PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The History of Halley's Comet [and Discussion]

D. W. Hughes, P. H. Fowler, Bernard Lovell, D. Lynden-Bell, P. J. Message and J. E. Wilkinson

Phil. Trans. R. Soc. Lond. A 1987 **323**, 349-367
doi: 10.1098/rsta.1987.0091

Phil. Trans. R. Soc. Lond. A **323**, 349–367 (1987)
Printed in Great Britain

The history of Halley's Comet

BY D. W. HUGHES

Department of Physics, University of Sheffield, Sheffield S3 7RH, U.K.

The history of Halley's Comet can be approached in three ways. First we can start with the origin of the comet and follow it through its sojourn in the Oort cloud, its transition from a long period orbit into a relatively short-period orbit until we finally arrive at its present position as a typical middle-aged comet with a large associated meteoroid stream. Secondly we can retreat from four and a half thousand million years of history to a mere two thousand years and we can start our history with the first known record made of Halley's Comet by mankind. In our third approach we can wait until the comet actually received its name, a christening for which we must thank French mathematical astronomers, and then we can chart its highlights as the first periodic comet, the first predicted cometary return and more recently as the spur to considerable scientific endeavour and government spending. This paper will review all three approaches.

INTRODUCTION

Halley's Comet is justifiably famous. It belongs to that group of comets whose return to the Sun can be predicted and thus prepared for. At present this group only contains about 120 members and P/Halley (the prefix P indicating that its orbital period is well known) is the most active, one of the largest and is intrinsically the brightest. It has been seen with the naked eye at each of its previous thirty apparitions and has been brighter than the brightest star in the northern sky in A.D. 374, 607, 837 and 1066. It's brightness near perihelion is such that, in any random selection of historic comets, P/Halley appears at the frequency of about 1 in 8.

The fact that the orbital period of P/Halley is about 76 years, close to our allotted time span of 'three score years and ten', makes its perihelion passage a 'once in a lifetime' phenomenon for most of us. It is not commonplace like Comet Encke, which returns every 3.3 years. Nor is it like Comet Kohoutek speeding past in 1973 not to return again for around 70000 years when it will be long forgotten and probably unrecognizable. P/Halley punctuates history regularly and remorselessly, a celestial exclamation mark every 76 years.

A third reason for the scientific and popular excitement engendered by the return of this comet is associated with the man after whom it was named. The large majority of comets are named after their discoverers. P/Halley is one of the few exceptions. Dr Edmond Halley, M.A., LL.D., D.C.L.(Oxon), R.N., F.S.A., F.R.S., was, in my opinion, England's second greatest scientist (see Hughes 1985*a*) and the man who, in June and July 1696, reported to the Royal Society that the comets of 1607 and 1682 had similar orbits and were probably returns of the same Solar-System minor body. Halley was the first man to calculate the orbit of this comet (see Hughes 1985*b*), the first to prove its periodicity and the first to predict its (and any comets) return. Edmond Halley and his comet stand at the watershed of cometary science. Before his time, comets were regarded as evil omens, the precursors of doom, disaster, disease and the death of kings. Their physical nature, chemical composition and orbits were unknown. Isaac

Newton showed the world how to calculate the orbit of a comet; Edmond Halley applied this technique to the data of twenty-four comets. He proved that one comet was periodic and as such was predictable. He also surmised (erroneously as it turns out) that the comets of 1661 and 1680 were also periodic (129 a and 575 a respectively) and regarded all comets as being members of the Solar System (as opposed to interstellar).

Comets are usually divided into two groups. Long-period comets have periods in general between 10 ka and 10 Ma with aphelia a considerable distance from the planetary system, in that region of astronomical deep freeze between the Sun and its neighbouring stars. These comets have orbits which are inclined randomly to the plane of the Solar System. Short-period comets have been captured from the long-period group usually by the gravitational field of Jupiter. The mean short-period comet has an orbital inclination to the ecliptic plane of 10°, a period of 6.5 years, an aphelion distance of 5.5 AU, a perihelion distance of 1.5 AU and a dirty-snowball nucleus of diameter less than 0.8 km (see Hughes 1982, 1985*c*). The mass loss suffered by a comet during perihelion passage is a function of its size and the perihelion distance of its orbit. Typically a known short-period comet will lose between 1 and 0.1 % of its mass at each apparition. So short-period comets are decaying quickly and have a finite lifetime.

P/Halley is a non-typical short-period comet. Its nucleus is considerably larger than average and its period of 76 years puts it into an intermediate class between the mean short-period and long-period comets. The orbit has a higher than average eccentricity, which, at aphelion, finds the comet out beyond the orbit of Neptune and 10 AU below the ecliptic. The most unusual feature is the inclination, 162°. Halley's Comet has a retrograde orbit moving around the Sun in the opposite direction to the planets and the vast majority of short-period comets. The nucleus of P/Halley is only active when the comet is closer to the Sun than about 6 AU. For three years, centred on perihelion passage, the nucleus surrounds itself with a gaseous dusty coma; for two months before and five months after perihelion passage the coma is accompanied by a tail pointing in the antisolar direction. For the remainder of its period the comet is 'dead'.

The total history

The origin of comets is still somewhat of a mystery. The subject has been reviewed recently by Bailey *et al.* (1986). Two main classes of theories are prevalent now. In one, comets were formed just before the planet-building that took place in the nebula of gas and dust that surrounded the early Sun. We can go one step further and suggest that comets are the remnants of a disk of planetesimals, some of which accreted to form the major planets Saturn, Uranus and Neptune.

As the solar nebula evolved, dust, gas and ice became concentrated in an equatorial plane. The temperature gradient across this disc was such that between Saturn and Neptune the main constituents were dust and snow, the former having a composition similar to carbonaceous C1 chondrites and the latter being mainly H_2O snow but containing many impurities such as CO_2, NH_3, CH_4, these probably being trapped in the H_2O matrix as clathrates. The dense equatorial disc consisted of dirty snow particles orbiting the Sun on circular, direct coplanar trajectories. Interparticle velocities were low and collisions led in the main to accretion. This process is summarized in table 1. The loss of mass during this planetary aggregation is considerable and this mass loss is all in the form of dirty-snowball planetesimals having sizes

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

TABLE 1

(The accretion of Uranus and Neptune took place in a dust ring centred on the Sun, inner radius *ca.* 15 AU, outer radius *ca.* 40 AU, thickness *ca.* 0.1 AU; the growth of these planets is illustrated below; the mass loss during this process was in the form of cometary nuclei.)

mass of largest planetesimal/g	number of bodies	timescale of aggregation/a	total mass of ring region/g
10^6	10^{25}		10^{31}
		10–100	
10^{14}	10^{16}		10^{30}
		1000	
5×10^{21}	4×10^7		
		10^6–10^7	2×10^{29}
4×10^{27}	50		
			2×10^{29}
10^{29}	2 (i.e. Uranus and Neptune)	3×10^8	2×10^{29}

ranging up to around 10^{22} g. These planetesimals are cometary nuclei. Orbital perturbations induced by close encounters with growing protoplanets led to three general results. The new comets could be perturbed into short period orbits of low perihelion distance. Here they decayed quickly. The comets could be perturbed into parabolic orbits, in essence being thrown out of the Solar System and condemned to a life wandering through the galactic disc in and out of the gravitational potential wells of other stars. A small percentage of the comets would be given slightly less than parabolic energies. Their orbits would have perihelia in the Saturn–Neptune region and aphelia between 2×10^4 and 2×10^5 AU from the Sun. These comets would return to the Sun with periods of between 1 and 10 Ma. As their perihelia were beyond 10 AU they would be inactive having no coma and no mass loss. This cloud of comets surrounding the Sun is named after its main proponent Oort (1950). Their numbers would be depleted either by comets being pulled away from the Sun by passing stars or by being perturbed into lower-perihelion-distance orbits in which they started to lose mass when close to the Sun and were in danger of being captured by Jupiter.

Jovian-capture is not a speedy process and usually takes tens of close planetary passages. During this time the eccentricity is lowered until the comet is finally perturbed into a short period orbit which has an aphelion at Jupiter's orbit as opposed to a perihelion.

