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Comet Science

The Study of Remnants from the Birth of the Solar System

Foreword by Roger Maurice Bonnet

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1.1 The first observations

Comets have been known to mankind since ancient times. Even in the time of the Chaldeans four thousand years ago, astronomers were struck by the unpredictable, changeable and sometimes spectacular aspect of these objects. Like the planets, which were referred to as 'wandering stars' by the Greeks, it was only natural that comets would attract attention by their motion relative to other stars. In addition to this, their sudden changes in brightness, the appearance of trails of light associated with them, and their rapid and apparently inexplicable movement across the sky could only cause consternation and amazement in the minds of their observers. They found themselves quite unable to understand their true nature or behaviour. The Egyptians gave them the name 'comet', or 'hairy star'. Together with the 'head', or central part of the body, and the 'tail', a rectilinear area of light, this 'hair' was indeed their most noticeable feature.

It is human nature to fear what is not understood; but, rather than admit their ignorance, astrologers preferred to attribute a divine origin to those events they were unable to explain. It was thus that a myth developed, according to which comets were messengers from beyond, announcing ill omens. This superstition persisted for centuries until, in the eighteenth century, the astronomer Edmond Halley demonstrated the true nature of cometary orbits. However, history has shown that the consequences of this myth remained present well after that date, and have not yet been entirely exorcised.

Figure 1.1. opposite
Comet West 1976 VI on 12 March 1976, with its tail 100 million kilometres long. Photograph by S. Koutchmy, courtesy of CNRS-IAP.

1.1.1 Aristotle's mistake and its consequences

It is known that the Greeks, adhering to the theories of Aristotle from the fourth century BC, and then of Ptolemy two centuries later, considered the Earth to be at the centre of the Universe. A bold hypothesis put forward by Aristarchos of Samos, according to which the planets were all moving around the Sun, was largely ignored in his day (around 250 BC). It lay forgotten for over a thousand years, until the work of Copernicus in the sixteenth century finally reasserted the heliocentric system.

In order to account for planetary motions, Ptolemy had assumed that each one of them followed a small circular path, or epicycle, whose centre itself moved along a circular path around the Earth. With the complications that this

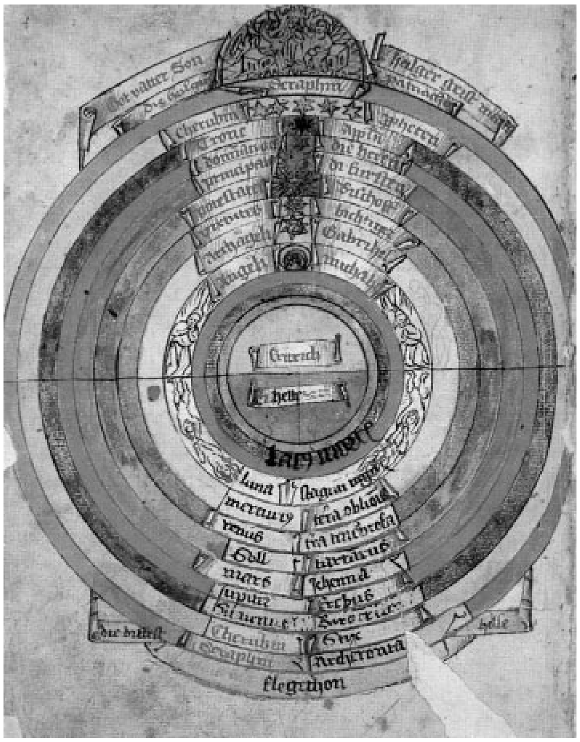

Figure 1.2.
The pre-Copernican geocentric Universe. The Earth, at the centre, is enclosed by a series of three layers representing water, air and fire, followed by more distant concentric circles representing in turn the Moon, the seven planets known at the time, and the Sun. German manuscript, *circa* 1450.

