphrates.' These four angels had been put there ready for this hour of this day of this month of this year, and now they were released to destroy a third of the human race. I learnt how many there were in their army: twice ten thousand times ten thousand mounted men. In my vision I saw the horses, and the riders with their breastplates of flame colour, hyacinth-blue and sulphur-yellow, the horses had lions' heads, and fire, smoke and sulphur were coming out of their mouths. It was by these three plagues, the fire, the smoke and the sulphur coming out of their mouths, that the one third of the human race was killed. All the horses' power was in their mouths and their tails were like snakes, and had heads that were able to wound.

Chapter 11: The seventh trumpet

Then the seventh angel blew his trumpet, and voices could be heard shouting in heaven, calling 'The kingdom of the world has become the kingdom of our Lord and his Christ, and he will reign for ever and ever.' The twenty-four elders, enthroned in the presence of God, prostrated themselves and touched the ground with their foreheads worshipping God with these words, 'We give thanks to you, Almighty Lord God, He-Is-and-He-Was, for using your great power and beginning your reign. The nations were seething with rage and now the time has come for your own anger, and for the dead to be judged, and for your servants the prophets, for the saints and for all who worship you, small or great, to be rewarded. The time has come to destroy those who are destroying the earth.'

Then the sanctuary of God in heaven opened, and the ark of the covenant could be seen inside it. Then came flashes of lightning, peals of thunder and an earthquake, and violent hail.

Chapter 12: The vision of the woman and the dragon

Now a great sign appeared in heaven: a woman, adorned with the sun, standing on the moon, and with the twelve stars on her head for a crown. She was pregnant, and in labour, crying aloud in the pangs of childbirth. Then a second sign appeared in the sky, a huge red dragon which had seven heads and ten horns, and each of the
seven heads crowned with a coronet. Its tail dragged a third of the stars from the sky and dropped them to the earth, and the dragon stopped in front of the woman as she was having the child, so that he could eat it as soon as it was born from its mother. The woman brought a male child into the world, the son who was to rule all the nations with an iron sceptre, and the child was taken straight up to God and to his throne, while the woman escaped into the desert, where God had made a place of safety ready, for her to be looked after in the twelve hundred and sixty days.

And now war broke out in heaven when Michael with his angels attacked the dragon. The dragon fought back with his angels, but they were defeated and driven out of heaven. The great dragon, the primeval serpent, known as the devil or Satan, who had deceived all the world, was hurled down to the earth and his angels were hurled down with him.

Of course, so far as the author of Revelations was concerned the symbolism was incidental to the theme. The woman is reputedly an image of Israel as the mother of the Messiah, and the dragon represents Satan. But the point to be made here is that the symbolism is that of our astronomical scenario. The relevant items are:

1. Hail and fire dropped to Earth, burning up trees and grass;
2. A burning mountain thrown into the sea;
3. A huge star falling from the sky, burning like a ball of fire and poisoning water;
4. The darkening of sun, moon and stars;
5. A star fallen from heaven opening the abyss, from which smoke pours sufficient to darken sun and sky;
6. Stinging locusts emerging from the abyss, like horses with scorpions’ or snakes’ tails, and with fire, smoke and sulphur issuing from their mouths;
7. A huge red multiple-headed dragon in the sky (the heads with comae), its tail dragging stars from the sky and dropping them to Earth;
8. A cosmic battle between Michael and Satan, with the latter, ‘The great dragon, the primeval serpent’, hurled down to Earth with his companions.

It is clear that the sources on which the author of Revelations drew were steeped in the myth of the dragon, the war of the angels or gods.
in heaven, and of the terrible consequences on Earth below. But
Revelations takes us considerably further because these terrestrial
consequences are now seen quite explicitly. Items 1 to 6 are impact-
inspired; and it is difficult to see an ordinary meteorite fall described
here, particularly with the crater formation, secondary ejection, and
Phaethon-like darkening of the sky. Items 7 and 8 are not consistent
with an ordinary meteorite nor an ordinary comet: the inspiration
appears to be a comet fireball complex, the comet multiple-headed.
Certainly if the whole passage is pure invention one would have to
congratulate the author on his clairvoyance; but it seems more likely
that there is an underlying reality, and that dragons, gods and angels
really did exist. Thus this text strongly suggests that the coming of the
Great Day is here being described in terms of an earlier great day,
when a huge red dragon—the Hebrew author would not subscribe to
a god—created destruction through impact on the Earth below.

We now begin to appreciate the rationale behind the ancient dread
of comets. Of course in time any calamity worth its salt would come
to be allegedly presaged by the appearance of a comet and this
inevitably complicates the problem of discriminating between fact
and fiction. Some mediaeval historians held that a comet appeared in
the sky at the time of the Deluge, and another at the time of Exodus,
but it is now assumed that these were attempts to give an
astronomical colouring to scriptural events. However if the calamities
being described correspond to an impact or series of impacts, then
not only would the association with a great comet become worthy of
serious consideration, but this would strengthen the historicity of the
event.

A connection has also been made between the events of Exodus
and the Phaethon story. The fifteenth-century Christian pro-
pagandist Orosius in his history of the world from the creation to AD
416, described the plagues sent on Egypt including the burning of the
Earth, and remarked that to explain these events ‘those who do not
believe in the power of God, using rather simple and foolish
arguments, derived the silly story of Phaethon’. Of course Phaethon
cannot simultaneously refer to the Flood and the Exodus, the point
to be made here is simply that what we see as an impact myth has in
the past been associated with the biblical story. In fact there is no
need for us to investigate the authenticity of these mediaeval sources.
As we shall now attempt to show the biblical account of Exodus itself
amounts to a description of an impact associated with a terrible
comet.
The epic events of the Exodus, the journey of God's people through the desert to the Promised Land, is of course a story of fundamental biblical and religious significance. At the centre of these events are the plagues sent on Egypt, the pillar of fire which guided the fleeing people, and the parting of the Red Sea. Once more one is faced with extremely fragmentary information, much of it textual; there may in fact have been more than one exodus from Egypt by more than one route. The biblical account has it that Egypt suffered a series of catastrophes in consequence of which the Israelites were allowed to leave. What we shall try to do here is show that the catastrophes are cosmic in nature, with many close resemblances to an impact event, and that there is a clear description of a great comet in the account. The most straightforward conclusion is then to assume that the astronomical catastrophe took place as described. Whether it caused the Exodus, was contemporaneous with it, or was spuriously associated with it by a later writer, is then a matter of judgement or, preferably, deeper historical analysis.

Ten plagues were visited on Egypt because of the refusal of Pharaoh to 'let the people go'. A variety of religious traditions has been read into these plagues, but, apart from the killing of the firstborn, they can be divided into two groups. One group is obviously a reflection of natural phenomena common in Egypt. The plagues of frogs, locusts and gadflies, and the deadly plague which destroys livestock, are in this category. But a second group of phenomena intersperse the first, phenomena with no obvious local explanation. These are:

Moses and Aaron did as Yahweh commanded. He raised his staff and in the sight of Pharaoh and his court he struck the waters of the river and all the water in the river changed to blood. The fish in the river died, and the river smelt so foul that the Egyptians found it impossible to drink its water. Through the land of Egypt there was blood. [Exodus 7:20–1]

Yahweh said to Moses and Aaron, 'Take handfuls of soot from the kiln, and before the eyes of Pharaoh let Moses throw it into the air. It shall spread like fine dust over the whole land of Egypt and bring out boils that break into sores of man and beast all over the land of Egypt.' So they took soot from the kiln and stood in front of
Pharaoh, and Moses threw it in the air. And on man and beast it brought out boils breaking into sores. [Exodus 9:8–10]

Moses stretched out his staff towards heaven, and Yahweh thundered and rained down hail. Lightning struck the earth. Yahweh rained down hail on the land of Egypt. The hail fell, and lightning flashing in the midst of it, a greater storm of hail then had ever been known in Egypt since it first became a nation. Throughout the land of Egypt the hail struck down everything in the fields, man and beast. It struck all the crops in the fields, and it shattered every tree in the fields. [Exodus 9:23–25]

'The hail fell, and lightning flashing in the midst of it' is an uncertain translation. An alternative is 'hail, and fire in the midst of the hail'. The anomalous nature of the hail is frequently emphasized in other sources. In Rev. 16:20–21 it is stated that 'Every island vanished and the mountains disappeared, and hail, with great hailstones weighing a talent each [about 50 kg], fell from the sky on the people.'

A non-biblical account is given by Philo Judaeus, who was head of the Jewish community in Alexandria in the first century AD. His main sources were Hellenic and Jewish. He describes:

'. . . constant thunderbolts. These last provided a most marvellous spectacle, for they ran through the hail, their natural antagonist, and yet did not melt it nor were quenched by it. . . . they thought that divine wrath had brought about these novel happenings: that the air in a way unknown before had conspired to ruin and destroy the trees and fruits, while at the same time many animals perished, some through excessive cold, others stoned to death, as it were, through the weight of the falling hail, others consumed by fire, while some survived half-burnt and bore the marks of the wounds inflicted by the thunderbolts as a warning to the beholders.'

Philo goes on to describe a violent scorching wind which then appeared, gaining force and intensity throughout the day and the night.

Then Yahweh said to Moses, 'Stretch out your hand towards heaven, and let darkness, darkness so thick that it can be felt, cover the land of Egypt.' So Moses stretched out his hand towards heaven, and for three days there was deep darkness over the whole land of Egypt. [Exodus 10:21–2]

The anomalous phenomena, then, are the foul-smelling and
poisonous water we have encountered in Revelations and the Phaethon story; soot spreading over the whole of Egypt which, like the locusts from the abyss of Revelations, brings out boils and sores; devastating hail and fire; a violent scorching wind; and darkness for three days. These events are by now so obviously cosmogonic that we need not labour the point, but simply refer also to an apparently miraculous event which took place during the subsequent wanderings: ‘They spoke against God and against Moses. . . . At this God sent fiery serpents among the people; their bite brought death to many in Israel’ (Num. 21:5–6). Fiery here translates seraph which is used also for a dragon or a winged serpent; the word ‘seraphim’ is from the same root. Events of this sort are found scattered through the Old Testament.

We have seen that there are occasional scattered extra-biblical references to a comet. One by the seventeenth-century scholar Rockenbach is interesting because he specifically refers to comet Typhon. In his De cometis tractatus novus methodicus (1602) he writes, claiming to use only the most trustworthy and earliest writers:

‘In the year of the world two thousand four hundred and fifty three as many trustworthy authors, on the basis of many conjectures, have determined—a comet appeared which Pliny also mentioned in his second book. It was fiery, of irregular circular form, with a wrapped head; it was in the shape of a globe and was of terrible aspect. It is said that King Typhon ruled at that time in Egypt. . . . Certain [authorities] assert that the comet was seen in Syria, Babylonia, India, in the sign of Capricorn, in the form of a disc, at the time when the children of Israel advanced from Egypt towards the Promised Land, led on their way by the pillar of cloud during the day and by the pillar of fire at night.’

Unfortunately Rockenbach’s sources are lost and the merging of Exodus and Typhon might still be apocryphal: since plagues were associated with the Typhon myths of ancient Greece and plagues were associated with the Exodus, then perhaps somewhere en route the two accounts became merged, perhaps by hypothetical mediaeval monks. The argument fails because, it seems to us, the Exodus account itself contains an accurate description of an outstandingly brilliant comet, presumably Typhon, which we identify as the probable progenitor of Encke.

The coma and gaseous component of the tail of a comet close to the Sun are self-luminous, fluorescing with a bluish-white light.
exceptionally large comet close to the Sun, of the sort met with perhaps once in centuries or millennia, would, as we have seen described, also have a long, deep red tail, broader than the white gaseous tail and extending further from the nucleus. Such a comet would be visible by day, with the nucleus, coma and the brilliant white gaseous tail, or at least that part of it not too far from the nucleus, visible. At night the broader, fainter red tail would be dominant in the sky, the nucleus and inner tail being low or more probably below the horizon.

Now the direction of movement of the people in the traditional account was generally east or south-east, which at the latitude concerned (30° North) is towards the rising Sun to a crude approximation:

‘When Pharaoh had let the people go, God did not let them take the road to the land of the Philistines, although that was the nearest way. God thought that the prospect of fighting would make the people lose heart and turn back to Egypt. Instead, God led the people by the roundabout way of the wilderness to the sea of Reeds.’ [Exodus 13:17-18]

A truly exceptional comet of the sort we are discussing, visible by day, would appear in the pre-dawn sky as a red band of light, its nucleus below the horizon. Should the comet lie anywhere near the ecliptic plane as does Encke, then with the anti-solar streaming of the tail and at the latitude concerned, the tail would appear to rise vertically up; the people would be moving towards the pillar of fire during the night. After sunrise, the white inner tail would dominate and there would be a pillar of cloud:

‘Yahweh went before them, by day in the form of a pillar of cloud to show them the way, and by night in the form of a pillar of fire to give them light. Thus they could continue their march by day and by night. The pillar of cloud never failed to go before the people during the day, nor the pillar of fire during the night.’ [Exodus 13:21-2]

The pillar of fire would be visible only in the second half of the night and the pillar of cloud would be best seen in the early part of the day before the sun rose too high. This situation could not last, however. If the comet were in a direct orbit, then on passing perihelion the tail, still pointing anti-sunwards, would now turn ‘upside down’ as seen by the observer. What had been a morning phenomenon would now
become an evening one. The pillar of fire would be seen soon after dark, but it would now appear in the sky behind the direction of travel:

‘Then the angel of God, who marched at the front of the army of Israel, changed station and moved to their rear. The pillar of cloud changed station from the front to the rear of them and remained there.’ [Exodus 14:18 19]

The account goes on to say: ‘It came between the camp of the Egyptians and the camp of Israel.’ However it is quite common for the inexpert to describe a sporadic meteor as falling behind a house or over a mountain, and the pillar being between the camps might be, if not an embellishment, merely a perspective effect.

We have then a plain description of an exceptional comet in a direct orbit of low inclination and small perihelion distance. As with the apocalyptic account in Revelations, if the passage is pure invention one would again have to congratulate the author on his powers of clairvoyance. Thus a reasonable interpretation of the Exodus account is that it took place much as described and the events seen until now as miraculous simply describe an impact with a fragment from a great comet during a close encounter. The progenitor of comet Encke satisfies all the orbital criteria and so once again we have a quite independent argument to associate that great comet with a terrestrial catastrophe.

It is recorded in Plato’s Timaeus that his uncle Critias told of ‘a story, strange but perfectly true’ which he had learned from Solon. Solon (639–559 BC) was a Greek merchant and student of noble descent, generally respected by his contemporaries, who had spent some years in Egypt on a sort of extended sabbatical, during which time he had visited a number of priestly colleges. He had been told by one of the priests:

‘The Greeks would always be children because they possessed no conceptions based on tradition and none of the knowledge of an old man. The basis for this lay in the many and manifold destructions of generations that had occurred and will continue to occur. The most violent were caused by fire and water, lesser ones in a thousand other ways. The report that Phaethon, the son of Helios, once put horses to his father’s carriage but was unable to keep it on his father’s course, with the result that he set everything
on Earth on fire and, having been struck by lightning himself, perished, is related as if it were a fairytale. What is true is the occurrence of a shifting of the bodies in the sky which move around the Earth and destruction after long intervals of everything on Earth by violent fire.'

This statement is 2,600 years old. As a description of the consequences of a large, active comet entering a precessing Apollo orbit, we can hardly better it now. Whether one sees in this ancient, fourth-hand account an intangible memory of recurrent catastrophe, or mere gossip, is a matter of judgement. Inevitably at some stage of any enquiry of this sort one will be tempted to go beyond the evidence. But it seems that at least we may have resolved the paradox raised at the end of Chapter 7: the expected events have occurred, and are recorded, but in the absence of the astronomical paradigm have gone unrecognized. At least one impact event so devastated an area that it was recorded as loosening the hold of the Egyptian oppressors over their Hebrew vassals, and at least one catastrophic deluge seems to have been caused by such an impact. But the enduring effect was the influence on modes of thought. It is only now, with our recently acquired knowledge of the environment of the Earth, that we can begin to understand, in a very imperfect way and 3,000 years later, the reality behind the gods and their miracles.
10 - 1369 BC

The comet Zeus was observed world-wide during at least the second and third millennia BC. We propose a revision of Egyptian chronology which permits synchronization with Hebrew and uncorrected radiocarbon dates. As a result, the Zeus/Typhon combat and the Exodus are reckoned to have taken place in 1369 BC, with consequent revision of early Middle Eastern history. If these deductions are valid, it is likely that megalithic temple-observatories were set up with Zeus in mind, while the Flood of earlier biblical times was due to an encounter round 2500 BC of the Earth with a swarm of meteors and comets which included Zeus.

10.1 Comet encounters and the framework of prehistory

That there have been catastrophic impacts within historic or prehistoric times is, we have seen, not only expected from the astronomy but also seems to be borne out by our analysis of ancient texts. Disasters such as the one described in Exodus have not been taken at face value, however, and this must in the main be due to later interpreters. With no comparable events in their own times to guide them, these later interpreters have tended to play down their significance and even write them off altogether as eschatological embellishment. It has been natural to see the miraculous destruction of Sodom and Gomorrah and the surrounding plain, for example, by the raining down of fire from heaven, as fiction. Maybe—but as Kulik first pointed out, had the Tunguska object fallen four hours later it would have destroyed St Petersburg (Leningrad). We believe therefore, it is not now reasonable to assume, without further study, that a biblical story of this kind has no foundation, especially as it tells of forewarning of the disasters given to Lot by two angels—the dragon pair.