The second class of origin theories has comets formed in the interstellar medium and specifically in giant molecular clouds close to regions of star formation. McCrea (1975) suggested that, under certain circumstances, the gas and dust in these regions could decouple from one another and the dust (with associated ice) could then satisfy the Jeans criterion. This being so, the gravitational energy of the region would exceed the thermal energy, leading to this specific region of the interstellar medium collapsing and forming a dirty-snowball aggregate; a cometary nucleus. These new comets are then captured by the Solar System during its passage through the giant molecular cloud. The capture process becomes more efficient if the relative velocity between the Sun and the cloud is low and the spatial density of comets in the cloud is high. As the Sun orbits the galactic nucleus it can thus augment its family of comets each time it passes through a giant molecular cloud. If, however, all the comets were formed at the dawn of the Solar System, the total number will have been decreasing ever since.

Both theories have the comets originating in giant molecular clouds, the first being the parent of our Sun and planets, the second being younger.

The next major highlight in the career of P/Halley was its capture by the planets from a long period, near parabolic orbit into its present day, near stable, inner Solar System orbit. As soon

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

as the perihelion distance of the comet was reduced to bring it into the inner Solar System it started to decay profusely at each close passage of the Sun. Gas and small dust particles (mass up to 10^{-9} g) lost by the comet leave the Solar System and feed the interstellar medium. Large dust particles ($m > 10^{-9}$ g) leave the comet at lower relative velocities and move in orbits that have parameters very similar to those of the parent comet. These particles slowly gain on or fall behind the comet until, after a few thousand years in P/Halley's case, they form an annulus of dust around the comet's orbit. Twice a year the Earth intersects the stream of dust produced by the decay of P/Halley, once in late April and again in mid-October. The geometry is shown in figure 1. As indicated, the annulus of dust is broad, and the comet and mean stream orbits are separated by a few degrees.

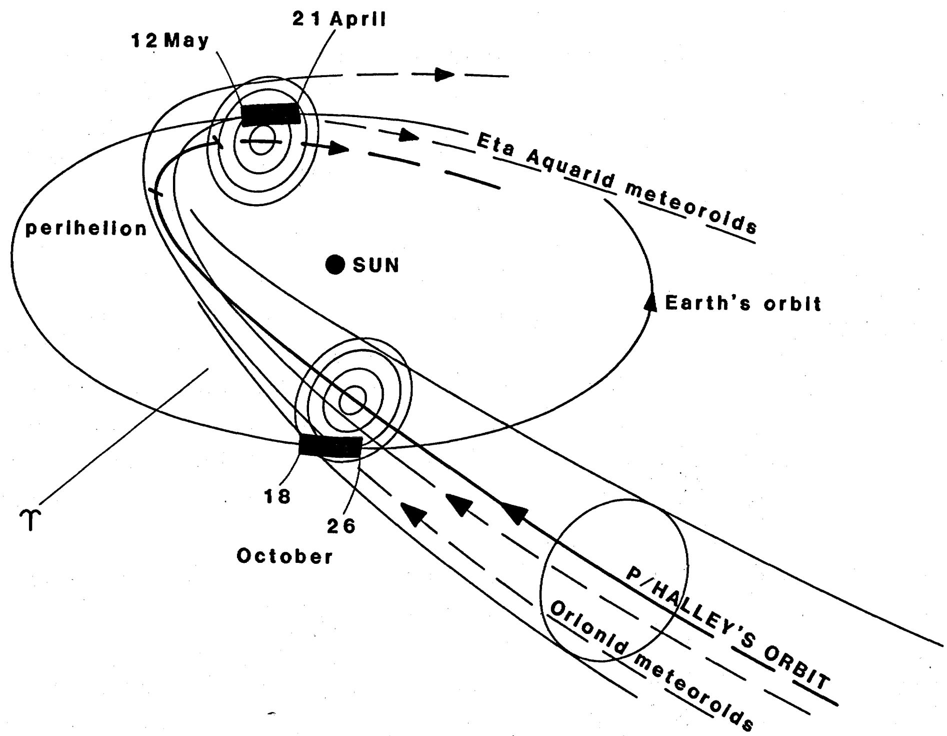

FIGURE 1. An annulus of dust surrounds the orbit of P/Halley and has been produced by the decay of the comet at previous apparitions. Earth intersects the annulus in October, when Halley dust is 'seen' as the agent responsible for the Orionid meteor shower and in April and early May as the Eta Aquarid shower. (The dashed portions of the orbits are below the ecliptic.) In May the Earth passes within 0.065 AU of the comet orbit and in October within 0.154 AU.

The overall history of P/Halley can be assessed by measuring four quantities, the total mass of dust in the dust annulus surrounding the orbit of the comet, the size of the dirty-snowball nucleus now, the density of that nucleus and the mean mass loss of the comet over recent apparitions (see Hughes 1985*d*).

McIntosh & Hajduk (1983), using meteoroid shower observations, estimated that the spatial density in the annulus in the region that produced the maximum of the Eta Aquarid shower was 3×10^{-24} g cm^{-3}. In October the Orionid maximum spatial density was about 10^{-24} g cm^{-3}. By extrapolation the authors concluded that the density near the cometary orbit was about 5×10^{-24} g cm^{-3}. Integration of these dust densities around the whole dust annulus gave a total dust mass of the stream of about 5×10^{17} g. During cometary decay low-mass dust particles and gas are also lost by the nucleus. The assumption that there is twice as much mass in this form as there is present in large dust particles leads to the conclusion that in the past P/Halley has lost about 1.5×10^{18} g.

Observations of the nucleus of P/Halley by the multicolour camera on the *Giotto* fly-by mission (Keller *et al.* 1986) show that the mean effective cross-sectional area of the nucleus is 100 km^2, which leads to the radius of the equivalent spherical nucleus being 5.6 km. (The nucleus is irregular in shape being at least 15 km long, *ca.* 10 km wide and having an albedo of about 0.04.)

The density of the nucleus is not known. Comet modellists (see, for example, Newburn & Reinhard 1981) usually assume a density of 1.0 g cm^{-3}. Wallis & Macpherson (1981) concluded that the observed non-gravitational forces can only in general be reconciled with H_2O outgassing if the mean density of the dirty-snowball nucleus is below 0.7 g cm^{-3}. If the density of the nucleus of P/Halley is assumed to be 0.5 g cm^{-3} (a compromise between the density of rock 2.8 g cm^{-3}; ice 0.9 g cm^{-3} and snow 0.08 g cm^{-3}) this, coupled with a radius of 5.6 km, yields a mass of 3.7×10^{17} g. Adding this to the mass that P/Halley has lost in the past indicates that the initial mass of the comet, before its capture into the short period orbit, was of the order of 1.9×10^{18} g and its radius was 9.6 km.

It can be easily calculated from the figures given by Newburn (1981) that P/Halley at its 1910 apparition lost around 5.1×10^{36} molecules. Spectra of the comet taken in 1910 have been interpreted (Newburn & Reinhard 1981) as indicating that the gas emitted by the comet is 83.4% H_2O, the remainder being molecules of a mean molecular mass 44 u. Therefore the mean molecule mass of all the molecules leaving the comet is 22.3 u, i.e. 3.7×10^{-23} g. Thus the total gaseous mass loss during the 1910 apparition was about 1.9×10^{14} g. Following our previous assumption this is equivalent to a total gas and dust loss of 2.8×10^{14} g.

If the cometary nucleus has a radius of 5.6 km and a mean density of 0.5 g cm^{-3} this is equivalent to it losing a layer of thickness 140 cm from its surface during the 1910 apparition. Most models of cometary decay (see Hughes 1983*a*) indicate that a comet with an orbit of constant perihelion distance will lose a layer of dirty snow of constant thickness each time it passes perihelion. So for P/Halley to slim from a radius of 9.6 km to its present radius of 5.4 km would take about 3000 perihelion passages. Likewise to decay completely from its present size would take a further 4000 or so close approaches to the Sun. Assuming that the orbital period remains reasonably constant at about 76 years it can be concluded that the comet was captured by Jupiter into its present orbit some 200000 years ago and will, some 300000 years hence, disappear completely, having all decayed into the associated meteoroid stream. In cometary evolution terms P/Halley is typically middle-aged, well behaved and of steady and predictable activity.

Each time P/Halley passes perihelion it loses mass, the nucleus decreases in size and the absolute brightness decreases. The apparent magnitude of a comet follows an equation of the form

$$m = H_0 + 5 \lg \Delta + 2.5n \lg r, \tag{1}$$

where H_0 is the absolute magnitude of the comet (the magnitude it would have if seen at zero phase angle when it was both 1 AU, from the Sun and 1 AU from the Earth), Δ is the comet–Earth distance, r the comet–Sun distance and n the activity index (the molecular efflux from a comet near perihelion is proportional to r^{-n}). In the main, the index n is 4.0 and when this is used in (1), H_0 is replaced by H_{10}. If one assumes that the brightness of a comet is proportional to the surface area of its nucleus it can easily be shown that

$$\Delta H_{10} \approx -0.724\,\Delta M/M, \tag{2}$$

where $\Delta M/M$ is the fractional mass loss per apparition and ΔH_{10} is the change in absolute magnitude per apparition (see Hughes & Daniels 1983). From the figures given above, $\Delta M/M$ for P/Halley in 1910 is 7.6×10^{-4}. So ΔH_{10} is 5.5×10^{-4} per apparition.

