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P/Halley: The Quintessential Comet

Michael J. S. Belton

Summary. Halley's comet is the focus of an international scientific enterprise now under way. Ground-based astronomical observations are already yielding new information about the comet's nucleus and atmosphere. In the coming year, remote and in situ investigations from the ground, Earth orbit, Venus orbit, interplanetary space, and within the comet itself are expected to reveal much more. The climax of the enterprise will be the penetration of an armored European spacecraft into the center of the comet in March 1986.

Two Soviet, two Japanese, one European, and one American spacecraft are in interplanetary space on their way to a scientific encounter with Halley's comet. Before this "swarm" (*1*) of spacecraft reaches encounter in March 1986, a wide range of other observations of the comet will have been made to provide an essential background of quantitative scientific data on the global properties of the comet and its long-term evolution. Some 900 astronomers in 47 countries have joined together in a worldwide observational network called the International Halley Watch, and already the comet is under intense investigation. It is now in its active phase, and its brightness is increasing by roughly −0.7 magnitudes (an inverse logarithmic scale; 5 magnitudes = a factor of 100), or roughly a factor of 2, every 4 weeks. Now at a heliocentric distance of 1.2 AU (astronomical units; 1 AU = 1.496 10^{13} cm), the comet will soon be briefly lost in the glare of the sun. But by the end of February 1986, the comet will move into darker southern skies and be available for study by one of the most ambitious scientific enterprises ever.

The author is at the National Optical Astronomy Observatories, Kitt Peak National Observatory, Tuscon, Arizona 85726. The National Optical Astronomy Observatories are operated by the Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation.

Discovery and Brief History

One of the first projects that Edmond Halley completed, in his new position as Professor of Geometry at Oxford University in 1703, was the computation of the orbits of 24 comets. He noticed that three had effectively identical orbital elements and made the then novel assertion that they were the same object; that is, that some comets are periodic. He predicted that this comet would again be visible from Earth in 1759, and the comet was recovered in rough accordance with his prediction. This comet has since been known as Halley's comet (or P/Halley, where P/ denotes that the comet has a short-period orbit).

P/Halley has played a significant role in the development of astronomy. Its orbit has stimulated development of advanced techniques of handling planetary perturbations; its orbital peculiarities have been used (unsuccessfully) as a gravitational probe to explore the outer regions of the solar system for as yet undiscovered planets; its atmospheric activity (Fig. 1) led to the first suggestion that reaction forces (due to the loss of sublimating material) could be important in the evolution of cometary orbits [a concept that eventually led Whipple (*2*) to the modern view of the nature of the cometary nucleus]; finally, in anticipation of its return in 1986, it has stimulated much new research in, and support for, cometary physics because it is a particularly attractive target for exploratory space missions.

P/Halley moves in an orbit that evolves quickly on astronomical time scales. Nevertheless, its dynamical age is probably quite old compared with the 3000-year orbital lifetimes of most periodic comets (*3*). Studies of its long-term orbital behavior and brightness (*4*) indicate that its nongravitational reaction forces and perihelion brightness have shown no perceptable change for the last 2000 years. One must take the orbit back over 210 revolutions (~16,000 years) in order to find an indication that the comet had a close gravitational encounter with Jupiter, the most probable planet to have captured the comet into its present orbit. But even this would have been a very unlikely event (*5*), and it is reasonable to assume that P/Halley has been around for a long time. In the shorter terms of human history, recorded apparitions of the comet go back 28 orbital revolutions to 240 B.C. (*6*)—a record among comets.

Significance for Modern Research

There are perhaps as many as 10^{12} comets (*7*). Most exist at distances from the sun that are measured in units of 10^4 km, and their randomly oriented orbits form a huge spherical cloud bound to the sun. A miniscule subset exists in low-inclination orbits associated with the giant planets, primarily Jupiter, with periods less than 100 years. However, of all of these comets there is only one, P/Halley, that predictably shows the full range of cometary activity (atmospheric jets, halos, dust and ion tails, and so forth) and that also follows a predictable short-period orbit. It is the unique coupling of these two aspects that is the basis for the special interest in P/Halley as a target for space missions.

