THE ORIGIN AND DISSOLUTION OF COMETS

By J. H. Oort
Sterrewacht, Leiden

[The Halley Lecture for 1986, delivered at Oxford on 1986 May 6]

Principal of Somerville, Ladies and Gentlemen:

Comets have been associated with important events in human history, often as bad omens. People were terrified by their unexpected appearance and by their fearful-looking tails. That such scares are not altogether unreasonable may be illustrated by the Meteor Crater in Arizona. The crater, which has a diameter of about 1 mile, has been made by a large meteorite which hit the Earth some 20,000 years ago. From the size of the crater it is estimated that the meteorite may have had a diameter of about 25 metres. From these numbers we can get an impression of what would happen if a *comet*, whose nucleus may have a diameter of 10 kilometres, would hit the Earth. From the statistics of comets it can be calculated that this will happen about once in 100 million years. Geologists have indeed found a number of circular structures of much larger size than the Arizona Crater, up to at least 50 kilometres, which are ascribed to collisions with large bodies at time intervals of this order. Still more interesting is the palæontological evidence that there have been periods in which many species of animals have died out, the most impressive being the disappearance of the dinosaurs at the end of the Cretaceous, some 65 million years ago. It is quite conceivable that such large-scale extinctions were a consequence of the decrease of sunlight due to the dust thrown into the atmosphere by a comet impact.

History

It had been evident from the earliest observations that the motions of comets differed radically from those of the more steadfast objects, Sun, Moon and planets. Instead of following circular orbits they seemed to move along straight paths. It was only in the beginning of the 17th century that through the great insight and the fantastic energy of the man in whose honour these Lectures were established, the true nature of cometary orbits was discovered. Halley showed that they moved along strongly elongated ellipses, and that the bright comets of 1531, 1607 and 1682 were apparitions of the same comet, which had a period of revolution of 76 years. This object, which is now known under the name of Halley's comet, has recently acquired new fame because it has been observed at close quarters from space vehicles. I shall presently give you an account of some of those observations.

Halley's comet has a long history. Its returns can be traced back over more than 2000 years. The earliest apparition established with confidence from Chinese chronicles dates from 240 B.C.; since then all its perihelion passages but one have been retraced in Chinese Annals; there are indications that even much earlier passages have been recorded. It is interesting to note that up to the 15th century almost all systematic information on comets has come from China and the Far East. However, particular accounts of striking comets are found in several places. The 1066 apparition of Halley's comet has been included in the famous large tapestry in Bayeux, made after the invasion and conquest of England by William the Conqueror in the Battle of Hastings in 1066. The 1301 return was depicted by Giotto in one of his famous frescoes in the Scrovegni Chapel in Padua in 1302. The space probe made by the European Space Agency, ESA, for an encounter with Halley's comet in the present year, was therefore named after Giotto.

Halley's comet is the only one with a long historical record. This is due to the fact that practically all bright comets have such long periods that none other has been observed more than once.

The history of the appearance of comets is an interesting subject. But this afternoon I wish to concentrate on two other aspects of comets, namely their structure and their origin.

Icy Conglomerates

Most comets move in strongly eccentric orbits. When one approaches the Sun it develops a huge halo, consisting largely of water vapour and dust particles, and extending to many thousands, or even millions, of kilometres. It is now generally accepted that this halo originates in a small nucleus, no more than a few kilometres in diameter. The dust in the halo is very dense; it completely hides the nucleus. But even if there were no dust the nucleus is far too small for its diameter to be measured from the Earth. This is one reason why it was so important to construct space vehicles which could look at Halley's nucleus from nearby and measure its actual size and shape.

Although we cannot *see* the nucleus, a lot of things became known about it. The man who has contributed most to our understanding of comets is Fred Whipple of the Smithsonian Institution. His picture of the nucleus as a conglomerate of frozen gases, predominantly water ice, in which vast numbers of solid particles are embedded has found general acceptance. It is popularly referred to as the 'dirty snowball' model. But in one respect the structure differs from the snowballs with which we used to fight as schoolboys: it lacks compactness and strength. Perhaps a better name would be snow *flakes*, but flakes of kilometre dimension.