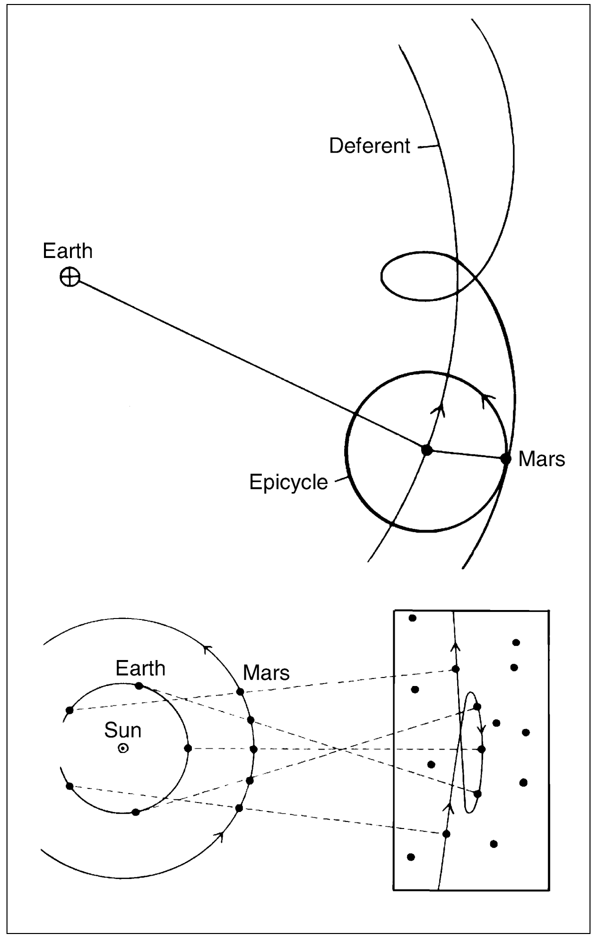

Figure 1.3.
The Solar System, according to Ptolemy and Copernicus. In Ptolemy's geocentric system, the planet is located on a small circle (an epicycle) which is itself moving along a larger circle (the deferent) centred on the Earth. In the heliocentric system of Copernicus, the planets follow circular orbits centred on the Sun. From Sagan, 1981 [74].

method introduced, astronomers of the time were able to explain planetary orbits. But what of the comets? Aristotle, finding himself unable to understand them as interplanetary bodies, assigned them an atmospheric origin. This belief, which was to persist for over twenty centuries, did more than anything else to convince people that there was a relation of cause and effect between cometary apparitions and certain terrestrial phenomena, whether they were of natural origin, such as floods, earthquakes and plague, or human, such as war.

This idea predominated right through from ancient times to the Renaissance. In this context, the unfortunately isolated voice of Seneca (4 BC to AD 65) in the first century AD seems all the more extraordinary to us today. He was indeed the first to suggest that comets might be periodic. Beyond this, he opened the way to a truly scientific approach, based upon observation and stripped of prejudice, as is illustrated by the following quotation from his *Natural Questions*:

Why be surprised that comets, which so rarely reveal themselves to the world, should not yet be subject to our

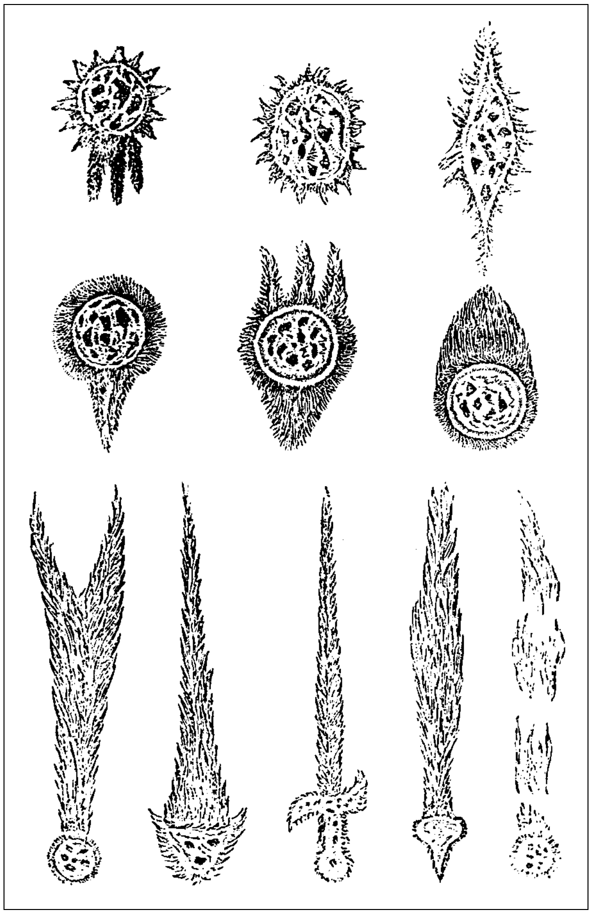

Figure 1.4.
Various cometary shapes recorded by Pliny the Elder. Engraving taken from the *Cometography* by Hevelius (1668).