Morris & Green (1982) found that P/Halley in 1910 had a preperihelion absolute magnitude of 5.49 ± 0.07 and a postperihelion absolute magnitude of 5.44 ± 0.05. The logarithmic mean of these values is 5.465. With brightness proportional to surface area it is found that the radius R of a cometary nucleus is proportional to $10^{-0.2H_{10}}$ and its mass M to $10^{-0.6H_{10}}$. The use of P/Halley as a typical comet gives the general relations

$$\lg M = 21.166 + \lg \rho - 0.6H_{10}$$

and

$$\lg R = 1.842 - 0.2H_{10}$$

(where M is in grams and R in kilometres and ρ is the density in grams per cubic centimetre). So P/Halley when it was first captured by Jupiter, 200000 years ago, had an absolute magnitude of +4.30 making it intrinsically only three times brighter then than it is now.

The recorded history

Until now, the earliest identifiable record of P/Halley is in the Annals of the Shih-chi. In the seventh year of Emperor Chin Shih-huang, 240 B.C., 'a broom star first appeared at the eastern direction; it was then seen at the northern direction. During the fifth month (24 May–23 June) it was again seen at the western direction' (see Stephenson & Walker 1985).

Edmond Halley (1705) recognized the comets of August–September 1682, October 1607 and August 1531 as being 'his' comet and he guessed correctly that the June 1456 comet was a previous appearance. Hind (1850) (and Laugier 1843) extrapolated backwards to include the comets of 1378, 1301, 1223, 1145, 1066, 989, 912, 837, 760, 684, 608, 530, 451, 374, 295, 218, 141, 66 and 12 B.C. Unfortunately Hind underestimated the tenacity and skill of later astronomical historians by writing 'Previous to the year 12 B.C. the accounts of comets become so vague that it would be vain to attempt to carry the inquiry into more remote antiquity'. He also made four mistakes, twice he picked the wrong comet in the year (912 and 837) and also P/Halley returned in 1222 and 607 not 1223 and 608. The long-term motion of P/Halley can be followed by using detailed celestial mechanics, including the effects of perturbations induced by close passages to the planets. Yeomans & Kiang (1981) calculate that perihelion passages occurred in, for example, September 315 B.C., September 391 B.C. and July 466 B.C. and continue back (with decreasing precision) to October 1404 B.C. From brightness considerations alone any ancient comet record has a 1 in 8 chance of being P/Halley so there is still hope for those willing to continue Hind's 'vain attempt'.

P/Halley, like all members of the Solar System does not have a fixed orbit. The pushes and pulls exerted by the gravitational fields of the main perturbing planets are continually in evidence. The orbital period, or to be more precise the time between perhelion passages, is shown in figure 2. The peaks near A.D. 374 and A.D. 1145 are due to a 2:13 commensurability

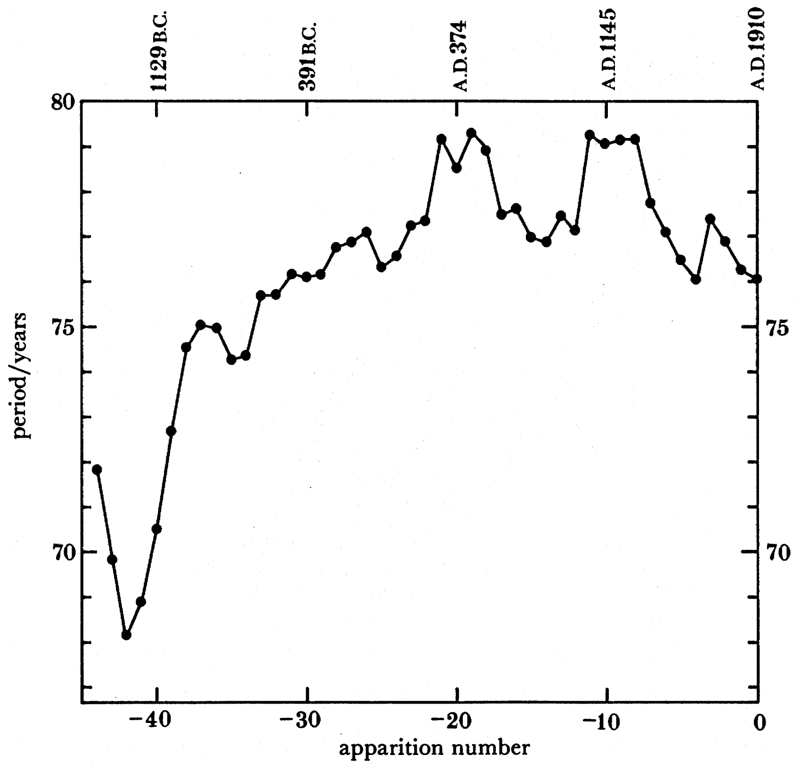

FIGURE 2. The orbital period (time between perihelion passages) of P/Halley for apparitions between 1404 B.C. and A.D. 1910 (data taken from Yeomans & Kiang 1981). So far the earliest identified record of P/Halley is that of June 240 B.C.

between the orbital periods of the comet and Jupiter. Over the past 46 apparitions the mean period has been 76.07 a. The retrograde orbit is precessing slowly and this can be seen from figure 3 in which the orbits between 87 B.C. and A.D. 1910 have been traced out in the mean orbital plane. This precession coupled with the obvious planetary perturbation helps explain why the associated meteoroid stream is so broad.

Hughes (1983 *b*) has investigated the way in which the absolute magnitude of P/Halley has changed during recorded history. This is shown in figure 4. The kindest conclusion is that the absolute magnitude has not changed recognizably during the past 2000 years and has an average value of about 5.40. If, as calculated above, ΔH is 5.5×10^{-4} per apparition, the change in absolute magnitude over the 25 apparitions shown in figure 4 would be +0.014, a value entirely in keeping with the previous conclusion.

So P/Halley has not become detectably less luminous during the past few thousand years. It's brightness as recorded by earthbound observers is entirely due to the relative position of our planet at the time of the comet's maximum activity. This is illustrated in figure 5, a diagram which is drawn in a coordinate system which has the Sun and the perihelion of the orbit of P/Halley stationary over the past 2300 years. When the comet is at perihelion the Earth is at the point shown on its orbit. Dashes interior to the Earth's orbit are roughly at monthly intervals. The comet markers along the cometary orbit are at intervals of 10 days. The tail lengths have been obtained by averaging the observations of the 1759, 1835 and 1910 apparitions. Figures above each comet marker represent the reduced magnitude M_R of the comet. The apparent magnitude can be estimated by adding 5 lg Δ to M_R, where Δ is the comet–Earth distance in astronomical units.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

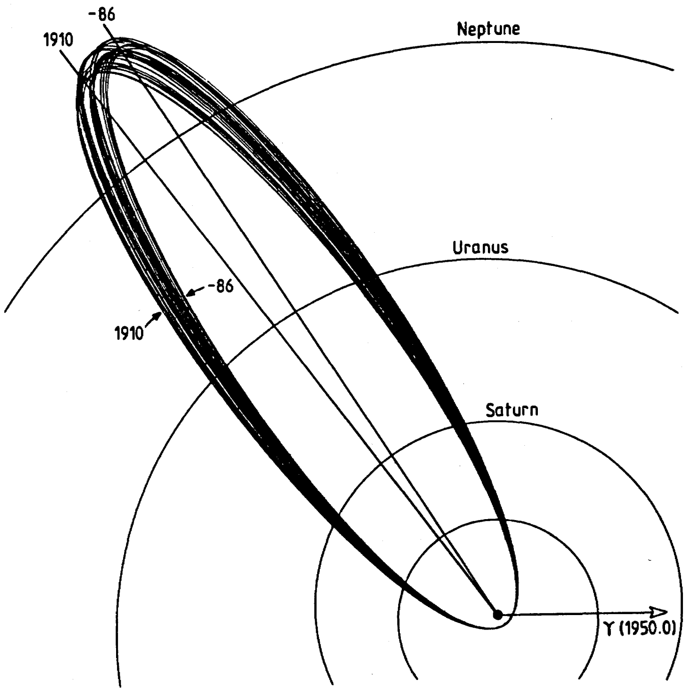

FIGURE 3. The Orbit of Halley's Comet referred to the first point of Aries at epoch 1950.0. The plane of the paper is the plane of the orbit and the curves marked Neptune, Uranus and Saturn have semimajor axes of 30.0, 19.2 and 9.5 AU, respectively, and have been drawn in that plane.