Most cometary nuclei are believed to have dimensions in the range of 1 to 10 km and masses near 10^{17} g (*8*), and they are not expected to have evolved appreciably since their formation (*9*). The present population of cometary nuclei probably makes up a few percent at most of

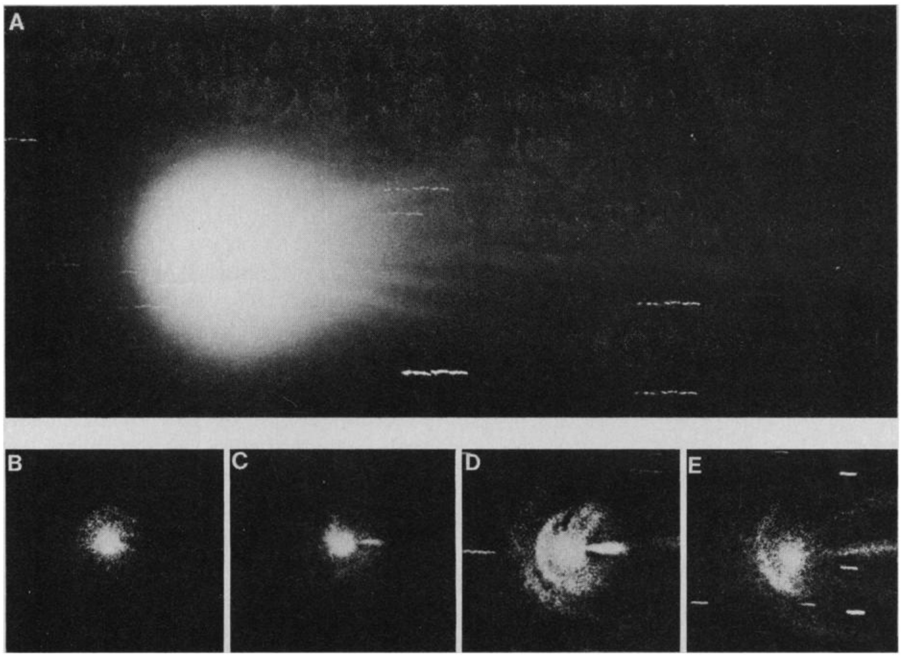


Fig. 1. (A) P/Halley as it appeared on 1 June 1910. A few days later a massive disconnection event occurred (*47*), and the plasma streaming toward the left of the picture was severed from the head. The spherical head of the comet, or coma, was roughly 220,000 km in diameter, glowing in fluorescent emission of C_2 and CN and sunlight scattered by fine dust. The tail rays are fluorescent in CO^+. [Courtesy of G. H. Herbig] (B through E) A time sequence of computer-processed, digitized photographs of the inner nuclear regions of the comet's atmosphere taken contemporaneously with the top picture. From the left the times of the pictures are 1910 May 31.2557, June 1.1915, June 2.1815, and June 3.2288 universal time. They show with great clarity active structures in the coma and the rapidity with which they change. [From (*20*)]

the mass of the planetary system; however, it is thought that, roughly 4.6 10^9 years ago when the solar system was being formed, they were a much more substantial component existing in the region of space now occupied by the outer planets. Since that time a large fraction of the nuclei has been lost to the galaxy through gravitational perturbation of their loosely bound orbits. Another large fraction has been consumed in the process of the formation of the giant planets, and a few must have collided with newly formed planets and satellites, helping to shape the surfaces that we see today and possibly in some cases implanting large quantities of carbonaceous and other volatiles.

The persuasive, albeit somewhat speculative, theoretical basis for these ideas (*10*) is the reason for the widespread conviction that studying comets will also tell us much about the early solar system. Because comets are low-mass, relatively unevolved relics of the primitive solar system, the peculiarities of their physical structure and chemistry hold the promise of yielding detailed narratives of many of the processes that occurred as the protosolar cloud collapsed and was transformed into the sun and the planetary system. Their volatile chemical composition (mainly water-ice, dust, and an unknown mixture of carbonaceous and other compounds) is a second key to their scientific significance. The gravitational escape velocity for particles on the surface of the nucleus is at most a few meters per second, and as the surface temperature rises on approach to the sun, subliming volatiles flow off, effectively unconstrained, into interplanetary space, entraining fine dust particulates in the process. As a result we are presented with an evolving and diverse set of physical and chemical phenomena that operate on linear scales of astronomical proportions as this cometary atmosphere interacts with the solar radiation field and the magnetized plasma of the solar wind. Learning the details of such processes in comets is expected to yield a more thorough understanding of many similar phenomena elsewhere in the universe.

Finally, I should stress that the chemical and physical nature of cometary nuclei is a true scientific frontier. There are few facts and much speculation. Understanding comets as comets is an important goal in itself.