rigid laws, and that we know neither the origins nor the destinations of these bodies, whose passages are separated by such immense intervals? The time will come when a careful study, pursued over several centuries, will throw light on these natural phenomena. A man will one day be born who will show us over which part of the sky these comets wander, why their motion is so great in contrast to the planets, and what is their size and nature.

This man was indeed born, eighteen centuries later. His name was Edmond Halley, and his discoveries were to confirm the brilliant intuition of the Roman savant.

Seneca's suggestions found no echo in his time, nor for many generations afterwards. His contemporary Pliny the Elder (AD 23 to 79) devoted a purely descriptive work to comets, in which he restated Aristotle's 'atmospheric' theory. This laid the way open to superstition.

Whereas the Greeks interpreted comets as apparitions to ordinary mortals of the gods of Olympus, the Romans saw in them a presage of ill omen. It was thus that Nero had several dignitaries assassinated, in order to escape from the curse associated with the passage of a comet, in fact the future Halley's comet. Later, apparitions of comets were said to have announced the death of Attila in 453, of the emperor Valentinian in 455, of Merovee in 457, of Chilperic I King of the Franks in 584, and of Muhammad in 632, among many others.

The comet of AD 1000, whose apparition coincided with an earthquake, caused even greater consternation; and in 1066 a further apparition of what was to become Halley's comet coincided with the death of Harold II, defeated by William the Conqueror at the battle of Hastings. The scene is immortalised on a now famous section of the tapestry at Bayeux. During the following centuries, comets continued to inspire terror, notably in 1402 and 1577.

In 1301, on the other hand, the Florentine painter Giotto was so impressed by a cometary apparition, which was once again none other than Halley's comet, that he portrayed it in the place of the Star of Bethlehem, in his painting *The Adoration of the Magi*. This is one of the rare cases in which a comet has been associated with a joyful event. Some have suggested that it was Halley's comet itself, during a passage in AD 12, which could have produced the exceptional brightness of the Star of Bethlehem, although the most popular hypothesis at present is a conjunction of Jupiter and Saturn in 7 BC.

Figure 1.5.
Halley's comet on the Bayeux Tapestry. This fragment of the tapestry shows the consternation of Harold II and his court when they saw the comet in 1066. Some time later, Harold was beaten by William the Conqueror at the battle of Hastings. By special permission of the city of Bayeux.

1.1.2 The advent of cometary physics

Throughout the Middle Ages cometary physics made little progress. The first astronomical measurements were made in the fifteenth century, in Germany and Italy. Regiomontanus (1436–1476) undertook systematic measurements of cometary motions. Frascator (1483–1553) suggested that cometary tails were always directed away from the Sun, and this was confirmed by the observations of Pierre Apian (1495–1552). A century later, Tycho Brahe (1546–1601) was the first to determine the distance of a bright comet, which appeared in 1577, by simultaneously observing it from two observatories separated by a distance of 600 km. He concluded that the comet had to be located much further away than the Moon. This constituted a decisive blow to the 'atmospheric' theory of comets.

The sixteenth century was also to see the advent of the Copernican system, with the publication by Copernicus (1473–1543) of his famous work *De Revolutionibus Orbium Celestium* in 1543. It was to be several decades before this revolutionary theory was accepted, notably due to obscurantist opposition from the Church. A further great step for astronomy was taken in 1609, when Kepler (1571–1630) formulated his laws governing planetary orbits around the Sun, in his work *Astronomia Nova*. This was to be the final blow to the Ptolemaic system.