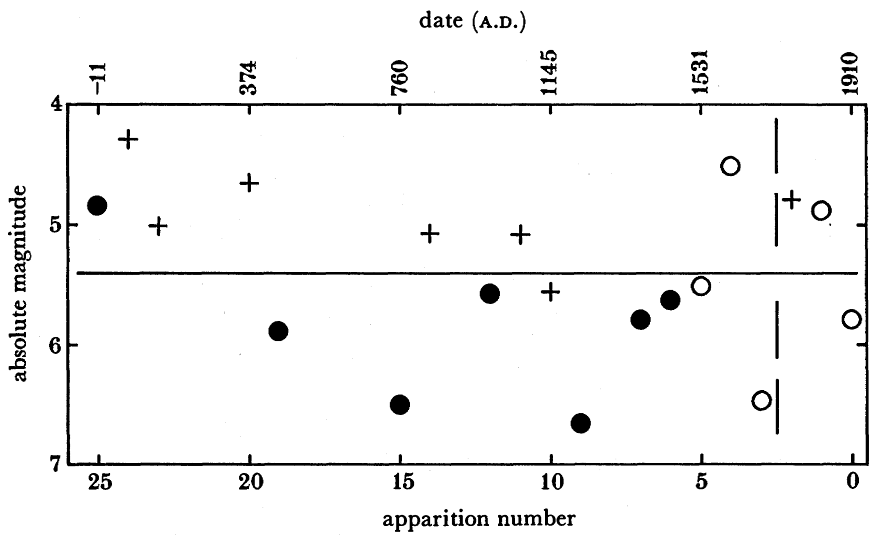

FIGURE 4. The absolute magnitude of P/Halley plotted as a function of the apparition number (1910 ≡ 0) with data from Hughes (1983*b*). Crosses refer to the postperihelion discoveries, open circles to preperihelion discoveries and filled circles to preperihelion discoveries with favourable Sun and Moon positions. The thin horizontal line represents the mean of the data. The vertical dashed line separates the unexpected from the expected returns.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

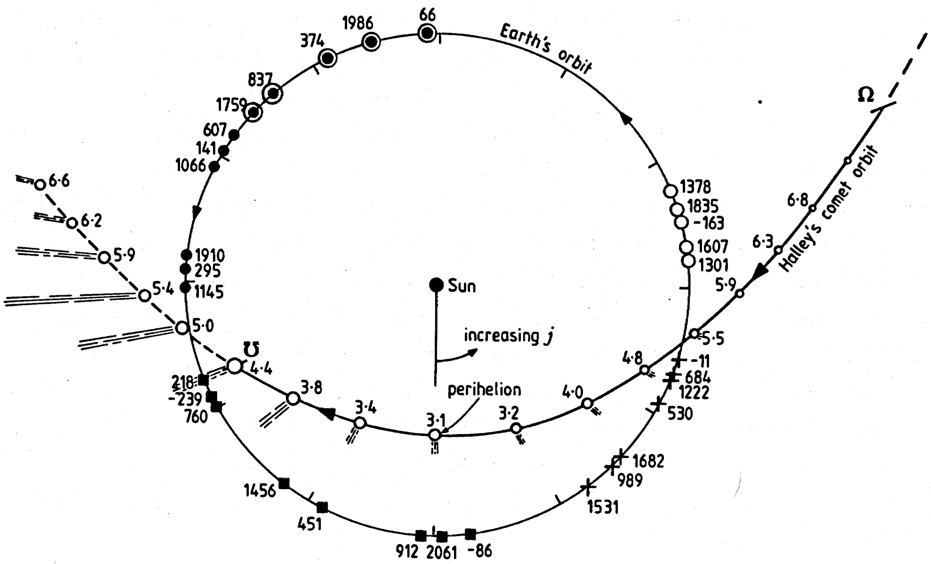

FIGURE 5. The symbols around the Earth's orbit represent the Earth's position at the perihelion passage time of Halley's Comet. Tick marks on the inside of the orbit are at approximately monthly intervals. Apparitions have been divided into five classes A, B, C, D, E. The comet is shown at intervals of 10 days along its path by a series of circles representing the size of the coma. This has a visible diameter of about 200000 km at maximum. The tail of the comet is represented to scale. The numbers above the cometary symbols are the reduced magnitudes. Apparent magnitude can be estimated by adding 5 lg Δ to this figure, Δ being the comet–Earth distance.
The angle j is the celestial longitude of the Earth minus the celestial longitude of the comet both measured at the time when the comet is at perihelion. The nodal positions given in this figure are for the 1986 apparition (see Hughes 1985*d*).

The 'spectacularness' of Halley's Comet is mainly a function of the comet–Earth distance, the rule simply being the smaller the brighter. As the comet coma and tail are more developed after perihelion passage even more spectacular displays occur when comet and Earth meet near the descending node (☋ in figure 5).

Following Bortle & Morris (1984) the apparitions of Halley's Comet can be classified according to the type of visual display. In this paper we increase their three groups to five.

Class A (○) (A.D. 1301, 1378, 1607, 1835) apparitions appear exclusively on the right of figure 5. The smallest value of the comet–Earth distance occurs well before perihelion and is typically between 0.1 and 0.2 AU. The comet is a considerable distance from the Sun in the sky and is seen as a slowly brightening object in the morning sky. Class A returns are specially favourable for observers in the northern hemisphere. Following the comet's closest approach to Earth it moves close to the Sun in the sky thus becoming very difficult to see. It remains in the vicinity of the Sun until it has faded below the naked-eye limit. The comet is usually only seen preperihelion.

Class B (+) (A.D. 1222, 1531, 1682) apparitions have their lowest comet–Earth distance (0.15–0.4 AU) just before perihelion when the comet is interior to the Earth's orbit and in the direction of the Sun. Here Halley's Comet is a morning object. It brightens quickly and is usually seen for a month preperihelion, during which time the brightness changes little. It then disappears into the solar glare shortly after perihelion passage.

Class C (■) (A.D. 218, 451, 760, 1456, 2061) apparitions occur when the comet is at or just past perihelion at the time the comet is closest to Earth. The comet is only seen with the naked eye for a short time during these apparitions. It usually appears rather suddenly and reasonably brightly as a morning object. At conjunction (i.e. when the comet and Sun have the same ecliptic longitude) the comet is north of the Sun. Afterwards it becomes an evening object, fading quickly as it becomes lost in the evening twilight. These apparitions have minimum Earth–comet distances greater than 0.4 AU.

Class D (•) (A.D. 1066, 1145, 1910) apparitions are exclusively on the left of figure 5. As seen from Earth the comet approaches from the vicinity of the Sun and is rushing towards us, hidden in the solar glare. It is first picked up by naked-eye observers after it has passed perihelion, at a time when it is most active. Suddenly it rises out of the morning twilight, its long tail beaming like a searchlight from the dawn horizon. If the closest approach to Earth occurs when the comet has a heliocentric distance less than 1 AU the comet 'disappears' as it moves to conjunction, only to reappear as an evening object. If the comet has moved beyond a heliocentric distance of 1 AU at the time of closest approach to Earth it slowly drifts from the morning sky to opposition (when it crosses the southern meridian at midnight) and finally fades away as an evening object.