Indeed it must be counted a scholarly error of extraordinary dimensions that the past history of short-period comets should have been so disguised in the form of mythology that their awesome consequences have been overlooked and have so far found no place at all in conventional prehistory. Standard interpretations of archaeological facts for example take no account at all of comets striking or threatening the Earth. It is of course possible that the omission is simply rectified without damage to our present understanding of the
course of prehistory. On the other hand, it is also possible that previous interpreters have, in their ignorance, so missed the significance of certain facts that the very framework of our present knowledge is seriously undermined.

It would of course be natural for historians to resist any demands by astronomers that they now re-examine the fundamentals of their subject. After all, a great deal of time and effort has been invested in arriving at our current picture and one would have to be very sure of one's ground if there were a need to go back and unscramble the analysis. Any extended resistance would in our view have to be counted as unreasonable however. The effects of cometary impacts like Tunguska, especially over an inhabited area, indicate that most of our earliest knowledge of an impact event would, by its very nature, reach us only by word of mouth through survivors whom it is unfair to credit with anything like our present understanding of astronomy. So, in the presence of words that might seem obscure or ambiguous, it is inevitable that the historian's picture will have been tinged by the later preconceptions. It seems to us therefore that a new study of the past is now mandatory. In such a study, the actual occasion of any great impact would have to be regarded as one of the most crucial issues.

As we saw in the previous chapter, there are grounds for associating the Typhon event with the Exodus from Egypt. This tells us some time before the first millennium BC is probably involved, well over 3,000 years ago. Unfortunately, this comes in a period of rather uncertain chronology. A decade or two back, many archaeologists might not have readily conceded this fact but the appearance on the scene of new techniques like carbon dating and dendrochronology has greatly upset the more conventional dating methods and the subject is now in a state of considerable flux. Even the documentary evidence is not beyond reappraisal. Admittedly the long-standing chronology of ancient Egypt, derived from what appear to be incontrovertible astronomical facts, is currently taken to be in broad agreement with the ages of artefacts derived by radiocarbon dating and corrected by tree ring counts using the bristlecone pine from California (see Section 10.4); and this does seem to provide modern investigators with some sense of security. However as we shall presently indicate derived radiocarbon dates may be subject to errors due to the very event or events we are seeking to analyse. Thus, a cometary impact could seriously disturb the stratospheric radiocarbon content and there might also be important low-level variations. The discrepancies
between radiocarbon and tree ring ages seem to be at their greatest in the second and third millennia BC, with signs of less discord as we advance or go further back in time. The facts therefore require us to be cautious. Chronology is of course fundamental to the whole science of archaeology and is frequently and intensively examined by experts. If we are to undertake any re-examination here in securing a date for the Typhon Exodus catastrophe, there is little that we can do but scratch the surface of what is an intricate and complex subject.

10.2 Egyptian chronology

In ideal circumstances, it should be possible to set up independent systems of dates for each of the nations of the ancient world using internal evidence alone. That the arguments deployed are in the end fundamentally sound can then in principle be confirmed by a study of contemporary artefacts traded between the nations and events like battles in which two or more peoples participated. Unfortunately, the internal evidence is often not good enough to establish independent chronologies of sufficiently tolerable quality. As a result, there is still a tendency in practice for much of the approved dating of the prehistoric world, especially prior to the first millennium BC, to be correlated with and ultimately derived from just one single internal scale, namely that of the Egyptian civilization. It is natural that this should be so since it is of the Egyptian civilization that we have the longest, the most continuous and the best-preserved remains. But if one has any reservations about this scale on grounds of principle, an examination of its actual basis can only add to them. Quite simply, the confidence with which conventional Egyptian chronology is upheld by modern experts seems out of all proportion to the certainty with which it has been established. If we are to obtain a good date for the Typhon event, the fundamental timescale itself will certainly bear further scrutiny.

At first sight, this conclusion might appear pretentious. After all, most of the great museums of the world base their collections on Egyptian chronology. Also, around 1950, the distinguished American Egyptologist, Parker, conducted a quite searching and apparently reassuring analysis of the ancient calendar and chronology. He placed what appears to be a seal of approval on what had been the already established opinion, namely that the ancient Egyptians maintained the so-called Sothic calendar. This, it is supposed, survived without break throughout the three millennia
before the present era. Subsequently, neither Neugebauer nor van der Waerden, both notable experts on the subject, have dissented from this view. So the Sothic calendar stands today virtually unchallenged, and with all the authority that its successful use for nearly eighty years can provide. Certainly we cannot escape the evidence that the Egyptians used an official year of exactly 365 days nor that they also observed the inevitable wandering of a 'solar' year of $365\frac{1}{4}$ days initiated by the heliacal rising of Sirius (= Sothis) and relative to which they fixed their seasonal festivals. Cumbersome though such a procedure might appear from a modern viewpoint, it would in practice have been very simple to use and there is no doubt at all that the heliacal rising of Sirius was of immense significance to the Egyptian civilization. In a land dominated by the requirements of agriculture, it was widely recognized as a convenient marker for the beginning of the annual inundation of the Nile. In the light of all this, one might well wonder whether there is any compelling reason for questioning Egyptian chronology.

As it turns out however, the evidence for a wandering solar year is really convincing for only two periods of Egyptian history. The first is during the Middle Kingdom presumed to be around 2000 BC. The second is the Ptolemaic Period between about 300 BC and AD 100. In the first case, we are aware of several, perhaps a dozen, 'diagonal calendars' in the pharaoh tombs of the time. These quite clearly show the heliacal rising of Sirius advancing one day every four years from near the end of Mechir (sixth month) to near the end of Pharmuti (eighth month) during the 300 years or so of the Middle Kingdom. In the second case, there is a specific reference by Censorinus of the third century AD to the heliacal rising on the first of Thoth (first month) in AD 139. Rather earlier, in 237 BC, there was the famous Canopus Decree, which played a major part in the original translation of hieroglyphics, representing what appeared to be an unsuccessful attempt to stop the wandering year in favour of a leap year system. On the basis of these and one or two additional facts, a continuous wandering year has been inferred.

Given it takes 1,460 years for a 365-day (civil) year to get back in synchronism with a $365\frac{1}{4}$-day (solar) year, it is the retrospective evidence of Censorinus that has served to define the Sothic calendar ever since. Heliacal risings on the first of Thoth are assumed to have taken place previously in 1321 BC and 2781 BC (and so on), and it is on the basis of this scheme that the Middle Kingdom dates, for example, have been placed between 2052 (approximate end of
Mechir) and 1786 BC (approximate end of Pharmutii) in the relevant Sothic cycle. Some measure of the intrinsic difficulties that exist in setting up this scheme may be gathered from the fact that even the choice of cycle for the Middle Kingdom was a subject of considerable controversy at one time. Also, only very few early references to other dates are available for integrating the remaining periods of Egyptian history into the framework. But a unique chronology seems nevertheless to emerge. Three great periods of high civilization are distinguished: the Old Kingdom (2664–2155 BC), the Middle Kingdom (2052–1786 BC), and the New Kingdom (1554–1072 BC). These are followed by the Late Egyptian Period (670–332 BC), when there were many contacts with Phoenicia, Syria, Lydia and Greece, and the Ptolemaic Period (332–30 BC), which began with the conquest under Alexander, for both of which the chronology is reasonably secure.

One of the most curious features of the final scheme is the lack of records supplying calendar dates of any significance in the comparatively more recent period between about 1100 BC and 700 BC. During most of this time, Egypt is supposed to have been in a state of serious decline with relatively few important links with surrounding nations. Such knowledge as we have of this period appears to relate to Ethiopian and Libyan empires rather than the heart of Egypt itself. The paucity of relics of this period in central Egypt as compared to the riches of the New Kingdom beforehand is sufficiently striking to raise very real doubts, at least in the minds of the uncommitted, as to whether an artificial gap in the historical sequence may have somehow been introduced by later insistence on the Sothic cycle. Thus, although archaeologists have come to depend totally on the validity of the cycle, it remains to this day a very disturbing fact that there is no known reference to the Sothic cycle in Egyptian texts. Like it or not, there is no secure basis for supposing the ancient civilization of Egypt attached any significance to the dates of 1321 and 2781 BC. We may continue to ask therefore whether the facts admit of any other interpretation.

An outstanding result of Parker’s investigations was the realization that the Egyptians also maintained a third calendar based on the motion of the Moon. Many primitive communities are known to have begun time-keeping with a lunar calendar and its seems Egypt was no exception. Indeed, Parker was able to demonstrate very impressively how an exact 365-day calendar might have grown quite naturally out of a lunar calendar in which its users regularly introduced
intercalary months so as to try and keep the lunar year in step with a solar year, itself regulated by heliacal risings such as that of Sirius. He showed moreover how the official year of 365 days could have been established this way well before its drift with respect to the solar year (or vice versa) was properly recognized. Thus, seasonal points or heliacal risings of other stars would have fluctuated by whole months relative to dates on a lunar calendar and this could at first have obscured any slow drift. Only after one or two hundred years would the early regulators of the calendar have been obliged to contemplate the disparity between the lunar-based and solar calendars and accede to a possibly unacceptable leap or let the solar year continue to drift. For this to have happened however, an official year, kept in step with the Sun and the seasons, must to begin with have been considered a desirable objective. According to this theory, which has not been improved on, the solar year probably would have been allowed to drift relative to the official one from near the start of the Old Kingdom, presumed to be 2664 BC, some 120 years after the beginning of the relevant Sothic cycle.

The persuasiveness of Parker's theory as a whole loses a little of its force however, when it is appreciated that later Egyptians in post-Middle Kingdom times were still continuing to maintain a lunar calendar. This they quite clearly did during the New Kingdom, and further impressive sophistications of the lunar calendar were introduced as late as 357 BC. On Parker's theory, given a Sothic calendar in which the dates of the seasonal festivals could have been fixed without difficulty, it is by no means obvious why the lunar calendar should have been kept going with such dedication. Parker did not meet this point satisfactorily. He evidently envisaged priest-astronomers who, while all the time maintaining a simple wandering year that required very little astronomical knowledge, also contrived to keep themselves in business through the centuries by perpetuating a special lunar-based system for calculating certain feast days and the like of such complexity and presumed importance that its basic redundancy was never detected. It has to be accepted that the truth of the matter could have been just this, but Parker does appear to have overlooked another possibility, admittedly a less convenient one, but one nevertheless that should be considered since it could explain why the lunar calendar did not become obsolete. That is that the Egyptians did for a period maintain a 365-day civil year observing the inevitable drift of the solar year and even returned to it after a time, but that there was also a period when the schematic 365-day
year was purposely deposed in favour of a more complex lunar calendar intended to be kept in step with the solar year. If this did indeed happen some of the modern basis for calculating Egyptian dates might have to be reconsidered. That is, there is an unsupported assumption of unbroken continuity in the calendar over three millennia, a picture which does not fit well with the continuing utilization of an unnecessary lunar calendar.

Now, although Parker implicitly rejects the hypothesis that the Egyptians did at some time cease to give priority to a schematic 365-day year, there is quite an impressive range of evidence that they did, and several expert chronologists have at various times upheld this view in the past. The very fact even that the late Egyptians divided their 365-day civil year into three seasons of four thirty-day months, plus five epagomenal days of festival is almost proof itself that the calendar was at some comparatively recent time treated as fixed or nearly fixed in relation to an agricultural or solar year. Thus, the three divisions of the civil year did not have arbitrary names but were specifically called periods of flood, sowing and harvest respectively. A possible way, for example, of ensuring that an official year of this kind did not wander too drastically from the solar or agricultural year would have been to introduce leap months. A deviation of two months would probably have been regarded as the maximum permissible if seasonal feast days were not to become intolerably unseasonal. Under these circumstances, we might expect to be aware of isolated royal proclamations or edicts requiring a certain date or festival day to take place some months later at a new time of the year. Surprisingly, there is just such a proclamation, otherwise hardly explained, known to have been issued in the reign of Ramses II. On the first of Phamenoth (seventh month) of his thirtieth year on the throne, Ramses announced that the next lunar year which would otherwise have commenced on the first of Phamenoth would now begin ten months later on the first of Tybi (fifth month). At the same time or very soon after, the Sed festival, the traditional start to the lunar year now on the first of Tybi, was brought forward to the heliacal rising of Sirius then at the first of Thoth (first month) thus introducing an effective leap of four months. Ramses II and his successors are the only kings known to have placed the Sed festival at this time of the year and the fact has proved impossible to explain satisfactorily on the conventional scheme. It remains to be explained why the New Kingdom pharaohs regarded the months of inundation heralded by the heliacal rising of Sirius as more properly associated
THE MONTH-TABLE AT THE RAMSEUM

29. Ramasseum month list, illustration from Lockyer's *Dawn of Astronomy*. The numbering is such that Thoth for example is 1, Tybi 5, Phamenoth 7, Epiphi 11 and so on. The blank rectangle is usually regarded as representing an intercalary month. Note however that Phamenoth begins the sequence from the right-hand side in accord with the lunar calendar initiated by Amenhotep I 200 years before. It seems the lunar calendar may have taken precedence over the Sothic calendar.

with those months whose names (Tybi, Mechir, Phamenoth, Pharmuthi) were originally associated with the season of growth. We shall return to this point later.

The most striking evidence in favour of a relatively fixed official lunar year at some time, that is fixed with respect to a 365\(\frac{1}{4}\)-day year, is the famous calendar written out at the start of the so-called Ebers Papyrus, first translated in 1870 by Brugsch. This begins by referring to a heliacal rising of Sothis on the ninth day of Epiphi (eleventh month) in the reign of Amenhotep I. (It is in fact by this solitary record that his date on the conventional scale of 1545 BC has been established. The calculation based on the assumption of a drifting year is \(4 \times (10 \times 30 + 9)\) years after 2781 BC.) The reference is followed by what has been widely presumed to be a lunar calendar based on Sirius. Thus the heliacal risings of Sirius in this calendar are supposed to regulate the lunar year so as to keep it *fixed* with respect to the seasons. No refutation of this interpretation is available other than a general *ex hypothesi* presumption against it. It is interesting to notice that at this particular time near the very beginning of the New Kingdom, there are many signs of renewed interest in a lunar calendar. Indeed, it is a time of intellectual ferment generally since the old Osiris cult was being gradually supplanted by official religions paying more direct homage to the sun-god. It is also a time immediately following on the restoration of the land to indigenous Egyptian people after a lengthy period of foreign subjugation under the Hyksos invaders. Since the Ebers Papyrus contains references to First Dynasty kings, many centuries previously, when the lunar calendar was originally set up, it is conceivable that Amenhotep I
was seeking to restore such a calendar. On this assumption the heliacal rising of Sirius would then continue to be associated with the eleventh month, and it seems highly significant that subsequent generations were soon to alter the name of the seventh month to p-n’Imnhtp (=Amenhotep) and that of the eleventh to Epiphi. (Very much later, the seventh month came to be called Phamenoth.) Thus, it is Parker’s conclusion that the Ebers Papyrus signifies a date on a Sothic calendar from which was projected forward a new lunar calendar. We agree with this important conclusion but would go further. It also signifies the date when a lunar calendar with Phamenoth as first month assumed priority. The splendid astronomical ceilings of the tomb of Senmut and the Ramasseum both belong to subsequent years and unmistakably display lunar calendars which take precedence over any other. These calendars begin with the month Phamenoth.

Corresponding to the reign of Amenhotep III some 150 years later, there exists the well-known water clock of Karnak. This is essentially a calibrated water jug which is filled to the brim at sunset and whose contents then flow out slowly through an outlet at the bottom of the clock in such a way that the water level indicates the passage of hours through the night. The interesting point about this clock is the sequence of time marks which change for each month in a way that reflects the actual variation of the length of the night throughout the year. This fact is really acceptably interpreted only if the months occurred with general approval at the same fixed time in a solar year. The Karnak clock is therefore good evidence for an officially intended solar year. Parker rejects this hypothesis. Since the implied date of the autumnal equinox is not consistent with Amenhotep III’s Sothic date, he prefers to claim obsolescence in the design at the time of making. This is a weak argument however because it arbitrarily adheres to the very assumption we are seeking to check. In fact, the monthly variations are consistent with a solar-based calendar set up in the reign of Amenhotep I and can be regarded as rather good evidence for what was intended to be a lunar calendar tied to the solar year, through at least the first 150 years of the New Kingdom.