P/Halley is one of a few comets that can and will be explored in situ by spacecraft in the foreseeable future. The technical success and scientific productivity of the international effort now under way will determine how fast we can move toward these goals.

New Data: Has the Nucleus Been Observed?

Since its recovery (*11*) on 16 October 1982, at a distance of 11 AU, P/Halley has been the subject of a series of intense imaging, photometric, spectrographic, and astrometric investigations that have used some of the world's most powerful astronomical instrumentation. The central issue so far has been whether or not any of the observations refer directly to the properties of the nucleus of the comet or, perhaps less significantly, to an atmosphere of dust or ice particulates that may surround it. While the issue cannot be conclusively dealt with, I will show that, while the comet was approaching the sun between 11 and 7 AU, the data seem to be consistent with the presence of an irregularly shaped, possibly heterogeneous, friable, slowly rotating object a few kilometers across, composed primarily of water-ice, fine dust, and carbonaceous material much like the model cometary nucleus originally conceived by Whipple.

Imaging. The first indisputable signs of comatic activity (from this point on I shall use interchangeably the astronomical term coma and the more physically oriented term atmosphere) appeared in images taken in 1984, 2 years after recovery by Djorgovski and Spinrad (*12*). The coma was structured, asymmetric, and could be traced to a distance of 30,000 km from the nucleus. Since then most observers, but not all of them, have detected a coma, but its morphology and brightness are quite variable (Fig. 2).

Among earlier observations (that is, for r greater than 6.14 AU; r, heliocentric distance) there is only a single case of an image being other than stellar in appearance. This observation, by West and Pedersen (*13*), was made in January 1983, when the comet was at 10.5 AU; the image shows a barely perceptable distortion. Jewitt and Danielson (*14*) have looked into the shape of images of the comet in their data, which were taken when r was greater than 8 AU. They find no evidence for a coma but note that a putative coma might still exist, contribute a large fraction to the total light, and yet not be noticed in such faint images.

Photometry

The light curve. In Fig. 3 I have plotted all the observations available to me as a single graph of total visual magnitude versus heliocentric distance. The data come from various sources (*15, 16*), so that the resulting trend can at best be considered an approximation, since I have necessarily had to make several crude assumptions to plot all the data together. Nevertheless the resulting curve has good coherence and is probably reliable to an accuracy of ±0.5 magnitudes.

The first conclusion that I draw is that the brightness of the comet is now increasing in such a way that it will overlap with the results at small heliocentric distance obtained in 1910; this generally confirms the repeatability of the comet's brightness, but there are some differences that may simply be due to the uncertainty of the 1910 magnitude estimates between 3 and 4 AU. A second conclusion is that the detection limit has increased enormously, by a factor of 2.5 × 10^3, as a result of technological advances since 1909.

I have evaluated the data in the context of a simple photometric and physical model (*17*) based on a dusty, water-ice nucleus warmed by sunlight. Figure 3 shows a best-fit model and two extreme cases: curve A is based on a nucleus that does not rotate, while for curve B the nucleus rotates rapidly. A wide range of models, with various combinations of rotation rate and assumptions as to the way dust is gained and lost by the coma, is possible between these two extremes.

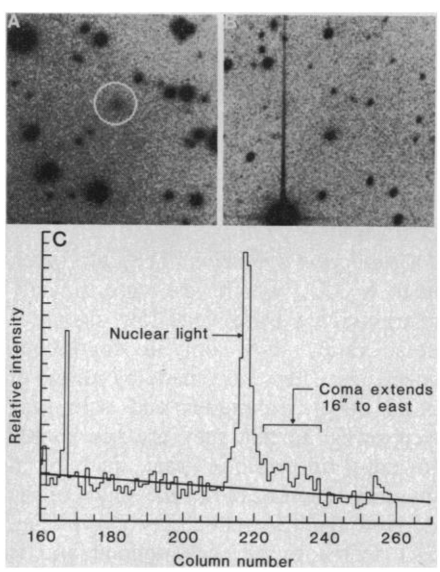


Fig. 2. (A) Early evidence of an extended atmosphere (coma) in P/Halley while on its approach to the sun. This image was taken with the 4-m Mayall telescope at the National Observatory on 17 November 1984. The asymmetric form of the coma is evident. [Courtesy of A. Crotts] (B) A later picture obtained on 14 March 1985. The comet is now far more condensed and shows only faint vestiges of the extended coma structure evident earlier. [Courtesy of R. Kennicutt] (C) The cross-dispersion distribution of intensity through a spectrum of P/Halley obtained on 30 October 1984 (4000-second exposure) (see also Fig. 5), showing evidence of an asymmetric coma extending some 60,000 km from the nucleus in the general direction of the sun (*48*).