The scene was then set for Edmond Halley's great discovery (1656–1742): comets follow highly elliptical orbits around the Sun, and thereby make periodic close approaches to both the Sun and Earth. The work of this English astronomer was based partly on many observations of past comets, and partly on the universal theory of gravitational attraction recently propounded by Isaac Newton (1642–1727), and published in his *Principia* in 1687. In 1705, Halley published the theory which was to bring

Figure 1.6.
The Adoration of the Magi, painted by Giotto di Bondone on the walls of the Scrovegni chapel in Padua, around 1301. The comet at the top of the scene may well be Halley's comet, the fresco being contemporary with one of its passages. This painting inspired the name for the European space probe Giotto.

him fame, under the title *Astronomiae Cometicae Synopsis*. He asserted that the comet observed in 1456 was the same as that observed in 1531, 1607 and 1682. As the period was 76 years, he announced its return for 1758, and indeed on 25 December of that year the comet was once again observed, to the glory, albeit posthumous, of its discoverer. At the same time, Newton's theory had been brilliantly confirmed and the foundations of cometary physics firmly established.

Once the period of Halley's comet had been determined, astronomers and historians began to look for its previous apparitions in ancient records. Their efforts were richly rewarded.

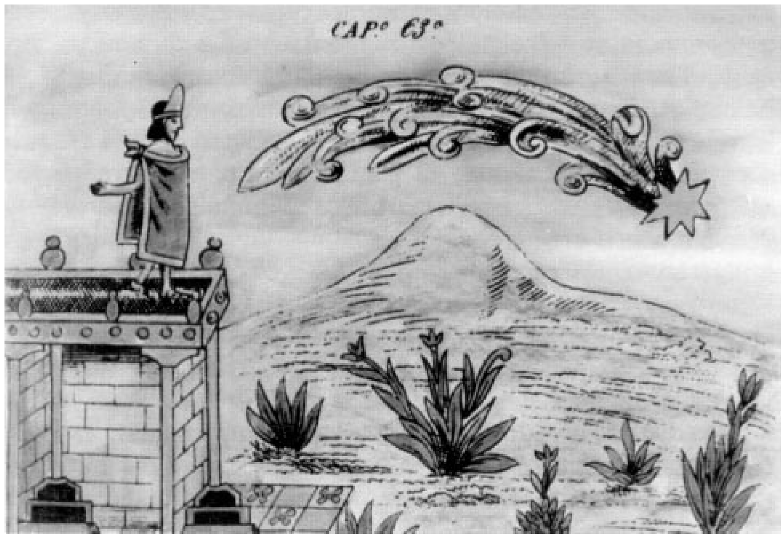

Figure 1.7.
Aztec painting showing the emperor Montezuma observing a comet. The Aztecs associated sinister prophesy with such events. Courtesy of D. Duran, *Historia de las Indias de Nueva España.*