While it approaches the Sun the comet begins to evaporate. The expulsion of matter into the coma is very irregular and explosive. At the 1910 passage of Halley's comet through perihelion major explosions occurred approximately once per day. At such an explosion a comet brightens rapidly. The velocities of the ejected streams of gas and dust can be measured. The expulsions appear to be localized in specific small regions of the nuclear surface. These 'ejections' appear to be a general characteristic of comets; but what causes the 'ejections' is still unknown.

One striking success of Whipple's work is the explanation it has given for the enigmatic systematic changes in the orbits of comets. Some comets slow down continuously in their orbits, while others are continually accelerated. Whipple showed how these decelerations and accelerations can be caused by the evaporation of ice in rotating nuclei. Owing to the rotation of the core the average momentum of the escaping gas will make an appreciable angle with the direction towards the Sun and will thus increase or decrease the orbital momentum depending on the direction of the nuclear spin relative to that of the orbital motion. Whipple and collaborators succeeded in measuring rotation periods by studying the outflow patterns. They are usually of the order of a day. In combination with the observed rate of gas production and Whipple's rough estimates of the core's mass this yielded effects of the right order to explain the observed accelerations.

Tail

Comets develop tails as a consequence of the radiation pressure exerted by the Sun on the solid particles expelled by the nucleus, as well as by the interaction between the so-called solar wind and the ionized gas in the coma. The action of the solar wind, which consists of ionized particles ejected by the Sun, leads usually to much higher velocities than the radiation pressure on the solid particles. The ionized 'rays' in the tail are thus often straight, and point away from the Sun, whereas the slower dust tails stay behind as the comet proceeds along its orbit. The solar wind is extremely gusty, being connected with the eruptions that are such striking features on the Sun. These circumstances, coupled to the eruptive nature of the comet's ejections, lead to striking, rapidly varying features in the tails (*cf.* Fig. 1).

The long tails of Halley's comet were photographed regularly for more than a month around perihelion and at the encounter with *Giotto*. They show ample evidence of the considerable activity of both Sun and comet.

Nucleus Observed From Space Vehicles

With all the information on 'streamers' and 'flares', and on the gas and dust in comets' 'atmospheres' we still know little about the actual nature of the core of a comet. The only way in which direct information can be obtained is through a space probe which can make observations from nearby. Halley's comet offered a unique opportunity. Various space agencies therefore developed vehicles for this purpose, the most important being the Soviet *Vega 1* and *2* spacecraft, which were to pass Halley's comet at distances of 8000–9000 kilometres, and the *Giotto* spacecraft, aimed at an encounter at only 500 kilometres' distance. Both projects were international; institutes of nine countries contributed to the *Vegas*; *Giotto* was a project of the European Space Agency, ESA. The *Vega* missions had the dual task of investigations on Venus and observations of the comet. The Halley campaign was further internationalized by two Japanese sondes, and by the so-called 'pathfinder' episode, when the course of *Giotto* was adjusted with the aid of the accurate positions of Halley's nucleus measured 7 and 4 days earlier by the *Vega* vehicles. Their observations were transferred to *Giotto* by means of NASA's VLBI measurements (*cf.* Fig. 2). The actual distance of closest approach attained by