Class E (⊙) (A.D. 66, 374, 837, 1759, 1986) apparitions are rather a mixed bag, the nature

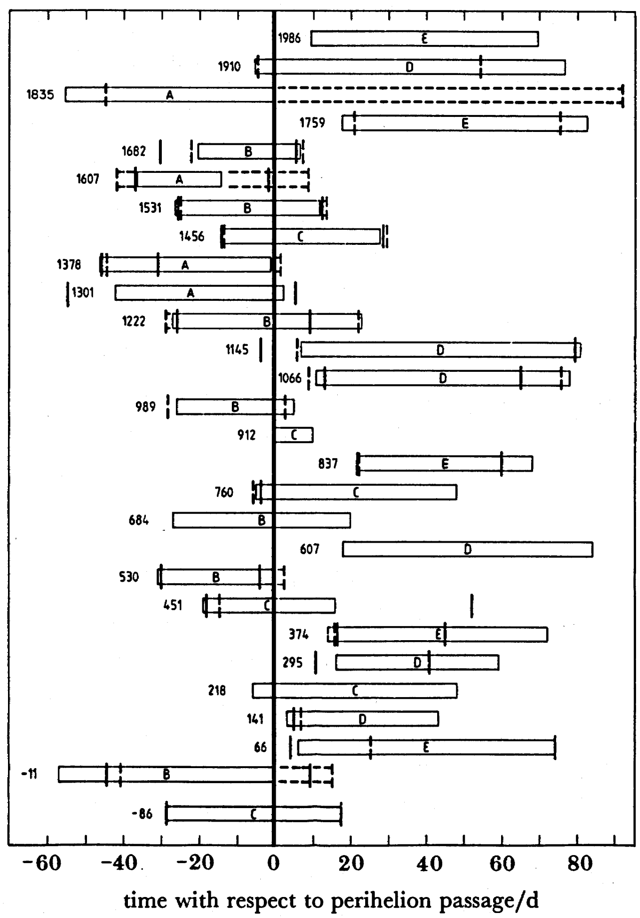

FIGURE 6. The period of naked-eye visibility of Halley's Comet at each apparition is represented by horizontal boxes. The thick central line corresponds to perihelion passage time. The five classes A, B, C, D and E are defined in figure 5. The end times of the full boxes have been taken from Bortle & Morris (1984), the heavy vertical bars from Yeomans & Kiang (1981) and the dashed vertical bars from Broughton (1979).

of the apparition depending on the position of the descending node. The minimum Earth–comet distance varies considerably, being only 0.03 AU for A.D. 837 but being 0.42 AU for the recent 1986 apparition, this later value of Δ occurring on 1986 April 11. The 1986 apparition would have stood a considerable chance of being overlooked by naked-eye observers in pretelescopic days. At its intrinsically most active phase the comet is on the opposite side of the Sun to the Earth making the return most unfavourable.

A survey of the historical records of P/Halley (Broughton 1979; Bortle & Morris 1984; Yeomans & Kiang 1981 and Yeomans *et al.* 1986) have revealed the time periods over which P/Halley has been seen (and recorded) by naked-eye observers. The periods, drawn with respect to perihelion passage time, are shown in figure 6, all data being derived from northern hemisphere observations. The five classes of observations clearly correlate with the position of Earth at the time of perihelion passage. The variation of the apparent magnitude of the comet during its periods of recorded naked-eye visibility are shown in figure 7*a*, *b*. It can be seen that the brightness varies considerably from apparition to apparition. In A.D. 837 the apparent magnitude reached nearly −4 making the comet, albeit only for a very short time, as bright as Venus. The miserly nature of the 1986 apparent magnitude curve is only too clear from figure 7*a*, *b*. The black dots on the curves in these figures indicate the times of first and last recorded sighting. These times vary considerably, mainly as a function of the class of apparition. Very roughly, the first records of classes A, B, C, D and E occurred at apparent magnitudes of 3.3, 2.8, 2.0, 0.6 and 1.8 and the last records at 2.5, 2.3, 1.8, 5.9 and 4.1 respectively. So any broad assumption of a fixed onset magnitude (as in Broughton 1979; Vsekhsvyatskii 1964) is fraught with danger.

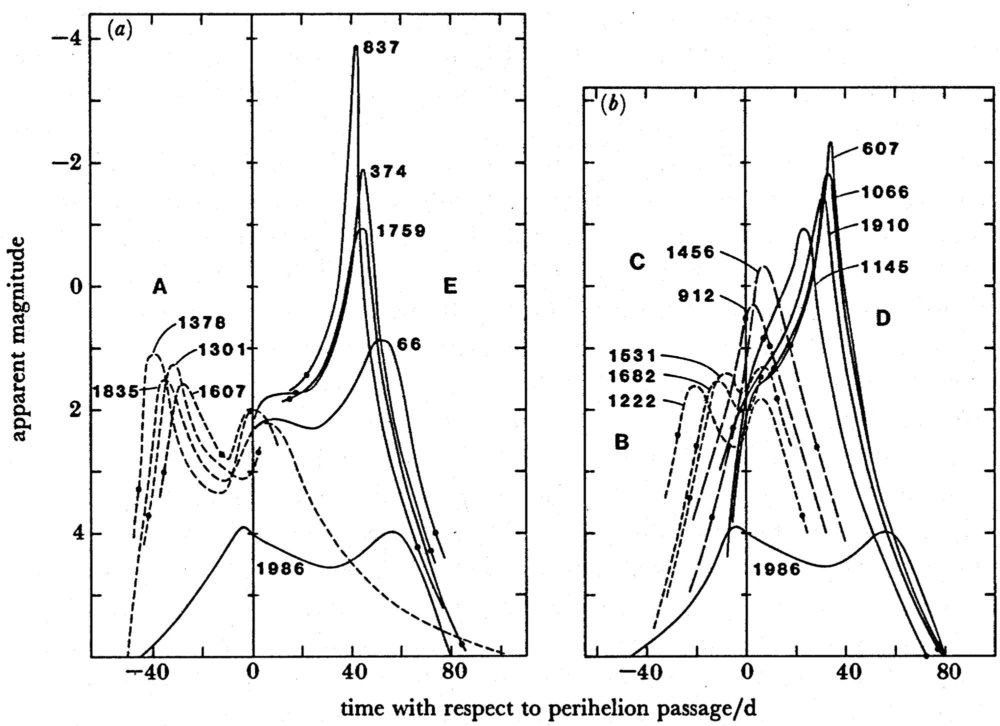

FIGURE 7. The apparent magnitude of P/Halley during its periods of naked-eye visibility plotted as a function of time with respect to perihelion passage, (*a*) for class A and E apparitions (*b*) for class B, C and D apparitions (see figure 5 for a definition) (data from Yeomans *et al.* 1986). The black dots indicate the time and apparent magnitude of the first and last recorded sightings.

The history of the named comet

The name 'Halley's Comet' seems to have been first used in France, the Abbé de la Caille (1759) being the first to suggest such an appellation, in May of that year. Charles Burney (1769) went so far as to state that 'the comet of 1759 is known throughout Europe by the name of Dr Halley's comet' and by the time of its subsequent return in 1835 this nomenclature had become commonplace.

The comet owes its prominence in scientific history to its proven periodicity. It was the *first* periodic comet, Edmond Halley recognizing that the comets of 1531, 1607 an 1682 had similar orbits and were thus probably caused by one and the same parent body returning every 76 years or so (we stress 'or so' because the period between 1531 and 1607 was 76.143 years and that between 1607 and 1682, 74.885 years). Bright periodic comets are rare. They are almost inevitably considerably fainter than the near-parabolic long-period comets. In fact, the ancient cometary records (pre-A.D. 1700) seem to contain only one periodic comet, this being P/Halley which, as we have said previously, seems to crop up at the rate of about 1 in 8. (Anyone with ample time on his hands could have great fun searching for P/Mellish (1917 I), which is the next brightest but has a period of about 145 years.) The list of periodic comets grew painfully slowly, the next additions being P/Lexell (seen only once, in 1770), P/Olbers (1815), P/Encke (recognized in 1819), P/Pons-Brooks, P/Pons Winnecke and P/Beila (recognized in 1826). By 1850 only P/Faye, P/de Vico and P/Brorsen had been added.

P/Halley was the first comet to return to the Sun as *predicted*. Edmond Halley wrote (in a later version of his synopsis, printed in Gregory (1726)) 'It is probable that its return will not be until after the period of 76 years or more, about the end of the year 1758, or the beginning of the next'. The comet actually passed perihelion on 1759 March 13.06, some 76.49 years after its previous passage. Astronomers were used to predicting planetary movement against the 'fixed' stellar background and now at least one comet could join that band of wanderers. People could look forward to its return whereas previously all comets crept up on them unannounced. The reputation of astronomy was considerably enhanced by the comet's return. An unnamed writer in *The Gentleman's Magazine* **29**, 206 (1759) wrote, 'By its appearance at this time, the truth of the Newtonian Theory of the Solar System is demonstrated to the conviction of the whole world, and the credit of the astronomers is fully established and raised far above all the wit and sneers of ignorant men'. Olmsted (1850) the professor of natural philosophy and astronomy at Yale also looked back with pride. 'So intimate is the bond which binds together all truths in one indissolvable chain, that the establishment of one great truth often confirms a multitude of others, equally important. Thus the return of Halley's Comet in exact conformity with the predictions of astronomers, established the truth of all those principles by which those predictions were made. It afforded most triumphant proof of the doctrine of universal gravitation, and of course of the received laws of physical astronomy; it inspired new confidence in the power and accuracy of that instrument (the calculus) by means of which its elements had been investigated; and it proved that the different planets, which exerted upon it severally a disturbing force proportional to their quantity of matter had been correctly weighed, as in a balance.' H. H. Turner (1908) wrote 'There can be no more complete or more sensational proof of a scientific law than to predict events by means of it. Halley was deservedly the first to perform this great office for Newton's Law of Gravitation.' 'Newton's great discovery of the Law of Gravitation, and the story of Halley's comet thus form an integral part of the most important event in the whole history of science.'