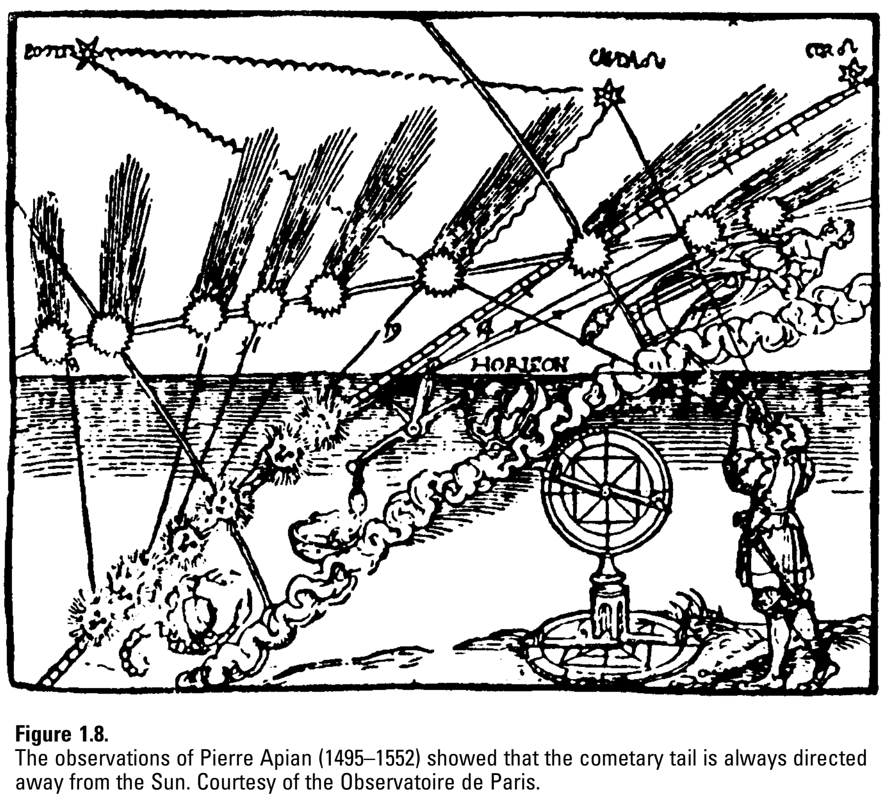

Figure 1.8.
The observations of Pierre Apian (1495–1552) showed that the cometary tail is always directed away from the Sun. Courtesy of the Observatoire de Paris.

Figure 1.9.
The English astronomer Edmond Halley (1656–1742), who observed in 1681 and 1682 the comet to which he was to give his name. He calculated its orbit and confirmed Newton's theories by correctly predicting its return in 1758. Courtesy of the Observatoire de Paris.

Since 240 BC, when the comet had been observed by Chinese astronomers, most of its apparitions had left some trace in the records of the time. Some of them had been quite spectacular. Apart from the examples mentioned above, the apparition in AD 451 should be noted, coinciding with the victory of the Romans and the Visigoths over Attila; as well as that of 1456, which the Church associated with the fall of Constantinople, taken by the Turks three years previously.

In 1759, after this brilliant confirmation of Halley's theory, it might be thought that the now identified comets would cease to terrify mankind. But this was not the case, for nothing at all was known of their size, nor of their true nature, and in view of their periodicity it remained a possiblity that one might actually collide with Earth. The French writer Molière mused in humouristic vein over this possibility in his *The Learned Ladies* ('We have had a narrow escape tonight, Madam. A world close to us has passed right by... '). But many were genuinely concerned, and controversy raged across the literary and scientific world. The comet of 1773 inspired widespread panic, despite scientists' reassurances of the low probability for such an event. Scenes of panic were repeated in 1798, 1816, 1832, 1857, 1872, and 1899. In 1910, Halley's comet once again moved the populace to the heights of emotion, this time in fear of highly toxic cyanogen gas from the cometary tail as it swept across Earth's atmosphere.

The last apparition of Halley's comet in 1986 has shown that, although comets no longer inspire the same terror, they nevertheless continue to fascinate the general public, in a way which goes beyond mere scientific curiosity. It could be said that the old superstitions have not been altogether eradicated.

1.2 In search of our origins

Paradoxically, it was at the very moment when comets were divested of their mythological aspect that their interest for the scientific world began to grow. Indeed, having been totally freed by Halley's discovery of the atmospheric character previously attributed to them, comets were recognised as bodies belonging to the Solar System, in just the same way as the planets and their satellites. For this reason, they deserved to be studied as such.

Many comets were observed in the nineteenth century. Among them, a comet of particularly short period, only 3.3 years, was closely