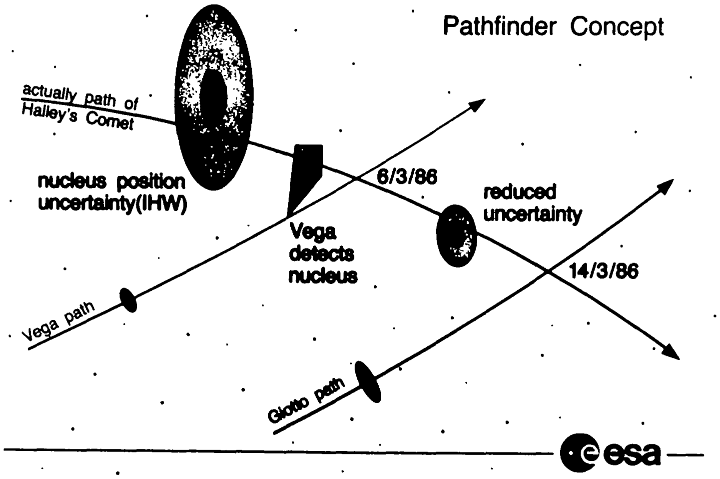

FIG. 2

Correction of *Giotto*'s motion with the aid of accurate positions of the nucleus of Halley's comet measured by the *Vega* space vehicles. (*Reproduced by kind permission of the European Space Agency.*)