Around this time of course, the inevitable drift of Sirius risings would have again been revealing itself and an official decision would have been necessary whether to let it drift or whether to introduce leap months. There is a strong suspicion that this newly established lunar calendar was run concurrently with a 365-day official year causing the solar year to continue to drift since there is an inscription
on the Elephantine stone associating Thutmose III some eighty years prior to Amenhotep III with a heliacal rising of Sirius on the twenty-eighth day of Epiphi. Not so much later, the Medinet Habu papyrus provides a possible association of Ramses II with a heliacal rising on the first day of Thoth. Nevertheless given the importance attached then to a lunar calendar and the desirability of resisting the drift of the seasons, a logical step around this time, maybe 200 years or more after Amenhotep I, would have been to restore the heliacal rising of Sirius to the start of Epiphi. It apparently did not happen quite like this however. Instead of going back, the calendar date of the heliacal rising was eventually advanced by four months. As we have seen already, it was Ramses II, halfway through his reign, who proclaimed the leap. The latter half of the reign of this king is distinguished for the quite mysterious and previously unexplained association of the heliacal rising of Sirius with the first day of Tybi, the opening month of the middle (formerly the growing) season. Since the heliacal rising of Sirius had strong historical associations with this time of the year during the early Middle Kingdom when Egypt was at its intellectual zenith, it could be that Ramses II took what he considered to be a sensible advantage of the need for an adjustment whilst continuing to preserve a lunar calendar, and chose to associate the heliacal rising with Tybi. It is of interest to note that after the initial announcement in the thirtieth year of Ramses II, there were according to Gardiner continued proclamations of the Sed festival in the month of Tybi at approximately three-year intervals — precisely what one would expect if there were being made renewed attempts to regulate a lunar calendar. Yet again however, the heliacal risings were allowed to drift, purposely or otherwise, and by the time another 150 years had passed and the twentieth dynasty was coming to an end, some of the principal lunar feasts were being celebrated in the following month. This fact has also caused some bafflement amongst experts. Gardiner for example suggested Mesore (twelfth month) became the first month of the year instead of Thoth. But Parker, rejecting this hypothesis, showed that the explanation was more likely to lie in the transfer of feasts from a ‘stationary’ lunar calendar to a shifting solar calendar. Such an interpretation would hardly be defensible had not a lunar calendar recently taken precedence. Parker’s analysis in fact makes it clear that the names of many feast days were transferred early on from a wandering year to a lunar year and then, rather curiously, from a lunar year back to a wandering year. This is very difficult to comprehend on the continuous wandering year hy-
hypothesis, but it is easily accepted if official switches of the basic calendar actually took place in the way we describe.

There is further evidence that the New Kingdom leaders sought to abandon the wandering solar year by instituting a lunar year. As both van der Waerden and Neugebauer have emphasized, the tombs of Seti I and Ramses IV possess elaborate inscriptions involving one particular diagonal calendar of the Middle Kingdom period along with instructions as to its interpretation. According to these critics, it looks very much as if the wandering calendar to which the inscribers refer had fallen into disuse. Again, this fact hardly sits comfortably beside their fundamental assumption that the calendar was in continuous use throughout and beyond the period in question. It favours more the assumption that the official calendar had actually been changed. To sum up therefore, Parker has shown how a new lunar calendar assumed priority and was maintained during the New Kingdom. It was however kept in step with an official 365-day year and inevitably as before there came a time when it was recognizably out of step with the seasons and it was necessary to introduce leap months. The adjustments during the reign of Ramses II are thus of fundamental importance.

As remarked already, calendrical information in the interval between the New Kingdom and the Ptolemaic period is so sparse as to be essentially non-existent. We do know of course that a wandering year was being used in a period following Ramses II and that it was in use during the Ptolemaic period. If we make the usual assumption that the Sothic calendar was continuous in the intervening time and project back from AD 139, a heliacal rising on the first day of Tybi would have occurred either in 834 BC or 2294 BC. The latter date is ridiculously remote and we are forced, however unexpectedly, to the conclusion that the thirtieth year of the reign of Ramses II was in 834 BC that Ramses II came to the throne near 864 BC instead of circa 1260 BC. This takes some 400 years out of the conventional system of dates, but it has the great advantage of explaining why there are no calendrical facts after about 1100 BC; the real date is around 700 BC.

If we continue to accept the broad outline of the succession of kings of the nineteenth, twentieth and twenty-first dynasties ending with rule by the high priests of Amun at Thebes, the revised date of Ramses II implies that this spell of central Egyptian history comes to an end around 550 BC, just before the accredited beginning of the later Persian domination. By this reckoning, the twenty-second, twenty-
third and twenty-fourth dynasties of Libyan kings (950–710 BC) in Lower Egypt and the twenty-fifth and twenty-sixth dynasties of Ethiopian kings (730–520 BC) are partly contemporaneous with the New Kingdom monarchs. It follows that the last great king of the twentieth dynasty, Ramses III, was on the throne at much the same time as the Ethiopian king Piankhy, who is known to have conquered Egypt from the south around 730 BC. That being the case, we can now comprehend some of the unexplained mysteries of the last will and testament of Ramses III. This is handed down to us in the form of the Harris Papyrus and records the great battles with Libyan invaders from the north including the ‘Peoples from the Sea’. These were eventually repelled and Egypt then lived for a while in comparative peace and prosperity. Curiously, however, the papyrus refers to an interregnum prior to Ramses III and his predecessor Set-nakht: ‘The land of Egypt was overthrown from without and every man was thrown out of his right; they had no chief mouth for many years formerly until other times... Other times having come after it, empty years, Arza, a certain Syrian, was with them as chief. He set the whole land tributary before him together; he united his companions and plundered their possessions. They made the gods like men, and no offerings were presented in the temples.’ There is no mistaking the implication that Egypt was a vassal state for a time, and under conventional chronology it has not been possible to identify Arza satisfactorily. Under our revised chronology, Arza is almost certainly Piankhy, and central Egypt is seen more clearly as a declining power caught between two warring giants. From the north was the advancing frontier of the Macedonian empire assisted by the peoples from the sea, and from the south, the forward thrust of the Persian empire across the lands of Arabia and Ethiopia. In the time of Ramses III, there was still sufficient strength and will in the Egyptian nation for it to reassert itself on the frontiers of these empires, but by 500 BC and then again in 300 BC, it had weakened to such an extent that it was prey to permanent domination, first by the Persians, and then by the Ptolemies, descendants of the Macedonians.

Let us now summarize some of the crucial dates in this revised scheme of Egyptian chronology. In Table 8, we list a number of prominent epochs on a conventional Sothic calendar. The corresponding dates on the revised scale are arrived at in the following way. First 834 BC is when the heliacal rising of Sirius takes place on the first of Tybi on a Sothic calendar projected back from AD 139. This wandering year calendar is assumed to have been initiated by a
Table 8. Revised Egyptian chronology

<table>
<thead>
<tr>
<th>Period</th>
<th>Revised date</th>
<th>Conventional date</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRE-DYNASTIC</td>
<td></td>
<td></td>
<td>Primitive lunar calendar</td>
</tr>
<tr>
<td></td>
<td>2313 BC</td>
<td>2781 BC</td>
<td>First Sothic cycle begins</td>
</tr>
<tr>
<td>OLD KINGDOM</td>
<td>2196</td>
<td>2664</td>
<td>First Sothic cycle begins</td>
</tr>
<tr>
<td></td>
<td>1687</td>
<td>2155</td>
<td>Major pyramid building</td>
</tr>
<tr>
<td>MIDDLE KINGDOM</td>
<td>1584</td>
<td>2052</td>
<td>Diagonal calendars in use</td>
</tr>
<tr>
<td></td>
<td>1318</td>
<td>1786</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1086</td>
<td>1554</td>
<td>Amenhotep I: Lunar calendar adopted</td>
</tr>
<tr>
<td>NEW KINGDOM</td>
<td>950</td>
<td></td>
<td>Start of Libyan dynasties (xxii, xxiii, xxiv)</td>
</tr>
<tr>
<td></td>
<td>834</td>
<td>1272</td>
<td>Ramses II 30th year: second Sothic cycle begins</td>
</tr>
<tr>
<td></td>
<td>634</td>
<td>1072</td>
<td>Tanite dynasty</td>
</tr>
<tr>
<td></td>
<td>512</td>
<td>950</td>
<td></td>
</tr>
<tr>
<td>LATE PERIOD</td>
<td>520</td>
<td>520</td>
<td>Persian domination</td>
</tr>
<tr>
<td>PTOLEMAIC PERIOD</td>
<td>332</td>
<td>332</td>
<td></td>
</tr>
</tbody>
</table>

Schematic tabulation of some principal dates in the conventional and revised Egyptian chronologies. The crucial revised dates are 1077 and 834 BC. Apart from the Libyan dynasties and later, the remaining chronologies relative to the conventional and revised New Kingdom dates are essentially the same.

leap following the two-month drift of a lunar calendar set up by Amenhotep I. This is a little arbitrary but is more or less in accord with the timespan of the relevant kings in conventional chronology and corresponds to Ramses II's edict. Amenhotep I's date is thus 243 years earlier, and is 1077 BC. Since this year occurs on the ninth of Epiphi in the previous Sothic calendar, its starting date was approximately 1,236 years earlier, that is 2313 BC. The Old and Middle Kingdom dates may now be interpolated accordingly while the beginning and end of the New Kingdom relative to Amenhotep I's dates are assumed to be the same in the revised and conventional chronologies.
Two independent confirmations of the revised chronology may be mentioned straightaway. The first of these comes from consideration of the pyramids. These objects have long remained inscrutable as to their purpose, but the precise orientation of the sides of the Great Pyramid to the cardinal points clearly indicates something of astronomical significance. In spite of this, it is customary to decry the early Egyptians' knowledge of practical astronomy; certainly scholars have floundered in their attempts to read the intent behind the pyramids, not least those who have staked a claim to understand their astronomical connections. Piazzi Smyth for example discovered a 'pyramid inch' on the basis of erroneous measurements. Nevertheless, there is abundant evidence of accurate astronomical alignment of many temples as well as the pyramids, and it was John Herschel in 1836 who first pointed out that the north-facing entrance of the Descending Passage, which slopes steeply downwards for over 100 metres into the Great Pyramid, was aligned precisely on the then Pole Star, Alpha Draconis, about 2160 BC before it precessed away from this position. This and other arguments led Piazzi Smyth to favour 2170 BC. Such dates agree very closely with that of the Great Pyramid construction on the revised chronology but have no relevance to the date of 2600 BC implied by the standard chronology.

A second confirmation comes from the Greenland ice sheet. Large volcanic eruptions over the past 10,000 years have ejected acid gases into the air, and these have left traces in snow layers. Many historical eruptions have recently been dated from Greenland ice cores, one of them being the Thera eruption in the Aegean Sea which some have associated with the end of the Minoan civilization. The strong signal in the ice corresponding to this event is dated at 1388 + 50 BC. Several layers of volcanic tephra from cores taken from the eastern Mediterranean sea bed have also been examined recently. These can be dated, and for the Minoan ash a date of 1390 BC has been found. These absolute dates differ greatly from the radioactive carbon dates of the Thera event adjusted to the standard scale, the latter being assumed to be in agreement with conventional Egyptian chronology. On this scale, the date is 1720 + 50 BC and there is an implied discrepancy of 330 + 100 years in adjusted carbon dates of this epoch (see Section 10.4) as well as in Egyptian chronology. These independent lines of evidence seem then to lead to the same conclusion: there is a major error in the standard chronology which, by our arguments, makes all Old, Middle and New Kingdom dates before 512 BC too early by 468 years.
10.3 Date of the Typhon catastrophe

With this revision, our attention now focuses upon the end of the Middle Kingdom. Pliny claimed that it was a king of this time, Typhon, who gave his name to the comet which is the subject of our investigations (although we have found no such name in the king lists). It is to this time that the Ipuwer Papyrus, ‘Admonitions of a Sage’, belongs. This was translated in 1901 by Gardiner and like Revelations, it is evidently a kind of warning, based on experience, of future catastrophe; it is in part a chronicle of catastrophic happenings which disrupted and overwhelmed Egypt, the length and breadth of the land. The chronicler describes how many people were once even driven to suicide, and the reader is left in little doubt that something fairly horrific is involved. The account bears many similarities to the description of events in Exodus of which some aspects at least, as we have seen in Chapter 9, are attributable to a cometary impact. The time of its writing seems also to be very close to that paraded in the inscriptions on the tombs of Seti I and Ramses IV. For some reason not previously understood at all, the people of these later times attached enormous importance to a particular year in the past in which the heliacal rising of Sirius took place on the twenty-sixth day of Pharmuti. This corresponds on our revised chronology to the date 1369 BC near the end of the Middle Kingdom. Somehow, judging by the magnificent and elaborate inscriptions on the tombs of these later rulers, their way of life, their religion, and their cosmology were intimately linked with this date. Given the extent to which the pharaohs of Egypt assumed the role of gods on this earth, it is not too much to suppose they saw in this date that supreme occasion, the end of an age, when one of their principal objects of worship chose to exercise its terrible power on the world. By continued reference to the event and, no doubt, to the remnant comet in the sky, rulers would have reminded people of the passing of the previous era and the fragility of their own. The opportunities for exercising control through fear of the gods are not at all difficult to imagine.

The revised chronology now has the considerable merit of fitting more or less perfectly with the known course of events in the neighbouring and powerful nation of Assyria. The Middle Kingdom for example corresponds almost exactly to the period during which the Cassites, a people from the mountainous country in the east, were engaged in extending their empire over Babylon. During this period, the Babylonian dialect of Akkadian became a leading language
throughout the Near East. The Cassite sovereignty eventually ended around 1160 BC and it is significant that the domination of central Egypt by the Hyksos people would under the new chronology have ended about the same time. It is questionable however, whether the Hyksos invaders were completely removed from Egypt at this time. Parenthetically, one might observe Manetho’s statement that the Hyksos ‘and their descendants were masters of Egypt for 511 years.’ If correct, this would now place their final departure exactly at the time Ramses II was expelling enemies, apparently Hittite, from Lower Egypt. The implication is that Hittite and Hyksos may be one and the same and that they remained dominant in Lower Egypt for many years. The Hyksos have been generally identified also as invaders from the East, and the suspicion may be entertained that these fourteenth-century invaders of Assyria and Egypt were of similar origin. Under Cassite rule however, Assyria considerably strengthened and prospered; Egypt on the other hand was rather mercilessly subdued. It is interesting to note that the powerful new dynasty of Assyrian kings started by Assur-Uballit I in 1356 BC came very soon after our date for the Typhon catastrophe. If the devastation caused by such an event was as complete as one might imagine, we might well expect to find some powerful opportunist on its fringe displacing the existing authority and assuming control.

We can hardly do better than refer to van der Waerden to get some idea of the changes that were overtaking Assyria at this time: ‘There must have been a very lively intellectual life in Babylonia and Assyria from about 1350 to 1100 BC. Older traditions were collected and systematized; for example, it was probably at this time that the gigantic astrological series Enuma Anu Enlil was composed. Many epics, prayers and other religious literary works were reshaped or created. Thus, probably in the twelfth century, a highly gifted poet moulded the magnificent Gilgamesh Epic into its final form.’ In many respects, this all seems very fitting for a highly organized people adapting their lives in the wake of a catastrophe on the scale of the Typhon event, possibly even preparing for the next. This period for example also saw the production of many astronomical calculations and the early development of a sophisticated lunar calendar. It is perhaps now possible to understand why the Egyptians in their newly found freedom around 1100 BC should very soon have emulated the brilliant civilization of their neighbours. In particular, we can understand a new weight of informed opinion favouring a lunar calendar instead of the wandering calendar to which the people had
previously been accustomed. We can also understand that this same opinion was oriented towards a Babylonian cosmology in which the sky-gods had assumed almost unlimited power over man. It was the prevalence of such ideas throughout the Near East logically supported by knowledge of what happened in and before 1369 BC that eventually formed the basis of what we now recognize as astrology—the theory that events on Earth are ultimately dictated by events in the heavens. However before astrology deteriorated into a hollow scheme for impossible things like the predictions of births and other affairs, it was notably preoccupied with the calculations of astronomical periodicities. Babylonian astronomers, influenced as they were also by Persian doctrine, were above all concerned with predicting the end of the world and the ultimate judgement by fire. Given what they evidently knew to be the cause of such events, the idea of planetary conjunctions was inevitably a natural and dominant theme. It may have been reasonable until now to see in these ideas the fanciful projections of uneducated minds. But perhaps it would be more sensible to see them as perfectly logical developments from an earlier knowledge of conjunctions with the Earth and periodicities in cometary orbits.

Perhaps we should have a little more sympathy for that lively theorist, whoever he was, who in due course first saw the mighty conjunction of Saturn and Jupiter in Pisces during 1396 BC, three years before the birth of Moses, as the cause of all the trouble; and who then foresaw in 7 BC the occasion of the next conjunction in Pisces, the signal for the arrival on Earth of the son of Zeus. It may be that the coming of a comet was thought to be linked in some way with such conjunctions for there is evidence that the star of Bethlehem may have been a comet. But whatever the facts, the widespread state of anticipation of the peoples of the Near East at this time for the coming again of the Messiah is a measure of the great conviction theories of this kind carried, not unlike that presumably, with which Einstein is upheld today. It is not altogether easy to see how such a theory could have produced such conviction unless the basis of its calculation, an earlier visitation by Zeus, had already impressed itself indelibly upon the popular memory.