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

The prediction of the return of P/Halley led to the production of the first comet-finder charts. Figure 8 shows an example and this has been taken from *The Gentleman's Magazine* of September 1756. This monthly magazine contained news, articles of general interest, poems, history, book reviews and scientific pieces. It was published in arrears, the September issue containing September's news and letters, so the finder chart was printed over two and a quarter years

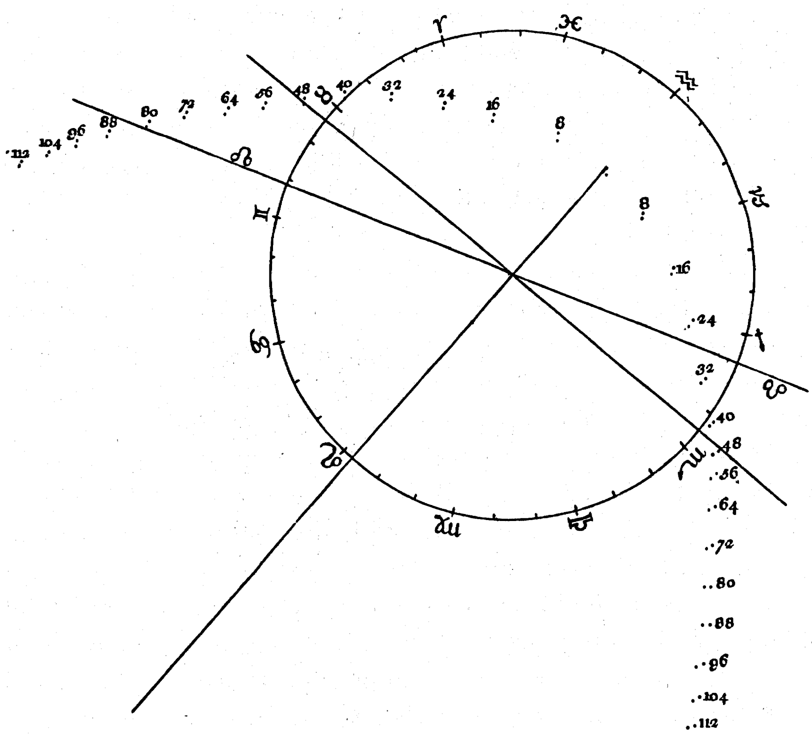

FIGURE 8. One of the first comet-finder charts. The Sun is at the centre of the large circle, which represents the orbit of Earth. The parabolic path is the projection of P/Halley's orbit in the plane of the ecliptic, the path being marked with numbers representing the position of the comet as a function of the number of days before and after perihelion passage. The ascending and descending nodes are represented by ☊ and ☋. Note that the comet moves in the opposite direction to Earth and the angle between the planes of the two orbits is 162°. To quote from *The Gentleman's Magazine* **26**, 413: 'To find the comet's place at any time, count how long it is before or after its perihelion, and mark the place in the projection of the parabola: lay one edge of a parallel ruler through that point, and also through the point of the Earth's place in its orbit at that time, and the other edge passing through the Sun, will cut the Earth's orbit at the comet's geocentric place. The tangent of the inclination, taking the perpendicular from the comet's place to the line of the nodes as radius, is the tangent of its apparent latitude, making the curtate distance of the comet from the Earth, the radius.' (The second straight line through the Sun is at *ca.* 18° to the line of nodes and is to help people without tables of tangents do this calculation.)

before the comet was first seen. It had two roles. If perihelion passage time was accurately known the chart gave the rough zodiacal position of the comet over a time interval of 224 days centred on that time. If, on the other hand, a comet had been observed on a specific date and in a specific zodiacal position the chart could be used to predict its movement across the sky assuming that it was Halley's returning comet. The chart could thus be used to check to see if an observed comet actually was P/Halley. The writer of the article also knew that P/Halley had only been seen in the past during a time interval of two to three months each side of perihelion so he used this condition to draw up a table of where the comet may expect to begin to appear in any month of the year (see *The Gentleman's Magazine* **26**, 413). People did not know when the comet was due; Edmond Halley's 'about the end of the year 1758 or the beginning of the next' had too easily slipped from the memory. Barker (1755) suggested the end of 1757!

In the mid-eighteenth century we can see P/Halley commence its role as the great spur to the calculations of accurate orbits and ephemerides. All the previous speculation as to its celestial position in 1759 would disappear if the perihelion passage time could be calculated accurately. In the 1750s the British mathematical astronomers had no time or aptitude for the task and it was left to the French. In 1958 Clairaut (Clairaut 1759) predicted mid-April 1759: the correct time was March 13.1. Preparations for the 1835 return started with Damoiseau (1820) predicting November 17.15 as the time of perihelion passage. By 1829 he had changed his prediction to November 4.81. In a series of papers Pontécoulant (1835) predicted November 7.5, 13.1, 10.8 and 12.9, Rosenberger (1835) predicted November 12.0. The comet passed perihelion on November 16.4.

The 1910 apparition was preceded by Ivanov (1909) calculating perihelion passage to be 1910 April 22.91. Cowell & Crommelin (1910) predicted April 17.11. These calculations were so accurate that the later 2.7 day discrepancy had to be explained other than by planetary perturbation, a problem that eventually led to the hypothesis of the spinning-nucleus jet effect. The main calculator for the 1986 apparition was Yeomans (1981) who included the non-gravitational forces caused by the jet effect as well as the perturbations induced in the orbit by the nine known planets. He predicted a perihelion passage time of 1986 February 9.66128. It occurred on February 9.45862 (see Yeomans 1986). Let me illustrate this paragraph by an example of one of the frustrations of science. Don Yeomans wrote to me on 18 January 1983. During the summer of 1982 he had been refining his work on the orbit of P/Halley 'Using an improved orbit determination program, I computed a new orbit based only upon the data over the 1759–1911 interval and this (unfortunately unpublished) orbit predicted a 1986 perihelion passage time of February 9.51. C'est la vie.' The despondency arose from the fact that P/Halley had been recovered on 1982 October 16 and the new observations completely vitiated calculation based only on the 1759–1911 sightings. But still, Yeomans was only 1 h 14 min out.

P/Halley's 1759 return had a negligible effect on our knowledge of the physical and chemical characteristics of comets. *The Gentleman's Magazine* **29**, 206 (1759) was 'disposed to look upon them as containing rather the materials and rudiments of habitable worlds...our earth in particular was once a comet...the Mosaic account of the creation is only an account of its reduction from that state to its present habitable form'.

By 1835 the burgeoning fame of P/Halley ensured that it was widely observed by the great astronomers of the day. F. W. Bessel, J. F. W. Herschel, W. Struve, C. P. Smyth and T. Maclear are typical examples. As is only to be expected it seems that the more they saw, the more complicated the comet appeared to be. 'Struve compared the appearance of the nucleus, about the end of the first week of October, to a fan-shaped flame emanating from a bright point; and subsequently to a red-hot coal of oblong form. On October 12 it appeared like the stream of fire which issues from the mouth of a cannon at a discharge and when the sparks are driven backwards by a strong wind. At moments the flame was thought to be in motion, or exhibiting scintillations similar to those of an aurora Borealis' (see Chambers 1910). Sir John Herschel wrote (1867) 'Although the appearance of this celebrated comet was not such as might be reasonably considered to excite lively sensations of terror, even in superstitious ages, yet, having been an object of the most diligent attention in all parts of the world to astronomers, furnished with telescopes very far surpassing in power those which had been applied to it at its former appearance in 1759, and indeed to any of the greater comets on record, the opportunity thus afforded of studying its physical structure, and the extraordinary phenomena which it presented when so examined have rendered this a memorable epoch in cometic history.'