PLATE I

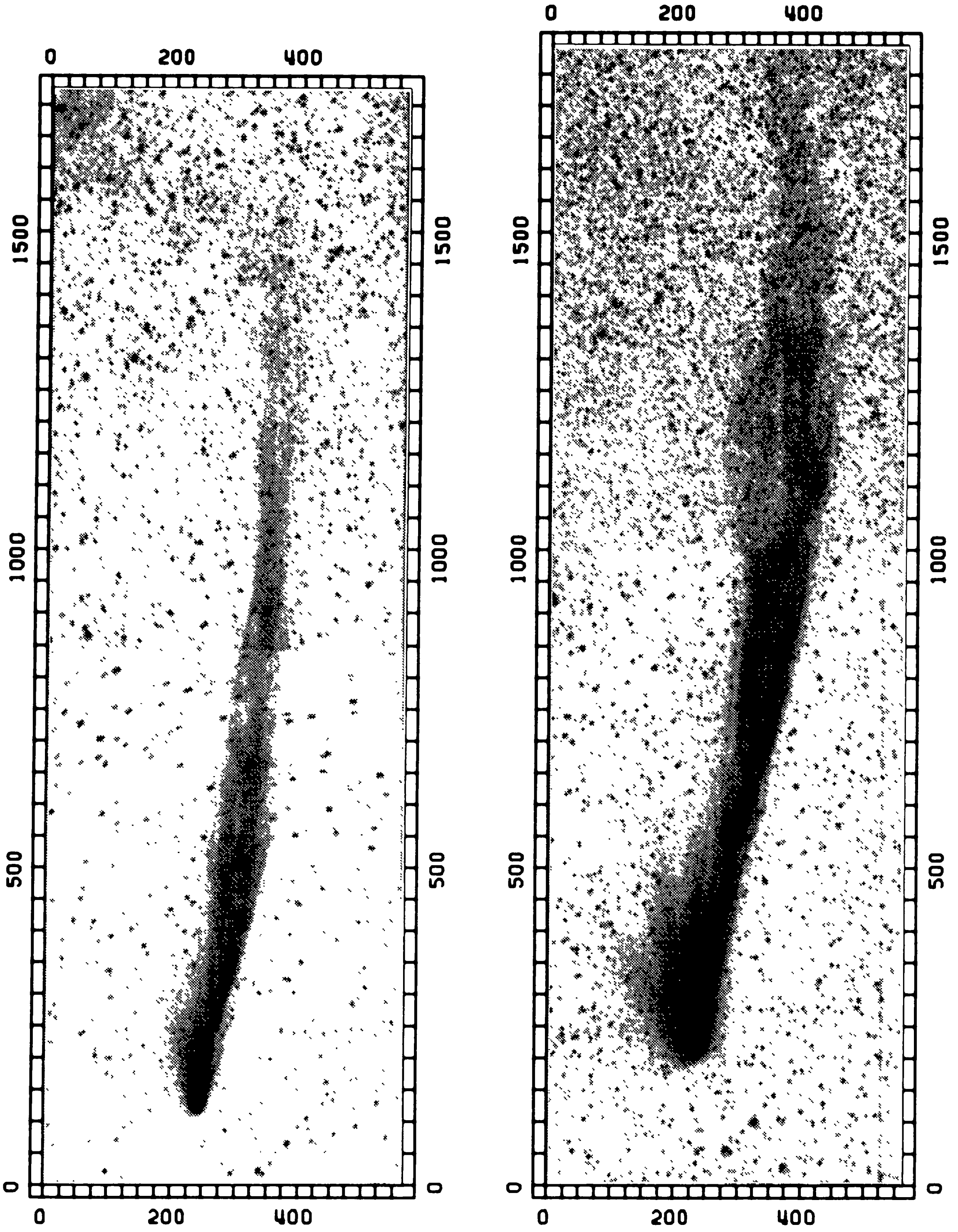

FIG. 1

The tail of Halley's comet photographed from the European Southern Observatory on La Silla in Chile on 1986 March 2/3 (left) and March 3/4 (right). The tail had a length of more than 15°, or 50 million km. (*Reproduced by kind permission of the European Southern Observatory.*)