At the start of this chapter, we speculated that knowledge of the Typhon event might cause us to revise some of our understanding of prehistory. As we have now seen, there is a well-supported interpretation of Egyptian chronology that places the event in 1369 BC. On this basis, the catastrophe turns out to be an exceedingly
powerful theme in the subsequent lives of the Egyptian and Babylonian peoples. Indeed if there were a cosmic disaster, one might expect the subsequent social structure and events to reflect it in some way, for example by commemoration at a particular calendar date. It is of interest to consider the calendar that Amenhotep I enshrined when Egypt re-established its nationhood following the Hyksos domination. It was one in which the modern months of January, February, March and April corresponded to Tybi, Mechir, Phamenoth and Pharmuti respectively. At this time, Tybi may have assumed importance as the starter of a New Year after the winter solstice—a new birth of Ra. It has been suggested by Parker that the two months linked with Fire, namely Mechir and Phamenoth were so named because of their association with artificial heat. The association certainly derives from the Old Kingdom but it is not clear that it has been correctly interpreted. Ramses II later adjusted the calendar so as to bring the period of annual inundation of the Nile in coincidence with the months of Fire, thereby suggesting some kind of logical association of Flood and Fire nothing to do with winter temperatures. One is tempted perhaps to see these months as commemorating in some way the events pertaining to two great disasters, first the Flood and then the event of 1369 BC. Thus another possibility is that these months long associated with Fire were adjusted by Ramses II to correspond to that period of the year when the Earth was encountering the main meteor stream in the sky resulting from the original fragmentation and which was perhaps still visible. The orbit of such a stream would be bound to drift with time and any feast days related to the Earth’s successful passage through the stream would have needed periodic adjustment. During April in Amenhotep I’s reign, close to the modern timing of Easter, there is the ‘Feast of the Repelling of the Troglodytes’ on the 21st Pharmuti which could well be seen now as a matter of necessity—the annual attempt to assuage the gods and avoid further attacks. A possible objection to this is that the term ‘troglodytes’ (‘cave-dwellers’ literally those who penetrate the ground) was a name applied by ancient writers to various tribes, real or apocryphal, especially in regions from Libya to the Red Sea. However it will be recalled that the sky divinities had underground and thunderbolt associations, and it is conceivable that these facets of the Egyptian Typhon (Set) as a thrower of explosive missiles are here referred to. The next feast day of importance was the first day of Pachons (ninth month) coinciding in Amenhotep I’s reign with May Day. In ancient Egypt, it celebrated the ‘voyage of Horus to Dendera’
but throughout the Old World generally this festival came to symbolize new life, perhaps the aftermath of calamity, and it acquired strong associations with fertility rights and rebirth. If, as we have implied, it was the intention of the Egyptians at the time of Amenhotep I to inaugurate a new fixed calendar it is not unreasonable to suppose the association of the above festivities with the actual date of the last catastrophe may have extended very generally to other nations as they recovered from the holocaust. Indeed, as we have seen, the months of March and July both took new names with Amenhotep I, their significance perhaps being that the meteor stream was then at its furthest and at its point of entry. Certainly dragons have been associated with new year festivals (and still are by the Chinese) and with the May Day festival until very recent times. It is also interesting that a May Day ceremony among the Celts, which lasted well into the eighteenth century, involved the kindling of bonfires on hilltops. These were the Beltane fires (in Gaelic, the 'Beal-tene', that is, 'the fire of Bel'), and the custom was of very great antiquity and certainly pre-Christian. Easter and May Day may thus survive as silent and misunderstood reminders of events which once assumed pre-eminence for many peoples.

10.4 Bronze Age chronology: carbon dating

An alteration of the kind we are making to Egyptian chronology can hardly be made without looking at the consequences elsewhere. Let us begin by considering the immediate environment of the Aegean and eastern Mediterranean area. At present, the links between Egypt and these surrounding countries before the first millennium BC do not depend greatly on known dates of particular events in the separate national histories. Very broad chronologies are built around the presence of contemporary artefacts—pottery and metal work in particular—in the stratified remains of each country. Carbon dating tends to play an essentially secondary role in these particular countries compared with what are considered to be the primary archaeological indicators.

The assumption is that particular skills such as working with bronze or with iron do appear more or less simultaneously over a wide area. This is not to imply simultaneity of discovery and invention but rather a diffusion of particular kinds of practical knowledge that is fairly rapid. It is perhaps a little disturbing that such a basic assumption is not particularly compatible with another often used principle in archaeology, namely that there has been a slow
diffusion of cultures from country to country. The picture in this case would be one of relatively sluggish intercourse between countries where it happens. This latter theory is increasingly challenged these days, however, so the assumption of near contemporary ages related to bronze-working and the like over a wide area is probably a fairly secure basis for establishing relative chronologies in neighbouring countries.

The period of immediate interest is the Bronze Age which is conventionally divided into three main intervals: an early period, circa 2800-2100 BC; a middle period, 2100-1550 BC; and a late period, 1550-1000 BC. The last of these brings us to the era of Saul and David and a reasonably secure Palestinian chronology based on biblical records. It is already well into the Iron Age. These intervals could be regarded now as requiring major adjustment as a result of the error in Egyptian chronology, but in practice we suspect the Bronze Age sequences based on stratified remains and their associated transition dates will remain essentially unaltered. Note, first of all, that the intervals do to a large extent reflect the relative placing of the Old, Middle and New Kingdoms respectively. In essence, current chronology places each of these kingdoms together with their technological and stylistic advances in the first half of the relevant subdivision of the Bronze Age, while the second half is a period of cultural stagnation or decline. The presence of associated artefacts in neighbouring countries towards the end of each subdivision has then been consistent with a presumed slow diffusion of knowledge and skills each time from an Egyptian source. Our revision simply moves the kingdoms in time towards the end of the corresponding period, thereby perhaps contravening the slow diffusion hypothesis but without seriously affecting the Bronze Age subdivisions.

One or two decades back, this contravention would have been regarded as a quite fundamental heresy in archaeological circles, but in recent years there has been a serious reappraisal of the hypothesis that the Europe of this time acquired most of its knowledge and skills by diffusion from the Near Eastern civilizations. Renfrew in particular has emphasized the reasons for looking upon the Aegean community as a 'stand-alone' development, if anything drawing from countries in eastern Europe to the north for its skills rather than from the south. In as much as this theory implicitly lowers the stature of Egyptian civilization, so also do our changes of timescale. As we have seen also, in later years Egypt appears to have been fought over
continuously by two other empires which were eventually its cultural and technological equals. In general terms therefore, our revision of Egyptian chronology need make very little change to the broad subdivisions of the Bronze Age in the immediate surroundings, and also it has the merit of being within the spirit of modern archaeological developments.

As one goes further afield in Europe however, the contemporary archaeological links with the Egyptian and Aegean civilizations become more tenuous, and increasingly the modern methods of radiocarbon dating have a more significant role to play in establishing chronology. Broadly speaking, whatever the uncertainties in calibration, the carbon dates tend to be producing a dramatic new set of relativities in European prehistory that now make it even more difficult to accept the idea that knowledge and skills diffused slowly from the Near East. The evidence for a new picture has been carefully discussed by Renfrew and it is one with which modern archaeologists are now coming to terms. The megalith builders of the Atlantic border, as discussed by MacKie for example, appear to have been motivated by forces that owe little to a pre-existing civilization in the eastern Mediterranean. If the new picture and its implied relativities are correct, our bringing forward of pre-twenty-second dynasty Egyptian civilization by 468 years must now imply also a similar advance in time of European dates based on C-14 measurements. In general terms, this is possible only if one uses uncalibrated radiocarbon dates, that is ones that have not been corrected to the system of the bristlecone pine. Such dates are designated B.C. rather than BC. They essentially imply an erratic but basically uniform atmosphere over the whole of Europe and the Near East through at least the last 10,000 years.

Radioactive carbon, or Carbon 14, is generated in the atmosphere by cosmic rays. A given sample decays with half-life of 5,500 years, and a terrestrial balance is expected between its creation by cosmic rays and its destruction by spontaneous decay. Quickly oxidized to carbon dioxide, it is taken up by plants from the atmosphere and so enters the food chain; on the death of an organism there is no further C-14 ingestion and the proportion of C-14 then declines at a known rate. Measurement of this proportion gives the age of the plant or animal from the moment its food intake stops.

However it is now recognized that the proportion of C-14 in the atmosphere may have fluctuated in the past; and a plant which died at a time of large C-14 abundance would be given a spuriously young
The significance of the bristlecone pine is that these ancient trees can be dated in two ways, by tree ring counts and by C-14 measurements. Any discrepancy is attributed to a global variation in the proportion of C-14 in the atmosphere, perhaps due to past changes in the cosmic ray flux. The tree ring data thus provide a calibration to be applied to other artefacts dated by C-14.

Fig. 20  Carbon 14 dates b.c. of Egyptian artefacts compared to historical date b.c. using the conventional Sothic calendar. The data are taken from Berger (1970). The solid line after 800 b.c corresponds to a period in which the two methods of dating are known to be in systematic agreement despite some relatively small random departures. The extension to earlier epochs which is displaced 480 years in historical date in general accord with the revised chronology seems to provide a satisfactory lower envelope to the artefact points. This is exactly as expected for material such as wood which may be long dead at the time of use, and a calendar which is in error by around 480 years before 800 b.c or so (see text). The dotted line gives the bristlecone pine calibration: so far as the magnitude of its displacement from the pre-800 b.c calibration is concerned, the approximate correspondence with the solid line is fortuitous. The enhancement of high-level radiation is seen as a likely cause of an excess Carbon 14 in bristlecone pine wood before 800 b.c causing the displacement.

The bristlecone pine dates start to deviate from carbon dates prior to 500 b.c or so in the sense that applying the correction makes a carbon date more remote in time. The deviation is around 400 years by 2000 b.c, not so very different from the error we presume in Egyptian chronology. It is clear then that the simplest way of continuing to preserve the relative dates of modern European archaeology whilst correcting the absolute Egyptian scale is to propose an error in the bristlecone pine calibrations. Although this
calibration has still to be checked against others, it has been widely accepted as immune from error. It might therefore in the end be an obstacle to the revision proposed in this chapter. The Californian bristlecone differs in one important respect however from the sites to which its calibration is applied: it grows at relatively high altitudes. It is therefore relatively more exposed to disturbances of the C-14 content of the upper atmosphere.

The dumping of the kinetic energy of a Tunguska-like object into the atmosphere will create a fireball whose temperature may briefly approach a million degrees. While this is quite low compared to that of a nuclear weapon, it is likely that relativistic particles (as well as X-rays and gamma rays) will nevertheless be produced within this plasma by ill-understood particle acceleration processes: Brown and Hughes have examined this for the Tunguska event. Rough calculations based on their work show that for every 50 megatons of energy dumped into the lower atmosphere about 6 tons of C-14 will be created, corresponding to about a 10 per cent increase in the proportion of atmospheric C-14, and yielding a dating error of 50 to 500 years in any organism which died shortly thereafter and which is now about 5,000 years old. The generation of C-14 will be more efficient at higher altitudes since the process tends to be quenched by higher atmospheric densities: the particle acceleration will take place in the plasma sheath surrounding the incoming missile. A few large fireballs, occurring in an epoch of high fireball activity, could raise the atmospheric C-14 content quite appreciably.

It might be considered that so long as tree counts are available for calibration these erratic inputs do not matter. However the atmospheric nuclear weapon tests of the 1950s and 1960s showed that radioactive fallout is patchy rather than diffuse. In the northern hemisphere, most of the C-14 generated by a fireball would reach ground level in the first year. Some regions, with dimensions thousands of kilometres, would receive two or three times the average C-14 fallout; smaller 'hotspots' with dimensions of tens to hundreds of kilometres would be subject to fallout up to twenty or thirty times the average. This patchy distribution is consequent on C-14 creation in the lower stratosphere or upper troposphere. Thus in an era of high bombardment an organism dying in one part of the globe might have a quite different C-14 age from one dying at the same time in another. The effect might be to create random error amounting to some centuries both in the straightforward dating and in the bristlecone pine correction.
Whether this would create a systematic error in the calibration is another matter. The bristlecone pine would have had to be more radioactive than other artefacts, mass for mass, prior to 500 BC. These trees are found at high altitude in the White Mountains of California and it is conceivable that an altitude effect such as in situ irradiation might have been involved, however until this question is properly examined, it must be admitted that, for reasons not yet understood, the calibrated dating fits the conventional chronology as well or as badly as our revised one, and the revised Egyptian chronology is better fitted by the straightforward dating uncorrected by the bristlecone pine (Figure 20). It is clearly now of great importance to check this conclusion by finding suitable calibration data characteristic of sea level, preferably from many different sites.

10.5 Biblical chronology

Let us now turn from the broad features of prehistoric dating and consider rather more precise local links with Egyptian chronology. Thus, a somewhat questionable aspect of Near Eastern prehistory is the almost complete lack of parallels in the course of events described by Egyptian and Hebrew chroniclers. Such has been the assumed weight of existing Egyptian chronology and the lack of correspondence this brings that some modern scholars have tended to look upon the biblical evidence as an unreliable presentation of events in the lives of a not particularly significant people. And this despite wherever detailed correspondence between biblical accounts and archaeological facts can be established, then it has usually turned out that the Bible is an accurate description of what went on. This has already been mentioned in the previous chapter. It must be deemed rather remarkable that some scholars should have succeeded in placing the Bible in such a light since there is no question that the ancestors of present Western civilization took the Book to be the fountain of wisdom. So how is it that this point of view has come about?

Three centuries ago, Newton sought to reconcile his new gravitational theory with Genesis by demonstrating that the solar system had been created in a single act and had remained in stable equilibrium ever since. The existence of comets, with masses at that time unknown, wandering through the solar system, was very damaging to this thesis, and Newton was greatly occupied with explaining them away. Even without them however, it was obvious that the gravitational action of the various planets would tend to
modify their respective orbits, and although in due course Laplace was able to show that some of the principal effects were periodic rather than secular, Newton could do little else but appeal for the intervention of divine providence to maintain stability and order. Newton's great rival Leibniz was duly led to mock his adversary who, he said, claimed God not only as a clock-maker, and a poor one at that, but also as a clock-mender. Nevertheless, so pressing was this desire for order that Newton even turned against his former pupil Whiston who saw in the Bible evidence for several catastrophic events, not least of which was a Deluge caused by the impact of a comet! Newton, recognizing the strength of the argument and the inevitability of cometary impacts, went so far as to maintain that comets were not really a disruptive element but contributed to the preservation of the original order by replenishing the Earth's stock of water. There can be little doubt now that Newton, conscious of the scientific and intellectual revolution he was leading, was driven with a kind of religious zeal to maintain supreme order in his surroundings by professing to uncover a completely clockwork universe. Little wonder that Whiston was dismissed from his post and Newton displayed such ferocity towards notions of catastrophism. To some extent, we can still feel the breeze! With the benefit of hindsight however, we see that Newton's reasoning in this matter was not of the best, and though his influence was considerable in his lifetime and his search for a completely mechanical universe dominated science for the next 200 years, his arguments to invalidate some of the biblical evidence were rightly treated with great suspicion. It is natural nowadays to think the validity of the evidence was the main reason for this suspicion, but the Bible was not really in question – it was the logic supporting Newton's vision of an orderly universe that was met with disbelief. Newton's contemporaries were really in very little doubt about Biblical history and its possible association with astronomically induced catastrophism. A hundred years later on, when religion and science were slowly disengaging, Laplace could presume the same orderly theory of gravitation free of preconceptions about the origin of the solar system, and face with equanimity the possibility that the Earth suffered catastrophic collisions with comets. He wrote:

'The axis and the movement of rotation would be changed. The seas would abandon their ancient positions, in order to precipitate themselves towards the new equator: a great portion of the human
race and the animals would be drowned in the universal deluge, or destroyed by the violent shock imparted to the terrestrial globe; entire species would be annihilated, all monuments of human industry overthrown: such are the disasters which the shock of a comet would produce, if its mass were comparable to that of the Earth.

'We see then, in effect, why the ocean has receded from the high mountains, upon which it has left incontestable marks of its sojourn. We see how animals and plants of the south have been able to exist in the climate of the north, where their remains and imprints have been discovered; finally, it explains the newness of the human civilization, certain monuments of which do not go further back than five thousand years. The human race reduced to a small number of individuals, and to the most deplorable state, solely occupied for a length of time with the care of its own preservation, must have lost entirely the remembrance of the sciences and the arts; and when progress of civilization made these wants felt anew, it was necessary to begin again, as if man had been newly placed upon the Earth.'

The situation then, as now, was thus one in which astronomers saw no basic conflict between celestial mechanics and the biblical evidence for catastrophes. But about this time also, the newly emerging sciences of geology and biology were coming to recognize the evolutionary nature of terrestrial processes and life generally. On the so-called uniformitarian hypothesis, obviously related in concept to physical ideas of secular stability, it was impossible to accept this evolution without also invoking a great age for the Earth. Much is now made in scientific histories of the differences between this geological timescale and Kelvin's calculation of the Sun's age, but this particular argument was still in the future. The main conflict was at first the biblical timescale, and by association, with implications of a catastrophist history. The argument raged through much of the nineteenth century with Darwin a principal figure. Inevitably entrenched and somewhat extreme attitudes were adopted. Biblical history and catastrophism became inseparably linked. So, when the uniformitarian theory eventually prevailed catastrophism was discredited and scientific faith in the biblical record as even an approximation to the truth was destroyed. Historically, this conflict has often been seen in a purely religious context: the more important aspect from today's viewpoint is that scientific faith in biblical
evidence was destroyed, whether or not any supernatural element in
the story was allowed for. In fact, the arguments deployed by
uniformitarians against catastrophism, suggesting the perpetual,
slow, long-term action of weak geological forces and steady
biological evolution, no longer carry the conviction they used to. As
we saw in Chapter 5, the stratigraphic record revealed by palaeonto-
logists is equally consistent with a steady procession of catastrophes.
The ages of the Earth and the solar system are now established by
physical measurements unknown in the nineteenth century and it is
not at all difficult to uphold this evidence and look upon much of the
Biblical record as a fairly authentic account of the trials and
tribulations of a single determined people through a relatively short
period of history quite unrelated to the age of the Earth. And this can
be done whilst making suitable allowances for supernatural
embellishments which would have some difficulty surviving in a
scientific thesis. The critic might complain that there is an element of
subjectivity in making such allowances and so there is. But where
correspondence with independent evidence can be established, any
argument will then tend towards greater objectivity. Thus in so
far as it can be treated as a historical record without supernatural
overtones, the Bible is not at all in conflict with science. This means
we should take the biblical timescale more or less at its face value.
Perhaps we can be permitted a somewhat jaundiced view of the ages
of Joshua’s ancestors. If so the Old Testament simply becomes a
record going back to about 2500 BC say, the occasion of the Flood.
During the period subsequently covered by the tale, it seems the
course of events was seriously disturbed by a pattern of major
catastrophes of extra-terrestrial origin. The time of Exodus figures
large in all the accounts.