For r greater than 7 AU the trend of the data is consistent with light scattered from an effectively bare nucleus; then, as the comet moves through distances less than 6 AU, it begins abruptly to "turn on" as the light from the developing coma increasingly dominates the total brightness. If we assume that the cometary dust can be characterized by micrometer-sized particles (*18*) and that the nucleus is a slow rotator, the observations at this distance imply a mass-production rate for dust that is a little smaller than the mass production rate given by the gas sublimation model (10^3 g sec^{-1}). This is a physically reasonable result, and calculation shows that the momentum of the gas flow at this distance should just be sufficient to accelerate small dust grains to escape velocity from the weak gravitational field of the model nucleus and explains why a coma should begin to form at this point. A fast water-ice rotator is, on the other hand, too cool for such behavior, and this model predicts a gas sublimation rate that is too low by six orders of magnitude. The best-fit model shown in Fig. 3 is based on a slowly rotating nucleus and the assumption that the dust-to-gas mass production ratio for the observed coma is independent of the heliocentric distance.

A relevant question at this juncture is: How "slow" is a slow rotator? A rough estimate can be made from the characteristic time scale over which the surface of a nucleus can radiate the heat content of its thermal skin. For a typical surface thermal inertia of 0.003 cal cm^{-2} $sec^{-1/2}$ K^{-1} (*19*), I find that a slow rotator near 6 AU is characterized by a period longer than about 38 hours. Closer to the sun this characteristic period decreases substantially, but nevertheless P/Halley appears to qualify as a slow rotator at the heliocentric distances considered here since the best available estimate of the rotation period, from data taken at the 1910 apparition, is roughly 52 hours (*20*).

Newly reported near infrared brightnesses provide an independent way of estimating the mass production rate for dust, because Hanner (*21*) has demonstrated that observations of many comets show a tight correlation between this rate and their total brightness in the photometric J band. Using Hanner's results and the J magnitudes of the comet reported when it was at a heliocentric distance of 4.83 AU, I estimate that the dust mass production rate was roughly 3 × 10^4 g sec^{-1}. This is somewhat larger than the rate predicted in the best-fit model (gas production rate, ~2 × 10^4 g sec^{-1}); however, taking the uncertainty of such estimates into account, it is reasonably consistent since physical arguments (*22*) imply that the two rates should be similar (although the dust rate should always be smaller) in a relatively fresh comet like P/Halley.

Intrinsic variability. Rapid, large-amplitude fluctuations in the brightness of P/Halley were first reported by Lecacheux and colleagues (*23*). The variations are as much as a factor of 6 in less than a 24-hour period. Each of several data sets has now been searched for periodicity, and although different periods have been suggested, no common result has emerged. Attempts to analyze the integrated data set have also been reported, but again there is no convincing result. Jewitt and Danielson (*14*) have noted that the large amplitude and short time scales rule out transient ejection of refractory grains as the cause of the variability, because otherwise a coma would have been seen. However, sporadic outbursts involving rapidly sublimating grains or particles that remain gravitationally bound to the nucleus could still be responsible.

In Fig. 4A I give a view of the data that

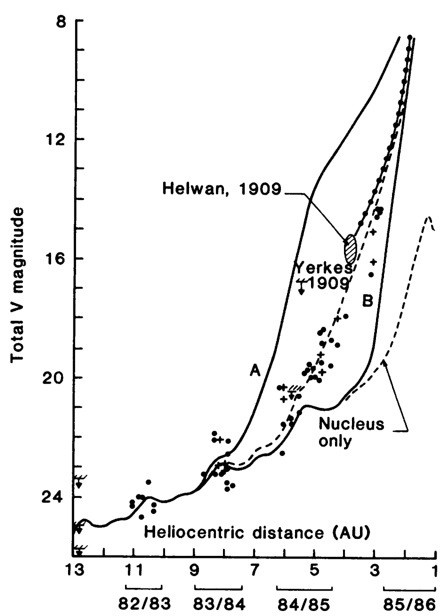
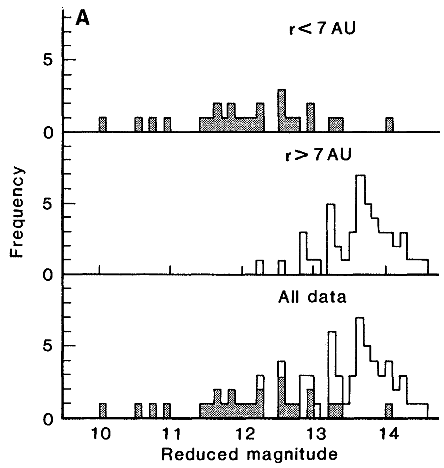