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PLATE II

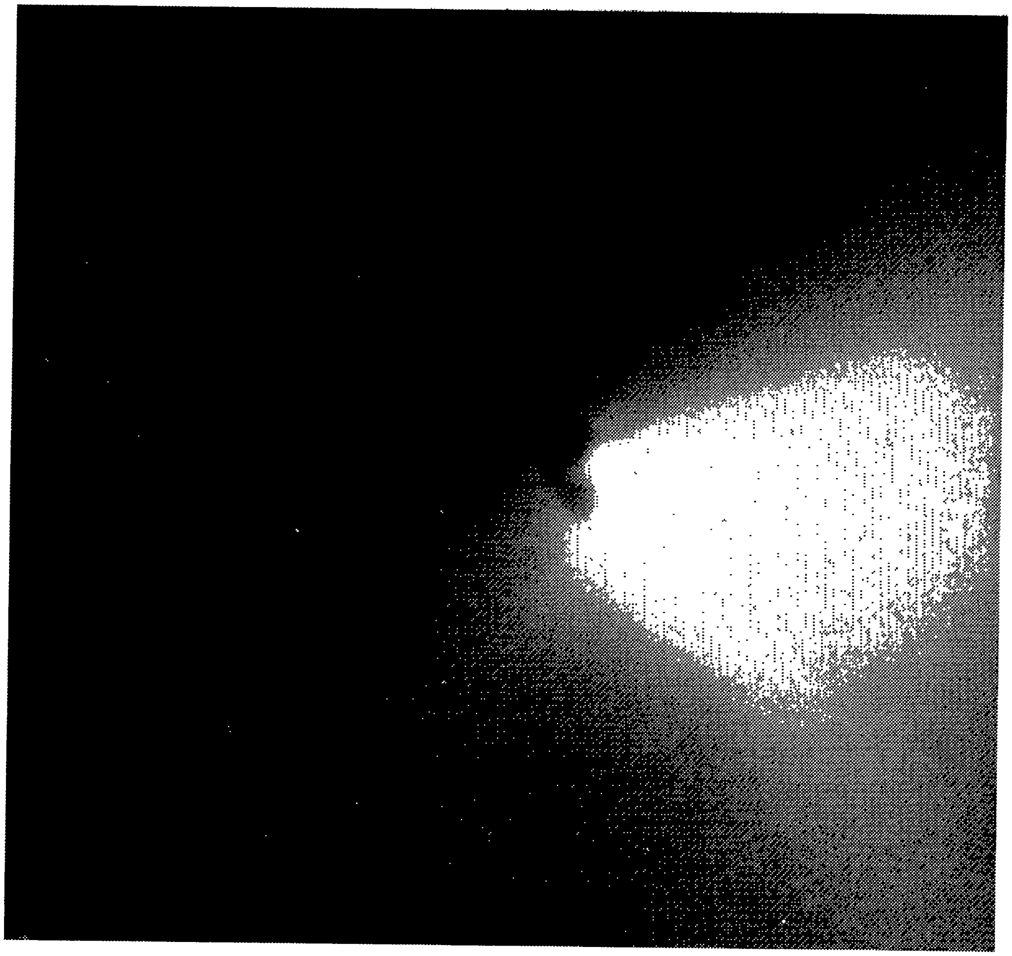

FIG. 3

This image was taken by the Halley Multicolour Camera on ESA's spacecraft *Giotto* on 1986 March 13 at a distance of 25,000 km from the Comet Halley. The nucleus is right of the centre; even the darkest part of it is clearly visible. The bright area is a dust jet, originating at the sunlit area on the nucleus. This dust jet is illuminated by sunlight coming from the direction of the lower right-hand corner of the photograph. The size of the image area is 111 km × 111 km. (*Max-Planck-Institut für Aeronomie Lindau/Harz, FRG.*)

Giotto was 600 kilometres. A serious risk for *Giotto* was the dust particles in the coma, because at the relative velocity of 68 kilometres per second even small particles could cause serious damage. The vehicle was therefore protected by a double shield which could withstand impacts of particles up to about 1 gram. Fourteen seconds before the closest approach *Giotto* was hit by a fairly heavy particle which shifted the angular momentum vector by 0°·9, and thereby impaired the radio link with the Earth for a considerable period.

Nevertheless the encounters have yielded extremely important results. In the first place the first reliable determination was made of a comet's size and shape. Both *Giotto* and the *Vega*s observed a length of 15 kilometres, and a width of about 7 kilometres. The albedo proved to be extremely low—2 to 4 per cent. The surface layer must be porous to produce such a low albedo. The *Giotto* observations showed a very irregular structure, with hills and valleys and ring structures "not unlike impact craters". There were two bright dust jets, of 10^3–10^4-kilometre size. The spin period is 53 hours. The gas production at the time of the *Giotto* encounter was 7×10^{29} molecules per second, $5{\cdot}5\times10^{29}$ of which were H_2O, with admixtures of 3·5 per cent CO_2, 10 per cent NH_3 and 7 per cent CH_4, as well as many secondary species. The *Vega*s showed $1{\cdot}3\times10^{30}$ molecules of H_2O per second. The dust-to-gas ratio varied between 0·1 and 0·25, by weight. Important data were obtained on the mass spectrum of the dust particles which ranged from 10^{-17} to 10^{-4} gram, and was proportional to $m^{-3{\cdot}5}$.

There were many other experiments, including measurements of the magnetic field and electron densities. Fig. 3 shows a picture obtained by *Giotto* of the nucleus and its ejections.

Origin

In the course of time various theories have been suggested for the origin of comets: many have held that they come from interstellar space; others proposed that they were due to ejections from the Sun; eruptions from Jupiter have also been suggested.

The natural way to approach the problem is to study their orbits. These vary over a wide range. Many have major axes of the order of that of Jupiter's orbit, and periods around 6 years. Others extend to distances of 100,000 astronomical units, with periods of tens of millions of years.

It is practical to divide the comets into two main groups, according to whether the periods are shorter or longer than 100 years. The former will be designated as short-period comets, the latter as long-period ones.

The short-period comets show a striking concentration near 6 years: 60 per cent have periods between 5 and 7·5 years; their orbits have generally small inclinations and have aphelia close to Jupiter's orbit. They are therefore referred to as the Jupiter family.

The long-period comets have radically different orbits. Not only are their orbits very much larger, but they also show no relationship to the ecliptic, being distributed at random. In order to display their characteristics at best advantage it is expedient to use the reciprocal major axes, $1/a$. This is equivalent to twice the energy of a unit mass moving along the orbit. The distribution of $1/a$, as shown in Fig. 4, is remarkable. It has a steep concentration around $3{\cdot}7\times10^{-5}$ AU^{-1}, corresponding to an aphelion distance of 54,000 AU and a revolution period of 4·4 million years. The curve falls to half its maximum value at $1/a = 1$ and $5{\cdot}5\times10^{-5}$, corresponding to aphelion distances of 200,000 and 36,000 AU respectively.