Two major figures in the history of science, namely Newton and
Darwin, thus found themselves in serious conflict with the secular (i.e.
non-supernatural) evidence of the Bible. In both cases, it has later
become apparent that although their main theses may have been
reasonably valid (i.e. mechanical universe, great terrestrial age) the
arguments they paraded against the biblical evidence were not at all
direct or necessary consequences of these theses. So it is ironical that
the eventual success of Newton’s and Darwin’s theories should then
have persuaded even biblical scholars of the unreality of much of the
Old Testament evidence. There grew up a willingness to treat much of
it as allegorical. More and more the tales were regarded only as of
value for their moral content, and increasingly they took on a
revelationary character special to the people involved.

These assumptions took an even firmer hold in the early years of the present century when historians began to discover very similar detail in some of the myths of different civilizations in the eastern Mediterranean. Biblical scholars simply could not allow this to be evidence of a general revelation since it denied any special status to the Bible. The view gained ground that the similarity in the events described was the result of the diffusion of knowledge. Increasingly the allegories became mere fairytales, thus minimizing conflict between scholars of the Old Testament and mythologists, and providing a ready-made explanation of discrepancies between the tales themselves and any realistic assumptions. The differences could simply be treated as results of the vivid imagination or incompetence of an unknown raconteur. This is a thoroughly dangerous theory, providing as it does virtually free rein to the imagination of the investigator.

In making this detour, we have sought to show how unimpressive are the grounds for neglecting the Old Testament as an accurate source of history. Inevitably, if there was a general catastrophe on the scale of the Typhon event to which the events of Exodus refer, independent dating of the event should confirm our calculation based on Egyptian chronology.

The Exodus of the Hebrew slaves from bondage under the pharaohs is undoubtedly the major turning point in the history of the Jewish people. Four complete books in the Bible bear witness to the events of the period: Exodus, Leviticus, Numbers and Deuteronomy. ‘Let my people go,’ Moses demanded; and the Pharaoh capitulated, permitting the twelve tribes of Israel to depart Egypt in huge numbers. They then wandered the desert for forty years before reaching the Promised Land. In that time, Moses received the Laws, and the whole structure of Jewish culture was formulated. They arrived in Canaan under Joshua’s leadership and conquered Jericho and other big cities. The Bible is quite specific about what went on: some of the cities were burnt. in some the inhabitants were allowed to go in peace, in some they were slaughtered, while in others, no capture was ventured. The taking of Jericho for example was assisted by an earthquake.

Modern excavations of Jericho are not at all at variance with this picture and they even permit a dating of some precision. The end of the middle period of the Bronze Age (circa 1550 BC) in Palestine is marked by the widespread destruction of fortified cities generally
assumed at present to have been Hyksos strongholds. It is supposed that the cities of which Jericho is one, were destroyed by Egyptian armies carrying out a war of retaliation subsequent to the expulsion of the Hyksos from Egypt. Whether or not this is true, the excavations at Jericho not only confirm the destruction but they now also reveal a later rebuilding. Then the city was again destroyed. The remains show a double defensive wall apparently broken down by an earthquake and they also display traces of an extensive fire and other signs consistent with attack by enemies. Kenyon suggests a period of 150 years after 1550 BC, during which Jericho was completely abandoned, then a period of renewed occupation lasting slightly over 75 years. This gives a date for the final fall of Jericho circa 1325 BC. And by this reckoning, the Exodus occurred in 1365 BC, in remarkably good agreement with the Typhon date of 1369 BC we have derived from Egyptian sources.

Heretofore, the date obtained by Kenyon has been inconsistent with accepted chronology and the biblical evidence since conventional theory has the Exodus occurring in the middle of the thirteenth century, that is around 1250 BC. Although there are no unequivocal records supporting this assumption, Ramses II has apparently been considered a suitably powerful pharaoh for whom the comings and goings of a crowd of escaping Israelites would be of sufficiently little consequence not to warrant a mention. This 'non-evidence' is hardly satisfactory by itself as a proof and the date therefore seems to be based on two things: one, general archaeological signs of what is presumed to be an extended Israelite conquest of Canaan at this time following their displacement from Egypt. Franken and others have disputed this theory since there is absolutely no certainty that Israel was responsible. Indeed, it may have been the work of the Philistines, other invaders of Canaan of the period, possibly originating from Crete. The second derives from the account in Exodus which has the Egyptians pressing the captive Hebrews to build the pharaoh store-cities, Pithom and Raamses. These are normally identified as Tanis and Tell el-Mashkouta supposedly built in the reign of Ramses II, but the evidence is equally if not more consistent with Middle Kingdom cities constructed by the Hebrews soon after their original enslavement, such as Tell el-Retebak and Qantir. The evidence for 1250 BC is thus far from secure. As we have seen also, such a date for Ramses II is in any case based on a misinterpretation of Egyptian chronology, and any reliance on this mistaken correlation is now likely to be incorrect. So, all in all,
Kenyon's dating has much to commend it and it provides good support for our revised chronology. In summary, Palestinian and Hebrew chronology are, in some important essentials as well as their broad outlines, in very good agreement with the new Egyptian dating.

10.6 Astronomically induced disasters as agents of history

The re-adjustment of Egyptian chronology also brings the New Kingdom kings into the immediately pre-classical period. Where the standard archaeological picture obtained from the cross-dating of pottery styles, has previously obliged one to place the Mycenaean and Spartan kings at the start of the Greek 'dark ages' in the thirteenth century BC, contemporaneous with the Egyptian New Kingdom, it now turns out that the Trojan wars must have been no earlier than 900 BC. In composing the dramas of the Iliad and the Odyssey, Homer was thus drawing upon events within a generation or so of their happening; they were evidently still fresh in people's minds, and Homer was not what he is usually credited with being, a mere collector of ancient tales from ages past. His audience must have been the immediate descendants of the Mycenaean warriors whose history he was recounting. Thus, Homer's claim that the Phrygians helped defend Troy against the Greeks is now in accord with the earliest Phrygian remains which date from around 800 BC. In central Anatolia, up to now, neither Phrygian nor indeed any cultural remains of any people have come to light which might be dated to between 1300 and 800 BC. The heroic civilization of Mycenae did not, as some historians would have us believe, vanish for half a millennium only to spring to life again as if nothing had happened. A critic has already argued against this thesis admitting the implications of conventional dating as little short of fantastic: 'The craftsmen and artists seem to vanish almost without trace; there is very little new stone construction of any sort, far less any massive edifices, the metal-worker's technique reverts to the primitive and the potter, except in the early stages, loses his purpose and inspiration; and the art of writing is forgotten.' None of these difficulties is present in our revised chronology. And as further evidence of the inconsistencies that the hypothetical dark ages of Egyptian and Aegean history have introduced, let us finally mention those quite mystifying ceramic tiles removed from one of the palaces of Ramses III. These show what appear to be Greek letters on the reverse side incised during the process of manufacture, although under standard chronology, the Greek alphabet was not invented until fully four centuries later.
Heretofore, of course, the late Mycenaean empire has been dated between 1600 and 1200 BC, not between 1200 and 800 BC as we now propose. The long prehistory of the Minoan civilization thus becomes a natural predecessor of the late Mycenaean. This people had its home on the narrow, mountainous island of Crete at the southern end of the Aegean Sea. The Minoans revered the bull as a symbol of power. Regular human sacrifices were made to appease the ‘Earth Bull’ who periodically devastated the island with earthquakes; likewise the ‘Minotaur’, son of Zeus, a monstrous and terrifying god, half-bull and half-man. The Minoan people were above all a seafaring race and energetic traders: given frequent contacts there is every reason to believe their Bronze Age developments were contemporaneous with those of the eastern Mediterranean generally. So, the accepted Bronze Age dates of Cretan life are probably more or less correct, as is that of its final decline into oblivion around 1200 BC. Until quite recently, Minoan developments tended to be considered as taking their lead from a superior Egyptian civilization. Renfrew has shown quite clearly that the society was essentially an independent culture basing its prosperity on the exploitation of its own vines and olives. Contrary to the earlier view, the influence of Egypt, though present, was relatively weak.

But as is well known, the truly splendid life of this people was brought to a singularly abrupt halt around 1400 BC. Not only was the unrivalled capital, Knossos, devastated by fire and tumult (although the famous palace survived), so also were all the other principal towns. There seems to be no doubt that a quite exceptional and unexplained catastrophe occurred around this time, with widespread destruction of buildings. It has been suggested, not altogether convincingly, that the major volcanic eruption of the nearby island of Thera may have been responsible. Certainly the explosion was the greatest volcanic event in post-glacial times. Whether the five centimetres of volcanic ash which settled over central and eastern Crete was sufficient to cause the collapse of the civilization is doubtful, however. Excavations on the island of Rhodes about 150 km east-north-east of Crete have revealed a similar depth of ash although continuity of life was there unaffected. Destruction by earthquake concurrent with the great explosion was suggested by Evans, who was understandably impressed by the collapse of 2,000 buildings in 45 seconds during an eruption of Thera in 1926. However all known Minoan sites except the palace of Knossos were destroyed, and the earthquake associated with a volcanic eruption is very small
It is only speculation at the moment but the near-coincidence in time between the Thera eruption, the decline of Minoan civilization and our proposed date of Exodus suggests that these events may have been interrelated. A 100-megaton event occurring over Crete would have been sufficient to destroy the whole island and might have induced the eruption 90 km to the north. It is known that a hydrogen bomb explosion can induce tectonic slip at fairly distant sites, and it is conceivable that a vastly greater disturbance in the eastern Mediterranean might have triggered the volcanic event. The Typhon event might then have been simultaneously responsible for the destruction in Crete as well as in Egypt. The survival of the palace of Knossos might be a problem with this view, however, and the evidence for tsunami generation, which surely must have occurred on this hypothesis, is debatable. It is intriguing nevertheless that a large disturbance of the sea in this area would have inundated the low coastal lands of Egypt, and that the parting of the Red Sea was recorded as being contemporaneous with the Exodus. Our understanding of the nature of Typhon as well as the statements in Exodus and the Ipuwer Chronicle render the hypothesis attractive. Thus: 'The Lord sent thunder and hail, and fire ran along upon the ground, and the Lord rained hail upon the land of Egypt (Exodus 9:23), and there was a great cry in Egypt for there was not a house where there was not one dead (Exodus 12:30) ... groaning that is throughout the land, mingled with lamentations (Ipuwer 3:14). ... He who places his brother in the land is everywhere (Ipuwer 2:13). That a vast area was laid waste need hardly be questioned, and the less so if the Phaethon tale, as we saw in Chapter 9, originated in northern Italy.

However, the inclusion of Crete does remain a little speculative. This is because the approximate epoch of the destruction partly depends upon some remnants of Egyptian New Kingdom ceramics found in the remains at Knossos. The study of these by Evans at the turn of the century seems at present to be regarded as providing a secure date. Obviously, if the correlation is binding, our revised chronology would advance the collapse of Knossos to a later date inconsistent with the Bronze Age limits. This would surely be incorrect. The conventional argument however appears to be that the last Egyptian remains found in Knossos should give us the date of its collapse. In fact, it is now known that Minoan civilization continued, much weakened, for at least another one or two centuries. So the
epoch of the fall of Knossos is now strictly independent of the crossdating of ceramics, important though this may once have been. If our sequence of events is correct, the successor of the linear A part-hieroglyph script used by the early Minoans, namely the linear B emerging at Knossos around 1400 BC and then at Mycenaean Pylos, would appear to be the natural and continuous forerunner of the eventual Greek script. It may be the catastrophe of 1369 BC was responsible for transporting the main stream but not all of Minoan culture to the Mycenaean mainland. Thus, although early Greek history still leaves room for doubt, taking it with that of the Egyptians, the Babylonians and the Hebrews does suggest there may have been a major hiccup in the march of civilization at this time.

No authors can justifiably make reference to proposals of this kind without mention also of the investigations by Velikovsky. In a quite remarkable piece of historical analysis some thirty years ago, this author not only drew attention to the parallels between the events described in Exodus and the Ipuwer Chronicle, but also to their implications so far as a catastrophic extra-terrestrial missile and ancient chronology were concerned. In his book *Ages in Chaos*, he proceeded to show how as a result of the 400- to 500-year shift this imposed on Egyptian chronology, not unlike the leap we have been discussing, the renowned Israelite King Solomon, *circa* 950 BC, became contemporaneous with the early New Kingdom monarch, Queen Hatshepsut, a descendant of Amenhotep I. Drawing upon many convincing parallels in the historical evidence, Velikovsky succeeded in identifying Hatshepsut as the Queen of Sheba. Egyptologists and biblical scholars have argued over the identity of the Queen of Sheba for many centuries, and this dramatic alignment must, if right, be counted as a significant and remarkable achievement. We need not assemble all the evidence here, suffice to say the theory that it was Queen Hatshepsut who made a voyage to the legendary Land of Punt, now identified as Palestine, is one that speaks with considerable conviction.

Unfortunately, Velikovsky’s researches have remained firmly outside the main line of historical enquiry, and his arguments involving a correction of Egyptian dates up to the end of the eighteenth dynasty, similar to the one we are proposing in this chapter, have not been given the attention by experts they deserve. The reasons for this are not hard to find. In the first place, Velikovsky followed up these quite plausible discoveries by drawing attention to further challenging parallels between the late New Kingdom kings
and rulers in the latter half of the first millennium BC. His later identifications contravened the usual stratigraphic sequence of events however, and archaeologists have generally found them quite unacceptable. But much worse than this, Velikovsky became seriously involved in pressing a quite impossible astronomical hypothesis to explain the catastrophic events. Although in the reaction to these ideas one can see the signs of an irrational adherence to the principle of uniformitarianism, Velikovsky himself was quite unable to conduct rational and scientific arguments in support of his case. The result has been to turn opinion firmly against all aspects of his work, sound and reasonable thought some of it is.

The aspect of Velikovsky's thesis that seems to have generated the most steam is his identification of the planet Venus as a gigantic comet that swept past the Earth before moving into its present orbit. Wildly improbable though this is for dynamical and many other reasons, there is no doubt that Venus did eventually assume a particularly significant place in many early astronomies. If undue reliance is placed on the mythological rather than the scientific evidence, the absurd speculations about Venus can at least be understood if not forgiven. How the confusion of blame between Typhon and Venus arose in some myths, assuming indeed it did, is obscure. We have already mentioned the great difficulty which may arise in unambiguously identifying a celestial object from Babylonian text. This problem will be greatly compounded when the translating scholar is unaware of the picture we have developed. Both objects would have the characteristics of being lost in sunlight at intervals, and being seen as morning and evening phenomena, but there may be stronger reasons for attributing the properties of one also to the other (see page 269). The Velikovsky thesis was therefore not so much wrong as hopelessly misguided.

As we have emphasized, we can do no more than skim over the surface of a vast field of knowledge; hopefully however we have alighted on sufficient points of significance to suggest to the reader that there are already strong indications of a completely new sequence of events in prehistory. Perhaps indeed, during the fourteenth century BC, there was a ferocious people from the mountainous regions of south-west Asia who succeeded in establishing ruthless dominion over a vast Near Eastern empire centred on Assyria and including Palestine and Egypt. Perhaps a major catastrophe in 1369 BC devastated these countries, so weakening their governments that the invaders were able to step in and assume power.
And perhaps this same catastrophe brought the Minoan civilization to an abrupt halt, never again to achieve its former glory. Cotterell has already suggested economic and social dislocation following the natural disaster on Crete paved the way for invaders, whom he identifies somewhat arbitrarily as Mycenaean Greeks. If there was indeed an astronomically induced disaster in this area, the role of catastrophism in the history and progress of mankind has to be at last recognized.

10.7 Systematic observation of cometary deities

Events of this character are so much outside normal experience that it is not at all easy to envisage the full consequences. However, it seems likely that environments relatively close to the epicentre of a fall in the ocean would suffer such a huge transformation that the survivors would be very soon obliged to move to new lands less affected by any inundation. Where these lands were already well settled, it would not be surprising if conflict ensued. Throughout history of course, many peoples have been involved in great migrations, no doubt for a whole variety of reasons, so it is not possible to see in such happenings a single exclusive cause. Nevertheless, if the Great Deluge and the Typhon event were real, large-scale migration is one of the probable effects of which we should certainly be aware. The local movements in Canaan and the Aegean are examples already discussed, but journeys further afield are possible. Students of language have long suspected from the apparent presence of certain prominent and common roots amongst different tongues all over the world, that evidence for substantial past migrations exists. An interesting study by Cohane suggests two principal dispersals, one world-wide associated with the Great Deluge, the other later for an unknown reason and on a lesser scale radiating from the Near East. Amongst the most common words are ones representing the pagan deities related to each event whether or not this is true, some of the more recent reconstructions of the course of events in European Neolithic society seem to add support to these ideas.