Fig. 3. The total visual brightness (preperihelion light curve) of P/Halley as a function of its heliocentric distance (ground-based telescope observing semesters are marked along the abscissa). Observations, from many sources (*15, 16*), made between recovery and August 1985, are plotted in the context of a simple model (*17*) together with a representation of the comet's observed brightness in 1909–10 (*49*). Curves A and B are extreme models parameterized by the way dust is lost from the coma and the rotation of the nucleus (see text). Symbols: (- - -) best-fit model; (●—●) observed, 1910 [data from (*49*)]; (+) averages of several current observations; (●) current observations. Hatched arrows indicate upper limits.



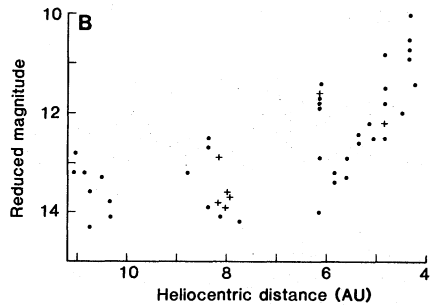


Fig. 4. (A) The brightness of P/Halley plotted as a histogram of reduced magnitude. The nearly symmetric scatter seen in the data for r greater than 7 AU may be due to variations in brightness caused by the comet possessing an irregular and spotty nucleus rotating with a period near 52 hours. (B) The dependence of reduced magnitude on heliocentric distance. Note the abrupt change in photometric behavior near 6 AU (see text). The cluster of data points at 11.7 magnitude at r = 6.1 AU (September 1984) may indicate that the comet was undergoing an energetic outburst at that time (see text). Symbols: (+) averages of several current observations; (●) current observations.

several groups (*16, 28*). At this distance we know from imaging and the visual light curve data that the comet already had a coma and, according to my simple interpretation of the light curve, may already have been contributing as much as half the total light. With one exception, the infrared colors show the comet to be considerably redder than the sun, a quality that almost certainly reflects the properties of coma particulates. (I estimate from Fig. 3 that the coma was contributing roughly 75 percent of the light in most of these early observations.) Cruikshank and co-workers (*28*) have found that their measurements are consistent with trends in many other comets, but they note that, if their data directly refer to the nucleus, then a red-colored object with surface materials similar to certain D-type asteroids in the outer part of the asteroid belt and with dimensions as large as 20 km is indicated. The exception referred to above is a measurement reported by Hanner and Tokunaga (*29*) for r = 5.12 AU, which seems to indicate a very blue color. In this case the observations were made at a heliocentric distance for which the best-fit model indicates that there could still be a substantial contribution from the nucleus to the total light.

may have a bearing on the nature of the variability. The "reduced" magnitudes (brightness reduced to unit distance from the sun and Earth) for r greater than 7 AU cluster around the mean value of 13.6 and show a scatter of ±0.5 magnitudes with a roughly symmetric distribution. Intuitively this is the kind of scatter that would be expected for stochastic errors in the measurements. If the variability were associated with a series of irregular outbursts, the distribution would be expected to be strongly skewed toward higher brightnesses, which is apparently not the case.

On the other hand, a randomly sampled variation (providing that it is reasonably simple) should give a double peaked distribution which is also absent (*23a*). It seems likely that measurement errors dominate the full data set for r greater than 7 AU and that, since variability is definitely present in some data sets, a search for its cause must be carefully restricted to the best sampled and most consistent of these.