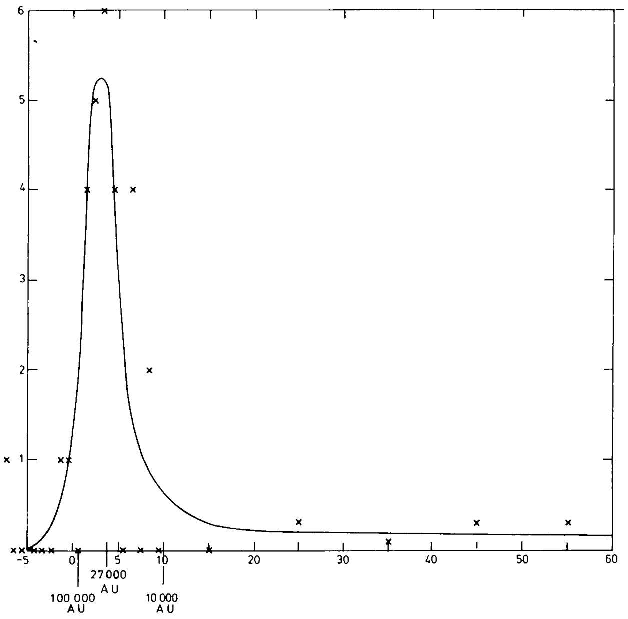

Fig. 4

Distribution of orbital reciprocal semi-major axes for long-period comets. The data are from Marsden, Sekanina & Everhart, *A.J.*, **83**, 64.

There are two slightly negative values (which would correspond to hyperbolic orbits); they are most likely due to observational errors.

Fig. 4 contains a rigorous constraint, with which any theory of the origin of comets has to comply. It gives indeed a formidable restriction.

We see that long-period comets come principally from a region between roughly 40,000 and 200,000 AU distance from the Sun. As the distribution of the aphelion directions is practically isotropic (*cf.* Fig. 5) the region is essentially a spherically symmetric, very thick, shell.

But how did the comets get there?

It is hardly conceivable that they were formed in such a region where the density in the pre-solar nebula would have been far too low to build structures of kilometre dimensions, such as comets. It is much more plausible to assume that the comets were born in the same region as the planets, by a gradual coagulation of small particles.

In order to grow *icy* conglomerates the region should lie at sufficient distance from the protosun for water to be able to condense. We may think of distances like those of Saturn or Uranus.

While the *large* conglomerates, the planets, came to move in stable near-circular orbits, motions of the smaller bodies may well have been less perfectly circular and therefore susceptible to expulsion by the planets. Some comets will leave the Solar System as the consequence of a single encounter with a planet, but in most cases they will be gradually diffused into larger and larger elongated orbits. The planetary perturbations will principally affect the major axes. However, when the orbits have become so large that the aphelia extend to a distance where perturbations by surrounding stars and gas clouds become appreciable, *all* orbital elements will become affected. In particular the perihelion distance can then be

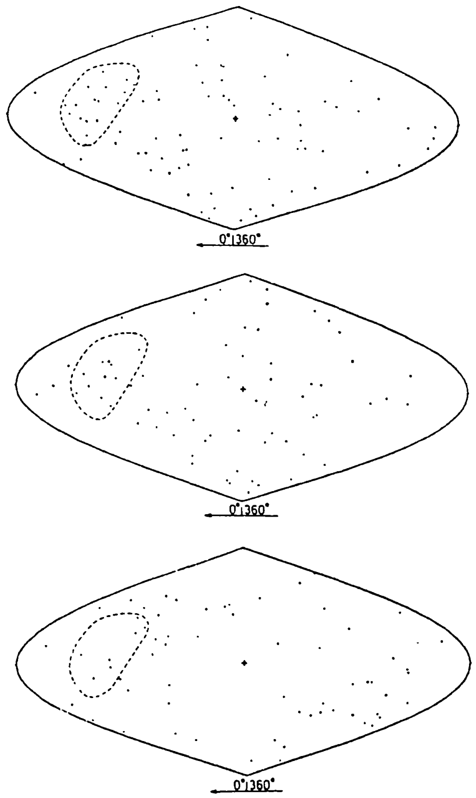

Fig. 5

Distribution of orbital aphelia of long-period comets in Galactic co-ordinates (equal area plots).