In Britain for example, the first farmers had arrived apparently from the continent by 3500 BC. They introduced the basis for a civilization which has developed more or less without break ever since. Unfortunately they did not develop writing and our knowledge of them is correspondingly limited. Also, although metal was used quite early on in Mediterranean and eastern European communities, these settlers remained isolated and continued to use stone. The
period of their dominance, the Neolithic, lasted from around 3500 to 1900 BC. Although it was once thought that the culture of Neolithic society was slowly enhanced by diffusion from the eastern Mediterranean, radioactive dating methods have led to the realization that the megalithic builders of the Neolithic were probably establishing themselves in Britain well before the principal cities of Sumeria appeared. According to Renfrew and MacKie, there came into existence a specifically Atlantic European people possessing a professional priesthood and customs involving collective burial in long barrows and new types of stone tombs. These skilful people who can, it seems, be distinguished from the earliest settlers, secured a foothold along the Atlantic borders all the way from Iberia up to the north of Scotland, not so much by organized colonizing expeditions but by what MacKie calls genetic and cultural mingling. They also reached into the Mediterranean but here they were closely restricted to the coastal regions. Impressive monumental stone architecture developed particularly in Malta during this period, but it looks as though the Iberian peninsula was the main cultural epicentre.

In France, Ireland and Britain, the building of graves and cairns was on a relatively small and local scale until about 2400 BC. In this section, we use uncorrected carbon dates after which megalith-building blossomed and became significantly more elaborate. This was the period in which quite a few stone circles were first set up, in which for example the passage graves at New Grange, Ireland, and the earthworks at Silbury Hill, England, were built, and in which the first foundations of Stonehenge were laid. Above all, the period 2400 through to 2000 BC saw the rise in Britain of what MacKie calls an astronomy-practising theocracy, exactly paralleling, it seems, the main phase of pyramid construction in Egypt. Accurate surveys of many stone circles in Britain by Thom and others have been interpreted to show that a proportion of them could have been used as solar and lunar observatories. But if this is so, there has been no really compelling explanation as to why so many of them were constructed. Indeed, astronomical motives have seemed so unlikely and the implied astronomical techniques have seemed so implausible that archaeologists on the one hand and statisticians on the other have been inclined to be very sceptical of the evidence from the surveys. Thom could only suggest, rather tamely, that the prediction of tides may have been important. But if celestial phenomena were really the object of their interest, then we would expect the magnificent periodic comet, the Olympus of Greek mythology, alias the World Tree, alias
the Cosmic Serpent, to have commanded quite as much universal attention as the Sun and the Moon, one should look for evidence of the cosmic serpent among the megaliths.

Among the earliest Stone-Age structures in Brittany and southern England, there are many linear arrays of stones and very long earthworks, often aligned with points on the eastern horizon. It is conceivable that these sites began with simple attempts to portray, not so much the Sun and the Moon, but this other, singular, most impressive object in the sky, namely the Cosmic Serpent. The plan layout of the early earthworks at Stonehenge, for example, was a circle out of which led an avenue towards the eastern horizon. If intended as a portrayal of something in the sky, the resemblance to Gill's description of the great daytime comet of 1882 (see Chapter 2), with its short stubby tail, is striking, to say the least. One of the earliest investigators of megalithic monuments of any renown was William Stukeley (1687–1765). Although he was the first antiquary to observe that the principal axis of Stonehenge is aligned towards the midsummer sunrise, Stukeley was unfortunately also given to making wild conjectures. Indeed, there is a long history of somewhat fantastic theorizing about megalithic monuments but there has been an equally irrational over-reaction on the part of some historians and scientists to almost any theoretical framework explaining them. The result has been a tendency to reject any non-archaeological evidence deriving from ethnography, linguistics and genetics, but Stukeley was no doubt closer in time to local tradition which had by then not been silenced by the arrival of a new rationalism. It is interesting to record his obsession with the idea that these monuments were serpent temples. He based his conclusions on Pliny's story in which the Gallic Druids made use of a 'magic egg' produced by a snake. He saw in winding megalith avenues, often oriented somewhere between north-east and south-east, evidence of serpent worship. Such notions have never been held in high regard by hard-headed researchers, but if our theory is correct, the probable starting point for all these monuments was symbolic and of religious inspiration. Only with the passage of time would the observers have detected patterns of motion among the Cosmic Serpent, the Sun and the Moon and gradually some edifices would have been turned over to the business of systematic measurement. We would not then be dealing with 'scientifically developed' observatories that degenerated into temples, rather with temples that blossomed occasionally into observatories. Similar ideas could be associated with the large and ancient earthen mounds in
northern America which were first constructed as early as 1000 BC. In this case, there are regular and symmetric forms suggesting sky alignments, and effigies which have counterparts among Indian representations of constellations. If the name of the mighty Serpent Mound of Newark, Ohio, does not prove an association of the kind we are suspecting, it does at least indicate how widespread were objects that resemble the Old World earthworks that were the source of Stukeley’s inspiration.

Over 900 stone circles are known in the British Isles, either still preserved, ruined, or as sites where their former existence is well attested. They are distributed all over the accessible highland areas with some indications of a later spreading to lower-lying land. The largest circles are as far apart as Brodgar in Orkney and, outside Britain, Carnac in Brittany. Using a system of dates based on the C-14 chronology of artefacts found in the vicinity of stone circles, various aspects of their evolution are now becoming clear. For example, it is now known that their constructed shapes were evolving from purely circular amongst the earliest to elliptical and egg-shaped configurations amongst the latest. The reasons for this development of pattern are not yet understood. It has also become clear that though nearly all the circles were being set up between about 2400 b.c. and 1300 B.C., most of them were constructed just prior to the latter date. This is very close to the ultimate stage of Stonehenge construction (culminating in the erection of the Great Trilithon around 1300 B.C.). There was then evidently some widely recognized purpose in setting up stone circles which reached some kind of climax at around this particular epoch. It is tempting to see the 1369 BC catastrophe as the culmination of a period during which the need to appease the sky god and or predict its imminent arrival became ever more pressing.

Hawkins and Hoyle have given reasons for supposing the fifty-six Aubrey holes, a ring of pits dating from the earliest phase of Stonehenge construction in the middle of the third millennium—were a crucial part of the monument; they regard Stonehenge as an analogue computer for calculating lunar and solar phenomena including eclipses. Thus, the number 56 happens to be the lowest multiple of the Saros eclipse cycle of 18.61 years close to a whole number, and it is possible to conceive of straightforward procedures in which the holes could have been used for predicting eclipses. But why, if so, were eclipses important? The enormous scale of effort required to build Stonehenge and similar monuments implies
a powerful motivation, and it is just conceivable that the eclipses were not of prime interest in themselves but were an index of the recurrent encounters with Zeus and Typhon. Thus $56 : 3 = 30$ is near integer (see page 267) so that Typhon-associated phenomena might, like the eclipse cycle, recur at roughly fifty-six-year intervals. Possibly something of these origins emerges in Plutarch's statement that Eudoxus associated 'Typhon, the demon of eclipses' with the figure of fifty-six angles. Perhaps the primitive builders of Stonehenge I arrived at this number by a simple year count between the first two spectacular encounters with Typhon rather than by a sophisticated astronomy requiring knowledge of the Saros. Another possibility is that a simple commensurability was detected between Typhon and a planet (see page 270).

Is there evidence to indicate that these settlers of prehistoric Britain were observers of comets? Their rock carvings, known in modern times for over a hundred years, may be the clue we seek. According to Morris, who has surveyed the petroglyphs at eighty or so sites in Argyll, Scotland, some of the most common motifs are those illustrated in Plate 30. He points out that the carvings are nearly always made where there is a fine, open, unobstructed view to the south on outcrops that are close to horizontal. Burl has given much attention to recumbent stone circles, ones with flat altar-like stones which seem to be set up with a view to the south in mind. On some of these are depicted the same motifs. Many of these patterns include larger rings or circles to which are attached parallel wavy tails, in some cases described by Morris as 'comet-like' figures. There have been many conjectures as to what these arrays of comet-like figures represent, the possibility that they simply represent comets does not seem to have been considered before. Plate 30 illustrates the carvings on an outcrop at Ardmarnoch, typical of many others, and another from Traprain Law near Edinburgh, and if it is as we suggest, then a truly awe-inspiring spectacle was being witnessed by prehistoric man. Similar elaborate carvings are to be found on standing stones.

If the purpose of Stonehenge was predictive as well as religious there is the interesting and mathematically testable proposition that the numerous alignments of this or other monuments represent an attempt to track one particular comet. If this were so, the evolution of this orbit through precession and non-gravitational forces might account for the sequence of abrupt changes in the construction of Stonehenge over its long history. Similar explanations might be invoked for adjustments to the alignments of Egyptian temples which
On the left are illustrated some of the most common motifs to be found among Neolithic 'cup and ring' markings on rock outcrops and megaliths at various places in the British Isles. In the centre is shown a typical set of markings on a flat rock at Ardmarnoch in western Scotland (Morris 1979). The wavy serpent-like lines with haloes surrounding the heads have been likened to comets and at least one such display in Yorkshire, England, is on what is known as the 'Tree of Life Stone'. Elsewhere markings containing various arrays of single dots have been tentatively identified as constellations of stars. It is possible therefore that the Ardmarnoch array shows a family of comets moving through a star field. Below is shown a carving from Traprain Law, now at the National Museum of Antiquities of Scotland in Edinburgh. Note particularly the appearance of a long curved comet tail and a huge halo surrounding a comet head that was probably as bright as the full moon (cf. Han tomb paintings of comets, Plate 20).
were first noted by Lockyer, since it is now quite clear that luni-solar precession is not itself an adequate explanation.

The general linking of stone circles with ancient superstitions, often as we have seen involving dragons and serpents, and the popular assumption that Stonehenge was a kind of arch-temple of the Druids, are of course well known. The consensus of archaeological opinion is that the connection of Druids with Stonehenge is a creation of nineteenth-century romanticism, but there is enough in tune with our general line of reasoning to suggest an association may after all be valid. From classical sources such as Posidonius, it is clear that the Celtic world considered Druidism a long-established institution by 200 BC, although how far back it goes in time is unknown. Caesar tells us that the Druids 'have many discussions concerning the stars and their movements, the size of the universe and of the earth, the order of nature, the strength and power of the immortal gods, and hand down their learning to younger men'. The claims of Caesar and Pliny concerning Celtic interest in calendrical matters have been confirmed by the discovery of a bronze plate at Coligny in France carrying figures that bear all the signs of reconciling a lunar calendar with the solar year. Classical history provides us with tantalizing glimpses of a people called the 'Hyperboreans', and although Herodotus claimed them as a mythical race, another writer, Hecateus of the fourth century BC, was in no doubt of their association with Britain. A fragment of his history cited by Diodorus reads:

"[The island] is at least the size of Sicily and lies opposite the land inhabited by the Celts, out in the ocean. This is in the far north, and is inhabited by the people called Hyperboreans from their location beyond Boreas, the north wind. The land is fertile and produced every sort of crop; it is remarkable for the excellent balance of its climate and each year it affords two harvests. The story goes that Leto [Apollo's mother] was born there. It is for this reason that Apollo is honoured above all the gods. There are men who serve as priests of Apollo because this god is worshipped every day with continuous singing and is held in exceptional honour. There is also in the island a precinct sacred to Apollo and suitably imposing, and a notable temple decorated with many offerings, and looking like a globe. There is also a community sacred to this god, when most of the inhabitants are trained to play the lyre and do so continuously in the temple and worship the god with singing, celebrating his deeds."
Whether the Hyperboreans' circular temple is a genuine reference to Stonehenge has been much debated. The new perspective does appear to put the Druids in a new light however. Certainly there is no hard archaeological evidence to link them directly with the much earlier megalithic culture, but with our model of events based on modern astronomical facts, and the ancient writings and archaeological facts of the eastern Mediterranean, we can now detect a semblance of order in the course of Celtic history from as far back as 3000 BC. Once again, Typhon assumes a crucial role, and dates of 1369 BC and around 2500 BC take on an added significance. It is probably true that the Atlantic megalith culture achieved its greatest flowering in Britain, but as MacKie has shown, its origins can be rather securely traced to the Iberian peninsula. But here it seems rather difficult to identify a prior history like that known in Sumeria for example. The advance of the civilization prior to 2500 BC shows much more the signs of a steady infiltration of a new culture into a previously existing primitive society. MacKie leaves the source of this culture quite open, but suggestively depletes the lack of solid evidence for any infiltration or diffusion from the east. The Phoenicians seem perhaps the most likely candidates, but the evidence unequivocally focuses attention on the Atlantic front. We will not speculate further but leave the reader with an inevitable thought: that around 2500 BC, the time of the Flood if our analysis is correct, saw the arrival of what seems to have been a stream of more sophisticated immigrants very conscious of what caused the calamity they survived and who rapidly took over the administration of the Atlantic border. From whence did they come? There is a temptation to see here the beginnings of a realistic framework for the well-known 'story, strange but true' told by some nameless priest to Solon and recorded in the Timaeus. But any link between the Platonic myth and the Cosmic Serpent is another story.

10.8 Calendars and constellations: the origins of astronomy

If short-period comets were indeed sky-gods, and the comet which we are now calling the Cosmic Serpent came spectacularly close to the Earth at intervals, then the desirability of predicting the returns would be clear - astronomy would grow out of theology. Obviously no extreme or exclusive claims can be made for the role of comets, as agricultural and navigational requirements provide their own impetus for observing the heavens. Nevertheless the extraordinary past behaviour of comets may well have generated an acute interest in...
celestial cycles. And if this was so, it is to be expected that significant vestiges of these origins may yet be with us in forms that have until now gone unrecognized. In particular, evidence might be found in the early calendric systems. Any calendar recording the recurrence of the Cosmic Serpent would operate concurrently with a solar one necessary for agriculture. As the comet faded out, say later than about 1000 BC, the comet calendar would either be forgotten or become a divine vestige of unknown purpose. Calendar systems reached their highest stage of development amongst the South American and Mexican civilizations, and we shall examine some aspects of these.

The Mayas had three calendars and a belief in the cyclic nature of time. They believed that the forces controlling the gods were subject to these cycles, although some gods were unaffected by them, others were trapped within them. According to von Hagen, 'Every moment of their lives was involved in the position of the planets. They feared that if the gods were not propitiated they would put an end to the world, and that is perhaps the reason for their obsession with an almost exact calendar. . . .'

The haab calendar was made up of eighteen months of twenty days, plus five empty days. This year was adjusted to give a solar year of 365.2420 days, closer to the 'real' year of 365.2422 days than our own Gregorian calendar, and confirming that they were keen and competent observers of the sky. A second calendar, the long count, simply reckoned the number of days from a date in 3111 BC of unknown significance. The third calendar was the tzolkin, 260 days long. Von Hagen remarks that 'No one knows why they settled on this precise number of days, unless it comes out of some "crystallized pantheon", for it has no astronomical significance.' This third calendar is of very great antiquity; it had great significance as a divine calendar; and it was used also by the Aztecs and Toltecs.

It happens that twice 260 days is the mean interval between oppositions (i.e. the synodic period) of any object in a direct orbit whose orbital period is 3.35 years. This is remarkably close to the present orbital period of comet Encke. These oppositions are well behaved in the case of the planets, because of their virtually circular orbits, but with an eccentric Apollo orbit involved their nature is quite different: successive synodic periods will vary greatly, and opposition will vary from a dramatic close encounter to a passage about 3 a.u. distant. The close encounters, of course, are the significant ones, but these will happen only very briefly, small
departures from optimum making a large difference to the encounter. Now 73 periods of 260 days equals 52 years almost exactly; no smaller number of these periods gives a whole number of years so closely. That is, the interval between very close encounters of the Earth, with a Cosmic Serpent of period 3.35 years, is 52 years (we have met a similar phenomenon with Leonid meteors, which recur in strength at 33-year intervals). And as it happens the Mayas and Aztecs were obsessed with a 52-year cycle, which they measured as 73 tzolkin years, for at the end of each cycle the fire god Xiutecuhtli returned, and was worshipped and propitiated by human sacrifice. It seems then that the major features of the Maya, Aztec and Toltec calendars are explicable along these lines and that their notion of gods trapped within cycles of time is understandable in a quite literal way.

Because of the high orbital eccentricity, perihelion passage would be a brief event during which angular motion would be rapid, the comet would presumably be at its most active, and any dimming of sunlight of which the tail might be capable would occur. These effects would be seen at about 3.3-year intervals, but the precision of timing of these phenomena would be lower because of their more diffuse nature. Nevertheless they would be spectacular and a record of the sidereal as well as the synodic interval might possibly be preserved in early calendars.