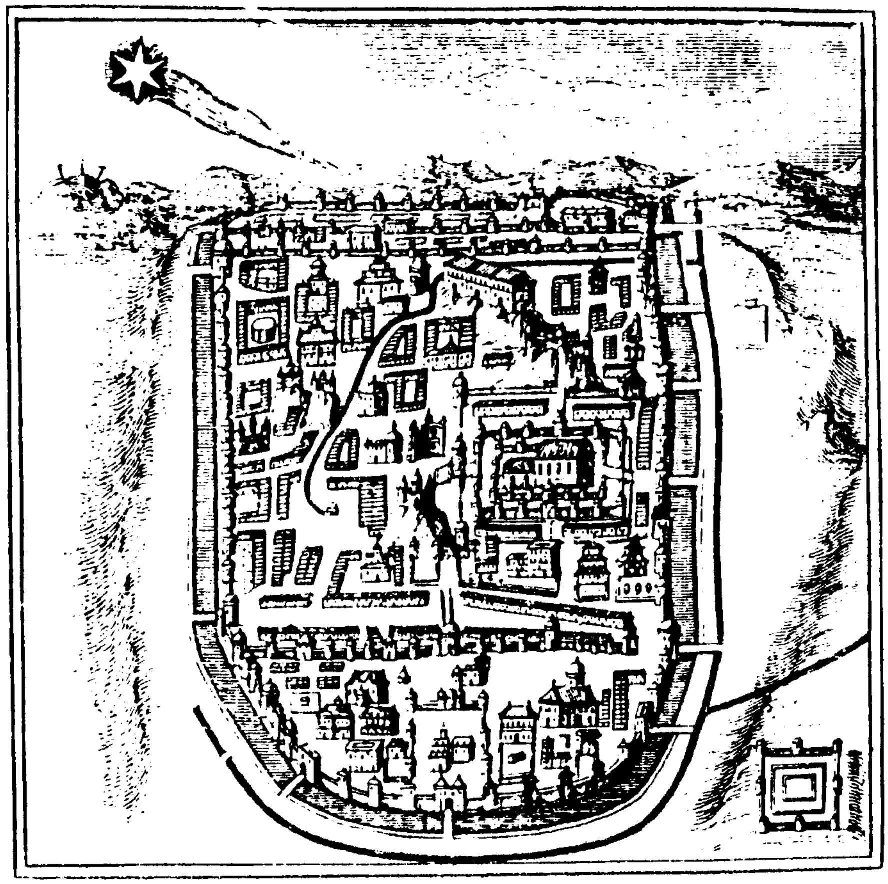

Figure 1.10.
The comet of AD 63 over Jerusalem. This was not Halley's comet, which appeared in AD 66. Courtesy of the International Halley Watch (IHW).

examined. This was comet Encke, observed for the first time in 1786, and named after the German astronomer Johann Franz Encke (1791–1865). Encke was the first to predict its return in 1822. The very short period of this comet made multiple observation possible, and Encke noticed that the period was not exactly that predicted by Newton's theory of gravity. In fact, it was about two and a half hours shorter. This slight difference could only be explained by the existence of another force, which was referred to as 'non-gravitational', its origin being unknown.

After Halley, the second great step in the history of cometary physics was made by the American astronomer Fred Whipple (born in 1906). In 1950, based on an analysis of the non-gravitational forces, Fred Whipple put forward a model to explain the nature of comets, that became famous under the name of the 'dirty snowball' hypothesis.

According to Whipple, a comet was not a diffuse aggregate of particles, as others had suggested before him, but rather a solid nucleus only a few kilometres across, composed mainly of water ice mixed with solid particles; whence the appellation 'dirty snowball'. When a comet is far from the Sun, its nucleus is too small to be observed by telescope. As it approaches the Sun, however, the side exposed to light is heated and the ice evaporates, carrying with it