Upper: New Comets ($a > 10^4$ AU, periods 10^6–10^7 y).

Middle: Intermediate (a 400–10,000 AU, periods 8000–1,000,000 y).

Bottom: Old Comets (a 40–400 AU, periods 250–8000 y).

(From Rhea Lüst, *Dynamics of Comets: Their Origin and Evolution* (1985) eds A. Carusi and G. B. Valsecchi.)

The dotted curve indicates a clustering ascribed by Biermann & Lüst to action of the recent passage of star.

changed sufficiently to prevent the comets from returning to the inner part of the Solar System. They are then released from further planetary perturbations (which were of a larger order than the *stellar* perturbations). It can be shown that this will happen when the orbits have come to extend to approximately 30,000 astronomical units.

At that stage some of the comets are caught in a 'trap', where they will remain semi-permanently, only to be released on a long time-scale by the continuing small stellar perturbations. This comet trap has the shape of a roughly spherical shell, the inner surface of which lies around 30,000 AU. At the outer side it will gradually thin out owing to the increasing probability of 'evaporation' by stellar perturbations. Half-density may lie around 100,000 AU. This region between about 30,000 and 100,000 AU, or between $1/a$ of 2×10^{-5} and 7×10^{-5}, is just that from which the long-period comets are observed to come. The coincidence can hardly be accidental. It is a strong indication that comets have indeed originated in a way like that I have sketched.

After their capture in this shell the cometary orbits will be gradually randomized by the continuing stellar perturbations. The inclinations and aphelion directions of long-period comets are indeed observed to be distributed at random, as shown in Fig. 5. The small uneveness that is present in the Figure can be attributed to the effect of 'recent' passages of stars or dense molecular clouds. There is a probably significant avoidance of low Galactic latitudes. It has been shown that this can be attributed to the gravitational field of the Galaxy.

It is evident from Fig. 4 that the observed comets have not come from interstellar space. If they had, their orbits would have been hyperbolic, with $1/a$ of the order of -1. No such comet has ever been observed.

The comets we now see, and of which the original orbits are distributed as indicated in Figs. 4 and 5, will generally never be seen again; approximately half will be perturbed by the planets into hyperbolic orbits, the others into orbits with larger values of $1/a$, where they will be gradually diffused into the domain of short-period comets and will ultimately disintegrate.

The number of comets in the cloud can be estimated from the frequency with which long-period comets pass through perihelion. It is found to be of the order of 10^{11}.

A rough estimate for the average mass of a comet may be derived from the *Giotto* and *Vega* measures of the dimensions and albedo of Halley's comet. These yield a mass of roughly 4×10^{16} grams. As an *average* comet will be at least an order of magnitude less luminous a plausible average mass may be of the order of 10^{15} grams, leading to a total mass for the comet cloud of 10^{26} grams, or 1/60 of the Earth's mass. Since the cloud is continually losing members owing to perturbations by passing stars and interstellar clouds the initial mass must have been rather larger.

Lifetime of the Comet Cloud

Estimates of the cloud's lifetime have diverged, owing to our incomplete knowledge of interstellar clouds. The discovery of the giant molecular clouds led at one time even to the belief that the entire comet cloud would be disrupted in a time shorter than the age of the Solar System, and that it therefore must have been formed anew since the epoch of the Solar System's birth. More recent observations (among others, by means of gamma-rays) have indicated that the molecular clouds as well as their internal condensations are less massive than had been initially assumed, and that the comet cloud can well have survived from the birth epoch of the planetary system, as originally conceived.

This is reassuring, since disruption of the cloud would have necessitated subsequent replenishment, which appears hardly possible. It had been suggested that the cloud might have been replenished by capturing comets from dense molecular interstellar clouds. However, the probability of capture is vanishingly small. The only realistic scheme would be to have it replenished from a reservoir conserved within the planetary system, and dating from the time of the birth of the Solar System. But there is no sign of the existence of such a reservoir, and it is not clear how it could have originated.