European and Asiatic calendars were unquestionably lunar and solar and tied to agricultural needs. Even here, however, one finds that although the early Roman calendar seems to have comprised twelve lunar months plus extra days to make up a year of 354 days, some early Roman authorities mention a year of ten months and 304 days, which makes no sense in terms of agriculture or planetary movements. Almost certainly this goes back to a time before the formation of the Graeco-Roman empires, that is, before the eighth century BC. As it happens, four such years amount to 3.33 solar years. The number four seems arbitrary but it may be significant that when the Greeks emerged from this period and set up a twelve-month year, they also chose to celebrate a major event, whose primary symbol was the torch of Olympus, on a four-year cycle. Speculative though this is, the numerology is sufficiently striking to suggest that a deeper investigation of these early calendars might be rewarding. Allowing for the errors introduced by rounding, the permissible range of period we find for the progenitor of Encke is, roughly:
from the 56 pits of the Aubrey ring: 3.27–3.32 years
from the 260 days and 52 years of the
Mayan calendar: 3.31–3.38 years
from the $4 \times 304$ days of the early
Roman calendar: 3.32–3.34 years
(cf. the modern orbital period of Encke of 3.30 years).

Evidently there is a degree of selectivity here as these numbers are
to some extent obtained in consequence of the preconception that the
Cosmic Serpent was important. Nevertheless to our knowledge no
explanation has been forthcoming until now for these early Mayan
and Roman calendars, and a stronger rationale than simply
predicting eclipses is obtained for the Aubrey ring.

If our interpretation of certain aspects of megalithic monuments is
correct, the comet was presumably seen at least as far back as
2500 BC. We have one further astronomical inheritance from this
period, the division of the sky into constellations. The traditional
pattern of constellations derives from the star catalogue of
Hipparchus (c. 190–120 BC) who in turn had access to descriptions of
the sky from Eudoxus (c. 403–350 BC) and the Phaenomena, a poetic
manual intended for sailors written by Aratus (c. 315–250 BC). The
astronomer Ovenden has been able to show that the constellations
are of vastly greater antiquity than the dates of these authors. Because
the pole of rotation of the celestial sphere is fixed at any one epoch,
stars within a certain distance of one pole will always be visible on any
clear dark night, while those within the same angular distance of the
opposite pole will never be seen. The size of these zones depends on
the latitude of the observer. However the poles precess, moving
around a small circle in the sky with a period of 26,000 years, so that
over the millennia different sets of stars will come to occupy the zones.
By studying the pattern of constellations given us by Hipparchus, it
should be possible to detect a blank area, an unknown region, the
extent and centre of which define the date and latitude of the
constellation makers. Ovenden went considerably further than this,
demonstrating that the constellations were arranged in a pattern
symmetric about a single point in the sky. For example the
constellations of Auriga, Perseus, Hercules, Bootes and others form a
ring whose centre is the north celestial pole in the middle of the third
millennium BC. Again, Hydra the water snake stretches for almost 90°
and yet its stars are all faint. The only reason for assigning a
constellation to these inconspicuous stars seems to be that Hydra
marked the celestial equator around 3000 BC. Combining these alignments, Ovenden found the constellations date from 2800 BC ± 300 years fitting by eye, or 2600 BC ± 800 years fitting by a statistical method. The latitude of observation was found to be 36°N ± 14°, and although it was suggested that the Minoans might have been the creators, most investigators believe the constellations to be of Mesopotamian origin. Many of the early constellation figures, some of which were handed on to us by the Greeks, portray creatures which are horned or have dragon-like appendages—all known attributes of later descriptions of comets. Certainly the constellations were seen as the mansions of the gods, their creation being described for example in the Enuma Elish as:

Then Marduk created places for the Great Gods.  
He set up their likenesses in the constellations.

The division of the sky into figures with possible cometary associations emerged then at just about the time we suppose man was first observing the celestial events that were eventually responsible for disaster. The possibility of a causal link exists, and although there is no denying navigational and agricultural reasons for mapping the sky, there is now also a real possibility that serious attention to the sky arose in part as a result of the spectacular and sometimes terrifying events that man was witnessing. After all, so far as is known, the civilizations of the Fertile Crescent had managed without constellations for a long time prior to these events. At least there may be further dimensions to our understanding of the origins of calendars and constellations, and their place in the evolution of the earliest civilizations.

Indeed, these may extend to the origins of astronomy generally. And the final picture will, we suspect, incorporate many facts which currently sit on the borderlines of knowledge. Thus if one takes a dispassionate look at the mythological evidence assembled by Velikovsky for example, setting aside his singular astronomy, one may conclude that there was a widespread anticipation of an encounter of the Earth with a comet or its debris in 687 or 686 BC. This event could have been, as he suggests, a significant turning point in the history of civilization, releasing new visions of the nature of the gods, perhaps finally weaning man away from sacred calendars and the view of life in which the world progressed through catastrophe, fire and flood from one 'great year' to the next. What van der Waerden calls 'the triumphal advance of cosmic religion' progressed in Greece.
Egypt and Asia, and from this time forward we become aware of the growth of systematic astronomy in Babylonia, apparently aimed first of all at determining fundamental long-term periodicities in celestial phenomena. According to the records, the Babylonians particularly observed the planets, objects that seem to have been given both 'scientific' and 'divine' names. The latter, like 'star of Zeus' or 'star of Ares', involved the names of divinities of great antiquity, yet it is an interesting fact that the new 'scientific' names did not survive. They were eventually displaced in the later classical period (post 200 BC) by names like 'Zeus' and 'Ares'. It has always been assumed of course that these dual titles applied to objects that were one and the same, but this can be seen now as possibly a fundamental error. If our theory is correct, the substitution of divine comets' names for planets has been a source of subsequent confusion.

Thus, the principal planetary names were at the start of the first millennium BC probably still applied to cometary deities which were presumably mostly in periodic Earth-crossing orbits. The main figure of the Silver and Bronze Ages (2500–1300 BC say) was Zeus–Jupiter–Marduk Athura Mazda Osiris (as it was named in the Greek–Latin Babylonian Persian Hellenistic Egyptian tongues), and it was recognized as the successor of Kronos–Saturn–Ninib–Zervan–Nemesis of the Golden Age (prior to 2500 BC say). It now seems much of the religious conflict inherited by the new rational age (700–0 BC) can be understood as relating to the baffling question whether the god Z–J–M–A–O took precedence over the god K–S–N–Z–N. It is very interesting to note that K–S–N–Z–N was worshipped as Time, an associated meaning of Kronos that has tended to evade explanation before now, and it is logical in the light of the earlier discussion if it was K–S–N Z N in the pre-fragmentation era that originally gave rise to sacred calendars around the world.

Among the early 'planetary' periodicities that emerged from the Babylonian observations was one significantly related to eclipses of the Sun and Moon for which van der Waerden has been unable to find any really satisfactory explanation. It was a period of 684 years. There is no question of the figure being a copying error since it occurs several times in astrological texts, yet there is no combination of known lunar periods capable of explaining it. It is tempting therefore to suggest that this figure is related in some way to the Babylonian doctrine of cosmic recurrence, attributing perhaps conflagration and flood to encounters with a predictable dragon also responsible for or somehow associated with eclipses. Admittedly the suggestion is
speculative but it is possible the ancients had come to believe in a rough periodicity in the phenomena observed around 2100 BC (3 × 684 = 2052), 1369 BC (2 × 684 = 1368) and 687 BC respectively and that these led the astrologers to anticipate great happenings around 0 BC. Some 2,000 years closer in time to these events than us, it is reasonable to suppose memories of what went on at these epochs still survived. The Magi would look back to events like the Flood, a subsequent time when for example pyramids were being constructed by Egyptian monarchs and hill-top temples were set up by megalith builders, another later time when for example Moses led the exodus to the promised land, and yet another when Sennacherib’s army was allegedly destroyed by a 'host from heaven'. If on some such occasions in the past the close passage of a great comet had led to celestial fireworks and local catastrophe of the sort we have discussed, then an integral part of the astrological theory would be the belief that these great historical events were heralded by, or caused by, the significant return of a god or comet. The search for periodicities would be important. That great comets came to be associated with planets may eventually be verifiable from Babylonian astrolabes, another approach is to look for associations through 684-year, 56-year or even 52-year cycles. The longer periodicity at least can only have been a theoretical construct and must have been based on multiples of shorter periods. The movement of Mars against the stellar background is generally retrograde but changes direction twice in the 780-day synodic period. The turning points can be timed to a day through naked eye observations, and to this precision the Martian cycle repeats itself against the same background of stars with a 171-year period; and 4 × 171 = 684 years. We have seen that in pre-classical times Halley’s comet must have been a brilliant object on its returns, over a thousand times brighter than Sirius, the brightest star. And nine revolutions of Halley’s comet, taken as 76 years, is 684 years. That is, there is a strong (4:9) commensurability between the Martian super-synodic period and that of Halley’s comet, and this cycle recurs on a 684-year period. No such commensurability exists between this comet and the other planets. Evidence has been given for associating a comet ‘Mars’ with the event of 687 BC; perhaps it is more plausible to attribute catastrophic encounters to comets in Earth-crossing orbits, but it is also possible that our forefathers may have come, illogically, to associate some contemporaneous near encounters with Halley’s comet as warnings of impending disaster. By the first millennium BC, the idea that comets presage catastrophe
as much as cause it is so deeply inbred that one should perhaps look for coincidences of this kind to explain it. If correct, then Halley’s comet has been known to mankind for a very long time as Ares—Mars—Nergal—Verethragna—Herakles.

There is also a 7:17 commensurability between the 8-year Venusian period used for predictions by the Babylonians, and returns of Encke’s comet taken as 3.30 years. This is a weak commensurability; but it has a 56-year recurrence time to within a month or so and its derivation follows the same logical route as the Halley/Mars one. Yielding to temptation, we may suppose this connection to be a significant one; and we should then look to myth for descriptions of a disastrous encounter with a giant comet Typhon, alias Aphrodite—Venus—Ishtar—Anahita—Isis, in 1369 BC.

It is appropriate that we end as we began, on a note of uncertainty, for the realization that mythology and early astrology are telling us about past comets means there is a great deal more research still to be done. Such research will require the skills of many disciplines and hopefully it will be encouraged by the new perspectives that have now been opened up.
Epilogue

The strands have now been brought together, and it is for the reader to judge the strength of the final rope.

Of course it would be quite possible to agree that catastrophic impacts have played their part in Earth history but dispute the interstellar connection. Or one could agree that the myths of old are based on things cosmic but deny our cosmic interpretation of Exodus. Or accept the revised chronology but deny the significance of catastrophe in subsequent migrations or megalith-building. The combinations are endless and we would be the first to agree that, in attempting to cover this enormous span, we have sometimes lived dangerously. But it is the overall strength of the rope that matters, and our case is simple: the Earth is a cosmic body; and it may sometimes be struck by other cosmic bodies.

People have been on the fringes of many of these ideas for a long time. That fear was a prime motive for building megaliths is not a new idea (Burl); likewise that catastrophe may have been a factor in the migration of the megalith-builders (MacKie); that a cosmic interpretation should be put on many myths has been suggested before (Bellamy, generally ignored); likewise that some Old Testament events describe real cosmic catastrophe (Whiston; Velikovsky, dismissed as a charlatan); that great impacts may have catastrophic global effects is an idea about 200 years old (Laplace; Wright); likewise that the ultimate source of the missiles is the space between the stars (Laplace).

What was missing from all these speculations was a workable astronomical scenario. It has taken a profusion of modern instrumentation—radio and optical telescopes, Earth-survey satellites, Moon missions and so on—to bring our knowledge to the point where that scenario can be supplied. And the result of this battery of high technology has been to turn the clock back to the ideas of 200 years ago. Why should this be? Part of the answer may lie in the words of the palaeontologist McLaren, who was speaking in a
somewhat narrower context: 'Geology was liberated as a science by Hutton and Lyell at the beginning of the last century by means of the great principle of "uniformity"... however, there has been a natural tendency to over-compensate and to avoid catastrophic interpretations even when the evidence calls for it.' Of course obscurantism is older than catastrophism, but it should have no place in science: one must judge the evidence of telescope, crater, iridium layer or thunderbolt on its merits.

So much for the past and present. What can we say of the future? Impacts of the dinosaur-destroying variety are too remote to concern us. But only fifty human lifespans separate us from the events of Exodus, only one from the Tunguska fireball. Within any human lifetime there is a 1 or 2 per cent chance that say a 1,000-megaton impact will take place somewhere on the globe, an event totally outside modern experience. The consequences would be devastating on a 'local' scale but this might well be completely overshadowed by other imponderables. A temporary drop in mean global temperature might be expected. These have in fact been detected by the geologist Flohn through the study of past lake-level fluctuations. During the last 700,000 years there have been abrupt changes in temperature, reaching about 5°C in fifty years and enduring for several centuries. These occur at intervals of about 10,000 years, but there are epochs when the frequency reaches about one in 1,000 years. To get enough dust into the stratosphere Flohn speculates that major volcanic eruptions may occur in clusters, but of course a cosmic mechanism for adequate dust injection is readily to hand. One gets the impression that the Earth is continually trying to glaciate but that these attempts are usually overridden by some feedback mechanism. The disquieting feature is that these abrupt coolings occur, as we would expect, even within warm interglacial periods. A 1°C drop in mean global temperature, in the growing season, would eliminate commercial wheat production in Canada; a 3°C cooling would move the limit of the corn belt in the USA to southern Iowa. According to a report of the National Academy of Sciences in 1975 produced to assess the likely global consequences of nuclear war, 'The United States and Canada have become the world’s “breadbasket”, producing about two thirds of all the grain and much of the other food that is available for shipment in international commerce. There is reason to believe that the dependence of other nations on grain grown in North America to feed their growing populations will become increasingly severe for many decades.'
In palaeontological terms a small impact with such effects would correspond to an undetectably small hiatus in the fossil record; in human terms it would be global calamity beyond imagination engulfing rich and poor alike. It has taken us 3,000 years to begin to understand the significance of comets. It might be another 3,000 years before a disintegrating comet again intersects the Earth's orbit, and we may choose to eat, drink and be merry, and forget the morrow; on the other hand we can see now that the decline over the years of the priest-astronomer from astrologer to soothsayer, and from thence towards magician and jester, has hardly been one to open the doors of perception.

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Bibliographic notes

In preparing the bibliographic notes below, we have assumed that the reader has already acquired some background knowledge of the subjects studied. Our rather limited aim therefore is to provide the technically minded reader with adequately referenced modern literature citations so as to guide him or her into the relevant research fields. Numbers in Roman type relate to the main reference list, italicized numbers to corresponding pages of the text. Except where appropriate, we have not specifically referenced the more familiar passages from classical authors. So far as more general references are concerned, our listing is by no means exhaustive but simply provides an introduction to the topics considered.

Chapter 1: Universe to galaxy: the cosmic framework

The history of scientific thought warns us against supposing that because a particular world view is prevalent at any one time, it is necessarily correct. It has frequently happened that ideas which seemed plausible at one epoch have been superseded by some totally different way of looking at things. Astronomical science in particular has been in a state of ferment and rapid development over the past decade or so, and in Chapter 1 we have tried to indicate that even the broad features of the universe (origin, redshift, structure of galaxies, star formation) may be interpreted in more than one way. Thus although our trail starts from the planetesimals, their ultimate origin is shrouded in mystery; and their study may eventually contribute to the resolution of such problems.

The postulate that the universe presents the same aspect everywhere and at all times, the so-called perfect cosmological principle, follows from the conservation laws of physics and ensures that these laws are continuous. The principle excludes a big bang or other types of evolving universe. If the universe appears to be expanding, then to uphold the principle there must either be continuous creation of matter in some form or else the apparent expansion must be an illusion. The former is out of fashion at the moment but has been vigorously defended by Hoyle. The latter is inherent in, for example, the so-called fib cosmology. Several mechanisms other than expansion might yield a systematic redshift and it has been shown that they fit the data more readily than big-bang scenarios.

The view that the universe is not expanding and that ordinary galaxies evolve by successive ejections of spiral arms from their nuclei, gradually
converting initially spheroidal systems into disc/halo structures, has been
developed by Clube.\textsuperscript{48} That the outer structure of an ordinary galaxy is
determined by frequent violent ejections of nuclear material had already been
proposed by Ambartsumyan\textsuperscript{4}, Burbidge & Hoyle\textsuperscript{19}, Pismis\textsuperscript{149} and others. The
chemical evolution of the Galaxy implicit in these ideas was first recognized by
Unsold.\textsuperscript{175} According to such theories there is recurrent activity in galactic
nuclei (e.g. Bailey & Clube\textsuperscript{6}) at intervals of approximately 100 million years.
During the short active episodes, successive active nuclei develop briefly into
quasars before disgorging oppositely directed ejecta at relativistic speeds. The
effects invite the question ‘Does our Galaxy have a violent history?’ (Clube\textsuperscript{25})
and an affirmative answer seems to be born out by evidence that our Galaxy is
in a state of comparatively rapid large-scale expansion. In this chapter such a
picture of galactic evolution is contrasted with that of expanding universe
cosmology. We emphasize that it is the latter picture which is currently
subscribed to by most current astronomical opinion. Almost inevitably with
this world view, spiral arms are usually interpreted as density waves whilst the
gravitational collapse of galactic nuclei proceeds in accord with the predictions
of general relativity theory, forming black holes. This conventional theme is
very well covered in many technical as well as general books and is not
elaborated here. Black holes for example are not normally considered capable
of producing relativistic ejecta of the kind that could form spiral arms, so the
actual observed state of spiral arms may be looked upon as a means of critically
distinguishing the two theories of their origin. We therefore anticipated that
the study of Earth history would become a means of probing the state of spiral
arms.\textsuperscript{125} Globules, considered as seats of star formation, are a crucial
component of the theory. These objects were originally discovered in the
Galaxy as long ago as 1935, but the existence of cometary globules only
emerged in very recent surveys using the powerful UK Schmidt telescope in
Australia (see \textsuperscript{71}).