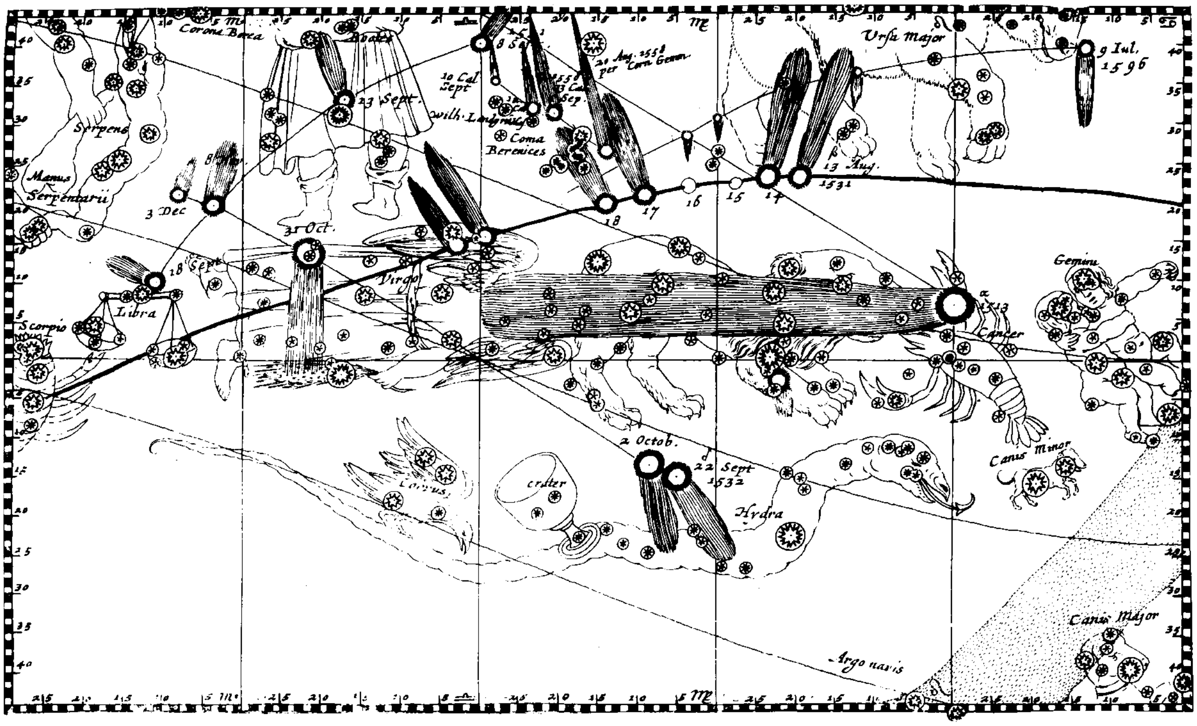

Figure 1.11.
Illustration of Halley's comet during its passage in 1531. Engraving taken from the work of Stanislas Lubienietz, *Theatrum Cometicum*, Volume 2, Amsterdam, 1667. Courtesy of the Observatoire de Paris.

any dust held within. A halo of dust is thereby formed around it, which reflects the light of the Sun and renders it visible from Earth. The sometimes spectacular variations in the appearance of comets as they follow their trajectories was thus explained. Those non-gravitational forces observed in certain comets are due to braking (or acceleration) as matter is ejected in the direction of the Sun.

It was not until 1986 that space exploration of Halley's comet could bring confirmation to Whipple's theory, although by then it had become so widely accepted that the result came as no surprise.

During the second half of the twentieth century, our knowledge of comets has gradually progressed and the great interest of these objects for the study of the Solar System as a whole has been revealed. For here are bodies which remain for most of their time at immense distances from the Sun. Some of them, such as Halley's comet, pass beyond the orbit of Neptune. Consequently, they are unlikely to have suffered any significant modification since the moment of their formation. Indeed the very weak gravity at such distances, particularly for objects of such small nucleus, would spare them any metamorphosis. Likewise, the low temperatures to which their nuclei are subjected mean that even the most volatile of their constituent molecules can remain in a solid state. The only change expected would be the loss by evaporation of an outer layer of ice and dust, each time they pass close to the Sun.

Figure 1.12.
Comet Bennett 1970 II over the Alps. IHW, photo by C. Nicollier.

Given that comets have evolved so little since their origin, they can be considered as an invaluable witness to the history of the Solar System. Moreover, such witnesses are rare. The terrestrial planets have evolved enormously, as is demonstrated by their great diversity. The Jovian planets are far away, and only their outer layers can be studied. As regards meteorites, these come from asteroids which, more often than not, have undergone numerous transformations. Hence the unique opportunity provided by these *primitive* objects, particularly since in certain circumstances they come close enough to Earth to be studied in great detail.

1.3 A unique laboratory

Apart from their interest as 'fossils', revealing the primitive composition of the Solar System, comets offer observers all the advantages of physicochemical conditions which differ radically from those prevailing in the terrestrial environment. For example, an extremely low temperature, of only a few dozen kelvins, within the nucleus; an extremely low pressure; an almost zero gravitational field; a transient cometary

Figure 1.13. opposite
Comet West 1976 VI in February 1976, photographed from Gromau in Germany. Photo by M. Grossman.