But what was discovered in 1835, remembering that this was an era before photography and spectroscopy? The answer must be 'very little'. The comet did, however, generate a sunward jet which 'underwent singular and capricious alterations, the different phases succeeding each other with such rapidity that on no two successive nights were the appearances alike' (Herschel 1867, p. 381). These observations encouraged the solid-nucleus hypothesis and it was suggested that reactions to the jet caused the nucleus to alter its direction slightly. Also the tenuous nature of the coma was illustrated by the lack of diminution in star brightness for stars seen very close to the nucleus of P/Halley.

A lot had happened in cometary science between 1835 and the next, 1909, appearance of P/Halley. The comet of 1843 had spewn forth a 100° tail in one day and then, while passing within 100000 km of the Sun's surface, had whirled this unbroken tail round through 180° in less than two hours. P/Beila had split in two. 1866 I and 1862 II had been accused of being the parents of the Leonid and Perseid meteoroid streams. The spectroscope revealed cometary light to be made up of both reflected sunlight and a hydrocarbon spectrum supplemented by metal lines when close to the Sun. CN, C_3, CH, CO^+ and N_2^+ bands were recognized. Radiation pressure was proposed as the force responsible for tail production. The photographic plate tended to replace the eye at the telescope. 'Comet tails, formerly smooth and ghostly, hardly visible phantoms now appeared on the plates as brilliant torches with rich detail of structure, with bright and faint spots, never before seen or even suspected.'

Much was expected of the third, 1910, predicted return of P/Halley. The comet was not easily seen being unfavourably low in the northern sky during its period of maximum brightness. Barnard (1914) rather gloomily wrote 'It is safe to say that it did not give us any new information concerning these strange bodies'. It was, however, the seed of considerable collaboration between scientists and observatories, the aim being to keep the comet under continuous surveillance. The engendered enthusiasm produced a flood of data, much of which was poorly calibrated. Unfortunately the will to examine this data carefully was, in the main, lacking, and it was twenty years before a major résumé of the results was produced by Bobrovnikoff (1931).

Scientifically, the passing of the cometary nucleus in front of the face of the Sun, the sweeping of the cometary tail over the Earth and the detailed day to day photography produced excitement in cometary circles even if they didn't generate startling results. Solar transits are rare, the only recognized one before P/Halley was that of 1882 II. Nothing was seen, indicating that the cometary nucleus either had a diameter less than 50 km or was a 'bee swarm' of smaller components. The tail of P/Halley swept across Earth during 18 and 19 May 1910. To the public the comet immediately assumed the guise of a gaseous menace. The fact that cyanogen had recently been detected in the tail of Comet Morehouse fuelled the apprehension. Scientists were encouraged to watch out for abnormal atmospheric phenomena, scientific balloons were launched, meteor watches were encouraged; nothing untoward was seen. The analysis of the plethora of P/Halley tail photographs indicated that the knots of plasma were being accelerated away from the Sun with a repulsive force of around 200 times larger than that due to solar gravitational attraction. Studies of the intensity distribution in the tail led to the suggestion that fluorescence was responsible for the line and band spectra.

The 1986 apparition of P/Halley has encouraged immense scientific activity. Remember

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

that 1682 saw the first telescopic observation of the comet and still in 1835 the astronomer could only rely on naked-eye observations and a drawing pad and pencil as the recording medium. 1910 was the era of photographic and spectroscopic endeavour. By 1986 not only had researchers expanded away from the confines of the visual radiation band to encompass ultraviolet, infrared and radio regions, their instruments could now leave the entombing atmosphere of Earth to travel freely into space and across space. Cometary science had not lain dormant between 1911 and 1982. The solid-nucleus model had been reintroduced. Cometary orbital analysis had produced evidence that no comet had entered the Solar System with a hyperbolic velocity thus confining them to membership of the Sun's family. Momentum transfer from a continuously flowing solar wind was found to be a sufficient source of force for ion-tail acceleration. And Oort's discovery of a parsec-diameter cometary cloud surrounding the Sun provided an ample deep freeze for storing comets.

Astronomers banded together in an International Halley Watch (see IHW 1986) an organization designed to coordinate observations and archive data. The goals were to standardize techniques where appropriate, to promote simultaneous observations by many techniques and to organize close temporal sequences of observations during the apparition.

P/Halley's reappearance 25 years into the space age has been the key to loosen the purse strings of some of the space nations. The European Space Agency has funded the *Giotto* Mission, a ten-experiment spacecraft, which flew past P/Halley on 14 March 1986 getting to within 600 km of the nucleus at 00h03 U.T. The Soviet Union funded two spacecraft, *Vega* 1 and *Vega* 2. These had fourteen experiments on board, *Vega* 1 passing within 8890 km of P/Halley on 6 March 1986 (at 07h20 U.T.) and *Vega* 2 passing within 8030 km on 9 March 1986 (at 07h20 U.T. too). Japan launched two spacecraft towards the comet, *Sakigake* and *Suisei*. Three experiments were carried between them and *Sakigake* passed within 6.99×10^6 km of the comet on 1986 March 11 (04.18 U.T.) and *Suisei* to within 151000 km on 1986 March 8 at 13.06 U.T. The initial plans for all these missions are summarized in Space missions to Halley's Comet, *European Space Agency special publication* no. 1066. The first results from the five space-probes are presented in *Nature*, **321**, 259–366 (1986). They reveal the comet to be essentially as expected. The scientists who for years had produced models of cometary environments to aid the engineers designing space-borne apparatus were not proved to be far out in their surmising. There were very few surprises. The environment was complex just as would be expected around an active source of plasma and dust set in the supersonic flow of the solar wind. At the centre of the coma was a single, avocado-pear-shaped, reasonably smooth black nucleus, again much as predicted. The amount of data returned from the combined missions was immense, a cornucopia of information that will take decades to analyse completely.

March 1986 was a memorable month in the history of cometary science and P/Halley in particular. Before that we had to stay on Earth, or close by, and peer at this three-dimensional object from afar. In essence comets were squashed flat against the background of the sky. Now for the first time spacecraft have been able to dive through an active comet. The third dimension has at last been added.

What comes next? P/Halley will return; and its path across the northern sky in A.D. 2061 can already be traced out. The observers of 1910 could not have imagined a fleet of spacecraft flying by in 1986. Why should it be any easier to imagine what the next 75 years will bring? We can however look closer to hand. We have just had our first 'distant-close' encounter with primordial material. It is certainly within our ability to rendezvous with a comet, to launch a spacecraft that will catch up with a comet and then 'get on board', keeping it company for years as opposed to flying through at around 70 km s^{-1}. Given the necessary funds the scientific space agencies can do the job. The subsequent step is sample return. In 1986 we rushed past Halley's Comet, by 2061 freezer boxes full of cometary material may be regularly being brought back to laboratories for analysis.

References

Bailey, M. E., Clube, S. V. M. & Napier, W. M. 1986 *Vistas Astron.* **29**, 53–112.

Barker, T. 1757 *An account of the discoveries concerning comets with the way to find their orbits and some improvements in constructing and calculating their places. For which reason are here added new tables, fitted to those purposes; particularly with regard to that comet which is soon expected to return.* London: J. Whiston and B. White.

Barnard, E. E. 1914 *Astrophys. J.* **39**, 373–404.

Babrovnikoff, N. T. 1931 Halley's Comet in its apparition of 1909–1911. *Univ. Calif. Publs Lick Obs.* **17** (2), 309–482.

Bortle, J. E. & Morris, C. S. 1984 *Sky and Telescope* **67**, 7–12.

Broughton, R. P. 1979 *J. R. astr. Soc. Can.* **73**, 24–36.

Burley, C. 1769 *An essay towards a history of the principal comets that have appeared since the year 1722.* London.

Chambers, G. F. 1910 *The Story of the Comets*, 2nd edn, p. 122. Oxford University Press.

Clairaut, A. C. 1759 *J. Sçavans* **41**, 80–96.

Cowell, P. H. & Crommelin, A. C. D. 1910 Greenwich Observations for the year 1909, Appendix.

de Damoiseau, T. 1820 *Memorie Accad. Sci. Torino* **24**, 1–76.

Gregory, D. 1726 *The Elements of Physical and Geometrical Astronomy*, vol. 2, pp. 881–905. London: D. Midwinter.

Halley, E. 1705 *A synopsis of the astronomy of comets.* London: John Senex. (See also (in Latin) *Phil. Trans. R. Soc. Lond.* **24**, 1882–1899.)

Herschel, J. F. W. 1867 *Outlines of Astronomy*, p. 380. London: Longmans, Green & Co.