Chapter 2: Galaxy to comet: the interstellar connection

The traditional separation of galactic and solar system disciplines in
astronomy owes more to default than analysis. It derives from an epoch when
our understanding of the state of the interstellar medium was incomplete to
the extent that regarding the solar system as isolated within the Galaxy was
considered justifiable. Radio astronomy has transformed the situation. It is
now known that there exist in the spiral arms, besides dust and young stars,
huge dense clouds of cold gas containing hydrogen and a whole variety of
interstellar molecules, many of them organic (Gordon & Burton\textsuperscript{69}, Solomon
& Sanders\textsuperscript{169}). It is just an accident of history that optical astronomers
discovered hot, tenuous gas in the galactic plane at an earlier stage, so
perhaps it was inevitable that the view should have been formulated first that
the cold gas derived by compression from the hot gas before condensing to
form stars, and that density waves were responsible for the compression. This
theory is now facing difficulties however it fails to account for detailed
observations of non-circular motions in our Galaxy (Watson & Clube) and the classical picture of star formation by collapse of a gas cloud is not found in computer simulations (Larson, Tohline; but see Hunter). An opposite viewpoint, consistent with ejection in a compressed state from galactic nuclei, that the warm clouds derive from very much colder material, has still to be studied quantitatively. But whichever of the several possibilities is correct, the cold clouds are now seen as an ideal place for the synthesis of kilometre or more sized bodies (planetesimals or planetoids), those that outgas on heating being the ones we recognize as comets (Napier).

In this chapter, we develop the idea that the observed globules are fragmenting-accreting aggregates of planetesimals in the process of forming planetary systems with central stars. It follows that as stars evolve and circulate through the Galaxy, their primordial clouds of comets disperse and disintegrate until a time is reached when the capture of new comets from the interstellar medium dominates what remains of the original cloud (Napier & Stanucha, Clube & Napier). The current solar system comets may be understood as recent captures (Hasegawa, Yabushita) following passage through Gould’s Belt between 10 and 20 million years ago. This model, in which the solar system continually interacts with the Galaxy, may be contrasted with that held by most astronomers at the present time, first quantified by Oort, in which it is assumed not to interact with its surroundings and to possess only a huge primordial cloud of comets. Other comet theories which have been proposed (e.g. Lyttleton, Vsekhsvyatsky) have met with severe objections (Whipple, but see Fellgett). If we are to discover the correct theory, it is evident that the determination of the ages and chemical compositions of comets, particularly isotope ratios, is crucial. This is an unsolved problem which satellite probes of the future may resolve. In 1986, the European Space Agency plans an expedition to Halley’s comet under the codename Giotto. In the meantime, the lunar surface and the terrestrial ocean beds are considered to be good places for examining recent deposits of cometary material.

Chapter 3: Comet to asteroid: solar system debris

If comets are indeed interstellar in origin, sporadically captured from the spiral arms of the Galaxy, then it is natural to enquire whether other small bodies of the solar system may also have been captured. We have been led therefore to examine the origin of asteroids in particular. The asteroid belt was originally thought to be a fragmented planet between Mars and Jupiter (e.g. Ovenden), but in more recent times has been considered to be a collection of remnants from a primordial solar nebula (Kuiper). Since this nebula is supposed to have been flat, it has been seen as a problem for theory, how to disperse the asteroids into orbits of high eccentricity and high inclination. A decade or so ago, it began to be realized that there were similarities between Apollo asteroids and main-belt asteroids and that the former were the credible evolutionary products of short-period comets.
Since there are good grounds for supposing short-period comets evolve from long-period orbits (Everhart\textsuperscript{141}), we can entertain the obvious hypothesis that main-belt asteroids are themselves also the descendants of earlier generations of captured comets as well as an original solar globule. The discovery now of bodies which behave as if they were part comet and part asteroid lends support to this view (e.g. Opik\textsuperscript{141}). The rocket effect due to cometary outgassing (Whipple\textsuperscript{125}) is invoked as the mechanism which, coupled with planetary perturbations, transfers bodies from the unstable (cometary) to the stable (asteroidal) regimes; however, such transitions have yet to be calculated in detail. The asteroid belt is thus proposed to be in part the result of past capture episodes in the history of the solar system and we are led to view the numerous other short-lived phenomena amongst the moons and smaller bodies of the solar system as further evidence of recent capture. The mass distribution of these small bodies is that of the comets and asteroids; and the preponderance of direct orbits follows from the fact that satellites captured into retrograde orbits have shorter lifetimes (McCord\textsuperscript{119}). The rings of Jupiter\textsuperscript{145} and Saturn\textsuperscript{36, 170}, the inner moon of Mars\textsuperscript{165} and Chiron\textsuperscript{134} are among other examples considered.

Chapter 4: Asteroid to crater: the anatomy of impact

Some proportion of the missiles captured from interstellar space will collide with the planets and satellites of the solar system to form craters. There are now strong grounds for believing that most of the objects of 1–10 km diameter in Earth-crossing orbits are the end products of the evolution of short-period comets and are hence by the arguments of previous chapters, indeed interstellar. (To avoid confusion we have retained the conventional name, Apollo asteroids, for these objects and have not followed a recently revised subdivision by orbit.)\textsuperscript{144} Encke’s comet is the single known example of a comet currently in the process of becoming an Apollo asteroid.\textsuperscript{141}

All the inner planets and satellites are studded with impact craters. Most were formed early on but a quasi-steady impact rate has been maintained over the past 3 billion years, e.g.\textsuperscript{67, 68}; and for a comprehensive study of impact cratering mechanics see\textsuperscript{153}. There is evidence however that this average rate of cratering may have been slightly increasing and that the flow of missiles is in any case sporadic.\textsuperscript{67, 64} These facts are all comprehensible in terms of a model in which the Apollos are the missiles and they are regularly replenished during spiral arm passages.

Impacts have only rarely been considered by mainstream scientists as an important factor in the evolution of the Earth’s surface and biosphere. The amateur geologist Gallant is a notable exception: see his Bombarded Earth published in 1964.\textsuperscript{50} Whatever the reasons for this omission, it is now clear that it can no longer be maintained (Table 3), but the significance of the new astronomical evidence has still to be appreciated by Earth scientists as a whole (see Chapter 5).

Included among the missiles are meteorites. These are seen as fragment-
ation products of 100-km-sized bodies;\textsuperscript{100} traditionally these bodies have been identified as asteroids, and much effort has been expended in attempts to identify individual meteorites with particular asteroids.\textsuperscript{40} These parent bodies, in turn, have been interpreted (through meteorite mineralogy) as condensations from a hot primordial solar nebula.\textsuperscript{100} In actual fact, the reasons for identifying meteorites with main-belt asteroids are not compelling, further, although the 'hot' school of thought is still predominant amongst meteoriticists,\textsuperscript{182} there is also a view that many meteorite types may have formed in a much lower temperature regime,\textsuperscript{23, 25} over a much wider range of conditions than one would expect in a narrow strip of solar nebula around 2.5 a. u.\textsuperscript{181} These considerations have led us to propose that meteorites are fragments of a cloud of interplanetary boulders (cf. \textsuperscript{16, 69}) which in turn are the collisionally processed remains of the primordial globule.

53: 54; 63; 153; 163, 166; 182; 186; 74, 183, 75, 187, 84, 131; 157

Chapter 5: \textit{Crater to catastrophe: the aftermath of impact}

Following speculations going back to the time of Laplace and even earlier (\textsuperscript{103 110, 120, 176}) we develop reasons for supposing that cosmic bombardments are a major cause of biological extinctions. There have in fact been numerous hypotheses to account for individual extinction events.\textsuperscript{14} It has not been our aim to add further speculation which can neither be proved nor disproved, but rather to emphasize the inevitable \textit{derived} nature of the present theory; these collisions are bound to produce extinctions on all scales from local to global, a fact which has so far largely been overlooked by many scientists. Thus within the last decade many large terrestrial craters have been discovered;\textsuperscript{157} the lunar missions have led to a reconstruction of the cratering history of the Moon and so, presumably, the Earth;\textsuperscript{68} and wide-angle telescope surveys have revealed the existence of a substantial missile population in circum-terrestrial space.\textsuperscript{104} These new lines of evidence demonstrate that catastrophic impacts are indeed common occurrences over geological timescales; their significance in this context was first pointed out by the authors and is the foundation of their 'theory of terrestrial catastrophe'.\textsuperscript{125} As it happens, confirming evidence on the ground quickly emerged: several geological groups discovered exceptional concentrations of material apparently of extra-terrestrial origin at the Cretaceous–Tertiary boundary (\textsuperscript{5, 51, 167}) and it is to be hoped that other boundaries and nonconformities will be similarly examined. The erratic nature of the palaeontological record (e.g. \textsuperscript{129}) is qualitatively in agreement with the predictions of the theory, and it seems likely that a large part of the extinction record can be accounted for by the considerations outlined here, which thus provide a rational basis for gaining further insight into the progress and evolution of life on this planet.

That geological effects will follow in the wake of a large impact seems entirely reasonable, particularly as a great global vulcanism coincided with the dinosaur extinction event.\textsuperscript{156} Evidence is discussed for a sequence of lesser
impacts, since the event, causing sudden sea-level changes. These are interpreted in terms of a mechanism leading to ice-ages e.g. see also Particular attention is drawn mier alta to a coincidence in time between the close of the Eocene and the epoch of formation of the Popigai crater. All these aspects of catastrophism in Earth history highlight also the episodic nature of orogeny. The conflict between geophysicists who hold that the mantle is too viscous to permit continental drift and those who claim from the more visible evidence that it has nevertheless happened, is in principle resolved if one recognizes that the main part of plate tectonics takes place in violent episodes initiated by large impacts. Such ideas, if substantiated, would constitute a new fundamental theory of geological action.

Chapter 6: The mystery of the short-period comets

Numerical computations by Everhart show how long-period comets may be fed regularly into short-period orbits. Using observational evidence gathered by Kresak & Ptich, it is possible to calculate the current rate of production of Apollo asteroids. The observed number of Apollos is consistent with a capture of comets circa 10 million years ago as the solar system passed through the Gould Belt. The implied steady state number of short-period comets is considerably less than the actual numbers observed. (A contrary viewpoint was developed by Delsemme. This was based on primordial Oort cloud theory.) The short-period comets which we now observe are thus of recent origin and fragmentation due to tidal forces during a Jupiter or Sun encounter appears to be one plausible and certainly the least ad hoc cause. (See Marsden for a description of a giant Sun-grazing comet which split into perhaps thousands of fragments some of them, such as the great comet of 1881, themselves brilliant objects at perihelion.) Reviewing similar data, Drobyshevski has suggested fragmentation of a Saturnian satellite whilst van Flandern has proposed the recent explosion of a planet in the asteroid belt. Whatever process is invoked the effects imply a recently increased probability of active comets in Earth-crossing orbit.

Chapter 7: Prehistoric encounters?

The evidence so far mostly relates to Apollo asteroids and the impacts they produce, down to the telescopically detectable size of around 100–1,000 metres diameter. Missiles in the range of approximately 1 metre or less mostly burn up as fireballs in the upper atmosphere and have been well studied in recent years with North American and European networks of all sky cameras. Downward and upward extrapolation to the intermediate size range places realistic limits on the rate of Tunguska and super-Tunguska events. This rate is very significant on a historical timescale and is consistent with a current overproduction of meteor streams which is itself consistent with a current overproduction of short-period comets. The Taurids are the
most energetic stream and are additional evidence of the extremely active nature of Encke's comet several thousand years ago (e.g. Whipple, Whipple & Hamid). The prehistoric sky therefore contained at least one very active comet in periodic Earth-crossing orbit (Whipple & Hamid); we conclude that it is necessary to consider the effect these aspects of the prehistoric sky would have had on primitive peoples.

Chapter 8: Comets and gods

A survey of the theories of comets through the mediaeval and classical periods shows a clear development of attempts to describe their behaviour in rational, materialistic terms. It would appear that these attempts started with Greek philosophers as a reaction to explanations involving supernatural behaviour. To exemplify this, we have paid special attention to the writings of Lucretius as they appear in the translations of Latham, Munro and Bailey. The conclusion is reached that comets were for the most part treated as celestial deities in prehistoric times; and that the principal reason why the ancient records of Egypt and Babylonia carry so little information about comets is that, being regarded as gods, they were the subject of worship rather than objective analysis. As we have seen, newly formed comets and meteor streams were at some not so remote period very prevalent in the sky, and man would have been obliged to formulate some sort of picture of what was going on. As it happens, comets were not seen as objects subject to the control of deterministic physical law but as benign or malignant beings with minds of their own, and as such, they were not incapable of influencing the lives of men on Earth below. Indeed, they inspired great terror since man was conscious of the disasters they caused. It may well be therefore that the polytheistic origins of many modern religions relate to primitive beliefs about comets. This enables us to place the facts of mythology in a new light and it is concluded that many myths have a common core reflecting world-wide observations of a large active short-period comet. The genealogy of the gods is interpreted as a history of fragmentation.

Chapter 9: Zeus and Typhon

The modern astrophysicist tends to see astronomy as an exclusively modern puzzle. Armed with the laws of physics, he dissects the scene before him with the antiseptic calm of a skilful surgeon. But like the surgeon, he can overlook the mysterious origins of his patient. For some reason, astronomy is the oldest of the sciences and it is certainly known to have a past that is rooted in primitive polytheistic religion and celestial mythology (e.g. King). The question we address is why. In this chapter, we abandon those twentieth-century tendencies to see in much mythology mere tales with an astronomical flavour but take as our basis the assumption that many myths have a
common astronomical core overlaid with embellishments that have long ago lost touch with the original meaning. Taking as our starting point the modern analysis of Greek combat myths (e.g. Fontenrose**), we recognize a huge and threatening god-like pair of dragons that return at intervals. The Phaethon myth (e.g. Engelhardt^159) indicates astronomical associations with flood and fire. With brief reference to other myths world-wide, we bring together these themes in a detailed hypothesis involving a large disintegrating comet in Earth-crossing orbit during prehistoric times. By attempting fairly literal interpretations, along the same lines, of the events in Exodus and the apocalyptic literature of the Bible (following e.g. Freedman & Frost in ^84), we deduce an association with a comet which is not altogether speculatively identified as the progenitor of Eke's comet.

Chapter 10: 1369 BC

It is assumed that encounters with a huge disintegrating comet in Earth-crossing orbit, the progenitor of Typhon and of Ecke's comet, gave rise to two principal bombardment episodes of cometary fragments. The first in the third millennium BC was probably world-wide and precipitated the Flood; the second in the second millennium BC was apparently confined to the eastern Mediterranean basin and caused severe local dislocation of the peoples involved. The events are seen as fundamental turning points in human history and they fathered doom-laden beliefs in the end of the world which were probably realistic and which have never since entirely disappeared.

In this chapter, we describe a revision of Egyptian chronology based on recent research (e.g. Parker^140, van der Waerden^191) consistent with Hebrew chronology (e.g. Kenyon^89) that places the Typhon-induced catastrophes circa 2500 BC and 1369 BC respectively. This revision recognizes defects in the standard Sothic calendar, carbon dating and dendrochronological calibration using the bristlecone pine, all of which suffer through failure to appreciate the roles of Zeus and Typhon in prehistoric times. The realization that Zeus was the dominant feature of the prehistoric sky following a dramatic flooding of the inner solar system with many short-period comets leads us to new understandings of previously unexplained aspects of the Roman and Mayan calendars, a new partial understanding of the role of megalithic temple-observatories, and a new understanding of the origin of the constellations.

Although Parker suggests that the 365-day Egyptian civil year arose with astronomer-priests over a long period by averaging an intercalated lunar year, it is possible the simple day count became established rather more quickly with a populace observing the fireball displays and precipitation that came with regular annual passages through a dense meteor stream. If these events marked the start of another year, a new lunar calendar initiated by heliacal risings of Sirius would probably have been substituted only when the meteor stream had almost ceased to be visible. When this happened in the reign of Ramses II, the civil year had drifted a very long way from the time year, requiring the introduction of a discontinuity in the Sothic calendar, which is the reason for
the revision of Egyptian chronology proposed in this chapter.

It is remarkable that the simplest integer commensurability between the orbital period of Halley's comet and the longest Martian period is a cycle of 684 years. The same reasoning gives a weaker Encke/Venus commensurability whose cycle time is 56 years. Cycles of 684 and 56 years seem to have been significant in the ancient world and it may be the early Babylonian descriptions of gods and their 'stars' were a manifestation of these associations. When these dualities later became merged as the comets faded, myths describing close encounters of the Earth with the Encke and Halley comets would tend to be attributed to the planets Venus and Mars respectively. The erroneous deductions by Velikovsky from mythology, involving close encounters with Venus as a giant comet, and with Mars, are then in principle explicable.

Many of the facts relevant to this interpretation of prehistory were apparently known to mediaeval scholars, and we suggest the subsequent failure to comprehend fully the part played by a comet, namely Zeus, in terrestrial history springs from illogical applications of certain fundamental tenets of Newton (belief in a mechanical universe) and Darwin (belief in a great terrestrial age) to arguments which were developed to counter the biblical evidence with which they were confronted.

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