Evolution

The loss of comets occurs in two directions: most are thrown out, others are thrown back into the inner region of the Solar System. These latter will gradually further diffuse inward, in the same way as they had initially been diffused outward. It can be shown that if there were no fading or fission the diffusion would result in a distribution of $1/a$ where, except for the first interval, the number of comets per unit interval would become the same for all intervals. In reality comets do disappear during the diffusion processes, by their gradual evaporation, or, sometimes, by splitting and subsequent disintegration. As a result the $1/a$-distribution must decrease with increasing $1/a$. The table, giving the number of orbits per interval of 0·00005 AU^{-1} (with the observed numbers in each interval in parentheses), shows that such a decrease is indeed observed. The data are from an earlier investigation. No attempt was made to include modern orbits, because for the present purpose no great orbital accuracy is required. The decline in the

Observed distributions of 1/a

$1/a(AU^{-1})$	P(yrs)	distribution
0·00000–0·00050	>90,000	3·9 (24)
·00050 ·00100	30,000–90,000	0·7 (3)
·00100 ·00200	11,000–30,000	0·20 (7)
·00200 ·00400	3950–11,000	0·18 (8)
·00400 ·01000	1000– 3950	0·058 (12)
·01000 ·02000	354– 1000	0·023 (16)
·02000 ·04000	126– 354	0·007 (10)

frequency is considerable: between the second and the last line it diminishes by a factor of about a hundred.

The orbit of Halley's comet, with $a = 18{\cdot}3$ AU, period 76 years, lies just below the last line of the table. The comet is, in the comet time-scale, approaching the end of its life.

A rough idea about the average lifetime of a comet can be obtained from the quantity of gas and dust evaporating during its perihelion passage. Another estimate can be made from the observed number of splittings of comets. From the very scanty data it appears that the probabilities of a comet disappearing by evaporation and by disintegration through rupture are comparable.

The lifetimes found are just of the right order to explain the observed decrease in the frequency distribution of $1/a$. This fact gives significant support to the general model of cometary evolution described in the present lecture. There is, however, one striking discrepancy: the anomalously high frequency in the first interval. This shows that some 90 per cent of the 'new' comets, which return for the first time to the inner part of the Solar System, will not be seen again at subsequent returns, owing either to a radical decrease in intrinsic brightness or to an anomalously high percentage of splittings. As regards the first, it has been observed that the variation of brightness with distance from the Sun for new comets differs markedly from that for old comets; the new comets vary more slowly. As regards the splittings, we do not know why comets split, but according to Whipple there is some statistical evidence that "new comets are nearly ten times more vulnerable to splitting than old, staid comets".

A few words must be added about the short-period comets, in particular those belonging to the Jupiter family. A plausible scenario is that these were 'caught' by Jupiter from the inward diffusing stream. But it has not yet been entirely established that this could yield the observed size of the family.

My lecture tonight is a sequel to another Halley Lecture, on "Origin and Development of Comets" (*The Observatory*, **71**, 129), which I gave 35 years ago. In that lecture a more fitting tribute has been paid to the two great men, Newton and Halley, who unravelled the true nature of cometary orbits.

By far the greatest extension of our insight into the nature of comets in the period between the two lectures has come through the development of the icy-conglomerate model by Whipple and his associates (F. L. Whipple, *The Mystery of Comets*, Smithsonian Institution Press, 1985), and from the wonderful confirmation of this model supplied by *Giotto* and the *Vega* space vehicles (*Nature*, **321**, 259). I am particularly indebted to Dr. Reinhard and Dr. Lüst for providing pre-publication information.

The work by Marsden, Sekanina and Everhart (*A.J.*, **83**, 64 and **88**, 135) on the original orbits of comets has contributed substantially to our insight into the origin of comets.

I wish to express my indebtedness to W. B. Burton for valuable discussions on the statistics of molecular clouds.