Hind, J. R. 1850 *Mon. Not. R. astr. Soc.* **10**, 51–58.

Hughes, D. W. 1982 *Contemp. Phys.* **23**, 257–283.

Hughes, D. W. 1983*a* *Asteroids Comets Meteors. I* (ed. C.-I. Lagerkvist & H. Rickman), pp. 239–257. Uppsala Universitet Reprocentralen HSC.

Hughes, D. W. 1983*b* *Mon. Not. R. astr. Soc.* **204**, 1291–1295.

Hughes, D. W. 1985*a* *J. Br. astr. Ass.* **95**, 193–204.

Hughes, D. W. 1985*b* *Bull. Inst. Maths. Appls* **21**, 146–153.

Hughes, D. W. 1985*c* In *Dynamics of comets; their origin and evolution* (ed. A. Carusi & G. B. Valsecchi), pp. 129–142. Dordrecht: D. Reidel.

Hughes, D. W. 1985*d* *Mon. Not. R. astr. Soc.* **213**; 103–109.

Hughes, D. W. 1985*e* *Q. Jl. R. astr. Soc.* **26**, 513–520.

Hughes, D. W. & Daniels, P. A. 1983 *Icarus* **53**, 444–452.

I. H. W. Staff 1986 Space missions to Halley's comet, *European Space Agency special publication no.* 1066, pp. 161–178.

Ivanov, A. A. 1909 *Astr. Nachr.* **182**, 225–226.

Keller, H. U., Arpigny, C., Barbieri, C., Bonnet, R. M., Cazes, S., Coradini, M., Cosmovici, C. P., Delamere, W. A., Huebner, W. F., Hughes, D. W., Jamar, C., Malaiss, D., Reitsema, H. J., Schmidtt, H. U., Schmidt, W. K. H., Seige, P., Whipple, F. L. & Wilhelm, K. 1986 *Nature, Lond.* **321**, 320–326.

de La Caille, N. L. 1759 *Mémoires de mathématique et de physique, tirés des registres de l'Académie royale de sciences* 522–524.

Laugier, P. A. E. 1843 *C.r. hebd. Séanc, Acad. Sci., Paris* **16**, 1003–1006. (See also *C.r. hebd. Séanc. Acad. Sci., Paris* **23**, 183–189.)

McCrea, W. H. 1975 *Observatory* **95**, 239–255.

Morris, C. S. & Green, D. W. E. 1982 *Astr. J.* **87**, 918–923.

Newburn, R. L. & Reinhard, R. 1981 The Comet Halley Dust and Gas Environment. *European Space Agency special publication* no. 174, pp. 19–24.

Newburn, R. L. 1981 The Comet Halley dust and gas environment. *European Space Agency special publication* no. 174, pp. 3–18.

Olmsted, D. 1850 *The mechanism of the Heavens.* Thomas Nelson: London.

Oort, J. H. 1950 *Bull. astr. Insts Neth.* **11**, 91–110.

Pannekoek, A. 1961 *A history of astronomy*, p. 425. London: George Allen & Unwin Ltd.

de Pontécoulant, P. C. L. 1835 *Mém. prés. div. Sav. Acad. Sci. Inst. Fr.* (2) **6**, 857–947.

Rosenberger, O. A. 1835 *Astr. Nachr* **12**, 187–194.

Stephenson, F. R. & Walker, C. B. F. (eds) 1985 *Halley's comet in history.* British Museum Publications Ltd.

Turner, H. H. 1908 *Halley's Comet, an evening discourse to the British Association, Dublin*, 4 September 1908. Oxford University Press.
Vsekhsvyatskii, S. K. 1964 *Physical Characteristics of comets*. Jerusalem: Israel Program for Scientific Translations.
Wallis, M. K. & Macpherson, A. K. 1981 *Astron. Astrophys.* **98**, 45.
Yeomans, D. K. 1981 *The Comet Halley handbook*, 1st edn, Jet Propulsion Laboratories.
Yeomans, D. K. 1986 In Space Missions to Halley's Comet. *European Space Agency special publication* no. 1066, pp. 179–197.
Yeomans, D. K. & Kiang, T. 1981 *Mon. Not. R. astr. Soc.* **197**, 633–646.
Yeomans, D. K., Rahe, J. & Freitag, R. 1986 Space missions to Halley's Comet. *European Space Agency special publication* no. 1066, pp. 1–24.

Discussion

P. H. Fowler (*University of Bristol, U.K.*). In his figure Dr Hughes highlighted the apparition of A.D. 837 as being the brightest historical apparition. Can one expect brighter future apparitions, or can Halley even hit the Earth?

D. W. Hughes. There is absolutely no reason why P/Halley should not get closer to Earth than the A.D. 837 value (see Stephenson & Yau 1985), and the brightness at any specific apparition depends drastically on the minimum geocentric distance. It must be stressed though (see Hughes 1981 for a review) that, size for size, Earth is 46 times more likely to be struck by an asteroid than by a comet. Kresák (1978) concluded that earth would collide with a body (asteroid or comet) of a diameter greater than 1 km every 1.5–2.0 million years. For something as large as P/Halley, impacts would occur about a factor of 30 less frequently.

Additional references

Hughes, D. W. 1981 *Phil. Trans. R. Soc. Lond.* A **303**, 353–368.
Kresák, L. 1978 *Bull. astr. Insts Csl.* **29**, 103–125.
Stephenson, F. R. & Yau, K. K. C. 1985 *J. Br. interplanet Soc.* **38**, 195–216.

Sir Bernard Lovell, F.R.S. (*Jodrell Bank, Macclesfield, Cheshire*). It is believed that the η-Aquarid meteor stream which occurs early in May and the Orionid stream of October may be associated with Halley's Comet, and it is possible to estimate the mass of meteoric material in this orbit. How does this compare with the mass loss from the comet computed from the *Giotto* data?

D. W. Hughes. The comparison is not easy to make because *Giotto* only produced an 'instantaneous' dust-emission value, the instant being 1986 March 14.0 when the comet was postperihelion and at 1.44×10^8 km from Earth and 1.35×10^8 km from the Sun. Also *Giotto*, at minimum, was 605 km from the nucleus. Added to this problem is the fact that P/Halley not only has a steadily varying activity which is a function of its heliocentric distance but also has a fluctuating activity (by a factor of about six) which is a function of its spin and nutation phase. The total dust emission shortly before closest approach has been measured to be 3.1×10^6 g s^{-1}. Thankfully *Giotto* only encountered 26×10^{-3} g of dust during its fly-by, the most massive impacting particle being 1.1×10^{-3} g. If this had hit Earth it would have produced a third-magnitude meteoroid. More massive particles were missed by *Giotto* so the emission result must be taken to be a lower limit.

D. Lynden-Bell, F.R.S. (*University of Cambridge, U.K.*). Some years ago Dr Kiang gave a rather pretty explanation of the periodic variations of the period of Halley's Comet in terms of the inverse pendulum problem. Others had attributed these periods to such things as new planets in the outer parts of the Solar System. In Kiang's theory this was due to gravitational interaction with Jupiter. Is this theory of the period changes still the accepted one?

D. W. Hughes. The variations in the period of P/Halley are explicable simply by invoking the gravitational perturbations due to the known planets plus the non-gravitational forces produced by thermal lag in the thin surface layers of the rotating nucleus. As P. J. Message (Liverpool University) has shown, the main resonance is due to a 13:2 commensurability between the periods of Jupiter and P/Halley. Nothing more exotic is needed.

P. J. Message (*University of Liverpool, U.K.*). The perturbations giving rise to the long-period oscillation in the orbital period (and other orbital parameters) of the comet are those associated with the 13:2 near-commensurability of orbital period with Jupiter. There is a free-amplitude oscillation, or libration, of period about six or seven centuries (depending on the amplitude) arising solely from perturbations by Jupiter, so there is no need to invoke any undiscovered planet! (The comet appears to have moved out of this oscillation now, as is shown by a plot of the intervals between successive perihelion returns.)

J. E. Wilkinson (*Capricornia Institute, Rockhampton, Queensland, U.S.A.*). Dr Hughes suggested that comets may have been formed in the Uranus–Neptune region of the Solar System. Do not the larger amounts of water ice observed, suggest an origin closer to the Sun, say in the Saturn–Jupiter region?

D. W. Hughes. I do not wish to be over specific about the nebula region in question. Comets were probably the 'left overs' of planetary formation throughout the whole Jupiter, Saturn, Uranus, Neptune region and it is highly probable that both the gas to dust mass ratio and to some extent the gas composition varied as a function of heliocentric distance.