A special situation applies at r = 6.1 AU (Fig. 4B) where, with the exception of two Soviet photographic measurements, the data of several observers agree and cluster 1.5 magnitudes above the general run of the data. These data coincide with the first indisputable appearance of a coma in the images and apparently document a major outburst in brightness. This outburst was evidently not abrupt, because examination of the images reveals a jet-like fan structure in the coma that was maintained for at least 1 month. It is also perhaps more than coincidental that the distance at which this event occurred is included in the range of distances for which even more dramatic, and famous, outbursts were seen in another distant comet, P/Schwassmann-Wachmann 1 (*24*) and at a distance where ice, if it were in its amorphous phase near the surface of the nucleus, would reach a temperature where it could transform spontaneously and exothermically to the crystalline form and provide a source of energy for such outbursts (*25*).

Figure 4B also shows clearly the abrupt change in general photometric behavior near 6 AU as the coma began to develop. Wyckoff and colleagues (*26*) interpret the sudden increase in the rate at which the comet brightened to be the onset of vaporization at the surface of the nucleus. However, I believe that vaporization had been proceeding for some time and that the abrupt change might simply reflect the crossing of a dynamic threshold at which the flow of the subliming H_2O vapor attains enough momentum to accelerate visible amounts of micrometer-sized dust particles to the gravitational escape velocity from the nucleus.

Color. Very few photometric measurements have been reported for the period when the comet was beyond 7 AU (*14*), and all seem to indicate that the comet has the same color as the sun. However, some spectroscopic studies discussed below report uncertainties in the color differences that are of the same order of magnitude as the color difference itself, so that it is quite possible that considerable differences from the sun's color in fact exist.

The first detection of the comet in the near-infrared occurred when it was at 5.39 AU (*27*). Since then, colors in that spectral region have been reported by

Spectroscopy

The first spectra were obtained when the comet was at 23.2 magnitudes, a heliocentric distance of 8.77, and 7.97 AU with the 4-m telescope at the National Observatory (*30*).

Continuum spectrum. The data taken near 8 AU, which are unfortunately characterized by a very low signal-to-noise ratio, show only a continuous spectrum. They were made by means of blind offset techniques and with long exposures, so that they are susceptible to many uncertainties that are hard to quantify. Nevertheless, the shape of the derived spectral reflectivity curve (Fig. 5A) seems to be well defined and is highly colored (the comet would appear greenish to the eye). It is quite unlike that of any other small object yet observed in the solar system, and it has not yet received a satisfactory interpretation. For r less than 7 AU, the spectra show a continuum slightly redder than that of the sun; this is a characteristic of the comas of many other comets.

Emission spectrum. Figure 5, B and C, shows the first detection of emission features in P/Halley's spectrum. Wyckoff and colleagues (*26*) have estimated a total production rate of 3×10^{24} mol

sec^{-1} for cyanogen (CN) at 4.8 AU and, if the comet's atomic composition is normal (*31*), a water production rate of roughly 2×10^{27} mol sec^{-1}. From the forbidden atomic oxygen line detected by Djorgovski and Spinrad (*12*), Spinrad estimates a water production rate of approximately 4×10^{27} mol sec^{-1} (*32*). At this stage the difference between these two estimates is not surprising or worrisome; and they compare well with the predictions of the simple model for a slow rotator, which yields a rate of 5.4×10^{26} mol sec^{-1} at this distance. Another molecule that has recently been detected is C_2. Spinrad and colleagues have found weak signs of the emission at 5165 Å in spectra taken when the comet was at 2.8 AU (*32*). This emission, which grows to dominate the visual spectrum of the comet's atmosphere near perihelion, is an important component of the photometric model. The best-fit model of Fig. 3 predicts that C_2 should have reached a few percent of the continuum spectrum brightness, and therefore probably should have been detectable, when the comet was as far from the sun as 3.5 AU. However, at that distance the comet was placed close to the sun in the sky and was not observable from the ground. Spinrad's detection of the molecule in the first spectra taken when the comet again became available for observation is therefore consistent with the simple model discussed here.

Astrometry

Precision. The accuracy and consistency of the astrometric data are truly remarkable considering the faintness of the comet. According to Morley (*33*), who has analyzed some 104 observations involving 12 observatories, the data show a scatter of only 1.5 arc seconds in each coordinate when compared with the best-fit orbital model. Given a continuing supply of positions of similar accuracy through early January 1986, Morley estimates a positional uncertainty of 300 km for P/Halley at the time of the European Space Agency's GIOTTO spacecraft encounter.

Nongravitational forces. A standard model for these forces has been introduced into the study of P/Halley's orbit by Yeomans (*4*), who finds their amplitude and direction to have been effectively constant for the past 28 orbital revolutions. The transverse component is well determined at 0.0232 km day^{-2}, and its sign indicates that the nucleus spins in an anticlockwise direction as seen from its "north" pole. The radial force is less well determined, but Yeomans believes that it is now determined to much better than a factor of two. Its amplitude is 0.21 km day^{-2}. The scale length, or range of heliocentric distances over which these forces act, is 2.808 AU, which is again consistent with predictions of the model when outgassing is controlled by water-ice.

The Nucleus: A Preliminary Assessment

The apparent success of the simple photometric and physical model used to mimic the light curve provides enough of an impetus to speculate a little further about the properties of the nucleus. The reader is advised, however, that this model represents only the author's point of view and that several other variations are possible. Using simple techniques (*34*), I find a Bond albedo of 0.26, a minimum value for the mean radius of 2.1 km, a mass of 7×10^{16} g, and a maximum value for the bulk density of 1.7 g cm^{-3}. Since this is already a reasonable value for the bulk density, and since it would seem to be physically unlikely that it would be less than 1 g cm^{-3}, I conclude that the value for the mean radius lies somewhere between 2.1 and 2.6 km. The albedo is very high, some ten times larger than that measured for comet P/Arend-Rigaux (*35*), the only other comet for which we are reasonably sure that the measurements refer to the nucleus. Perhaps the difference is a reflection of major differences in the degree of evolution of the surfaces of the two comets or in their basic chemical composition (*36*).

The agreement between the measured H_2O production rate and that predicted by the model at 4.8 AU, the discovery of detectable C_2 emission at 2.8 AU, the fact that the best estimate of P/Halley's observed rotation rate qualifies it as a "slow" rotator, and the fact that the coma appeared under conditions that lead to a high (~1) but physically reasonable estimate of the dust-to-gas mass production ratio are all substantial confirmation of the model, providing that

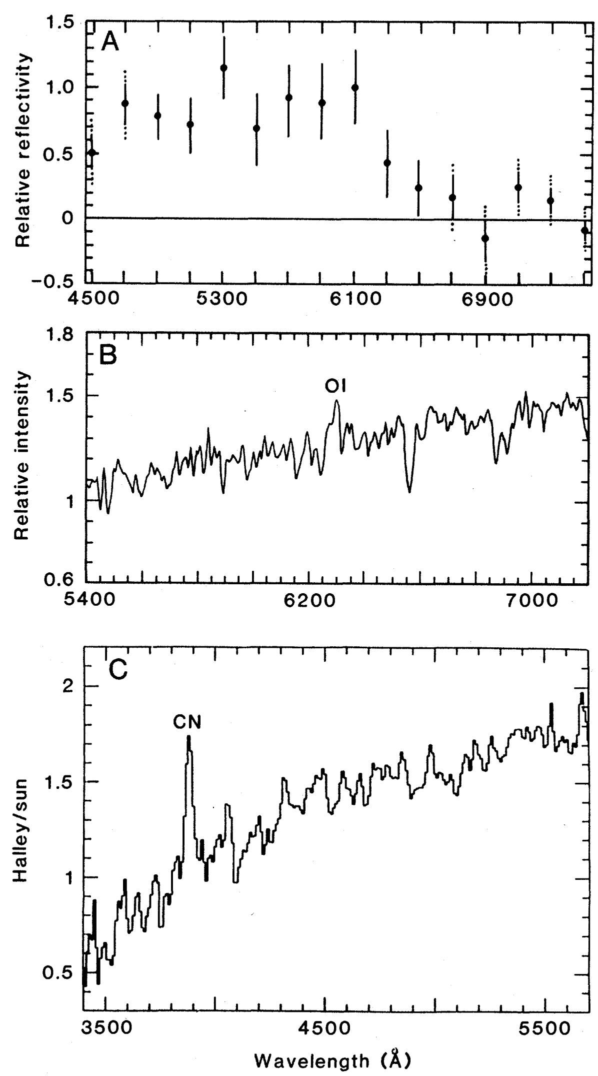


Fig. 5. Various spectra of P/Halley since its recovery in 1982. (A) The spectral reflectivity of P/Halley. This spectrum was taken when the comet was at 7.97 AU and is thought to be representative of the surface of the nucleus. If so, the nucleus would appear dark green in color. (B) The first detection of OI emission by Djorgovski and Spinrad when the comet was at 4.8 AU (*32*). (C) The first detection of the CN radical in P/Halley when the comet was at 4.8 AU (*26*).

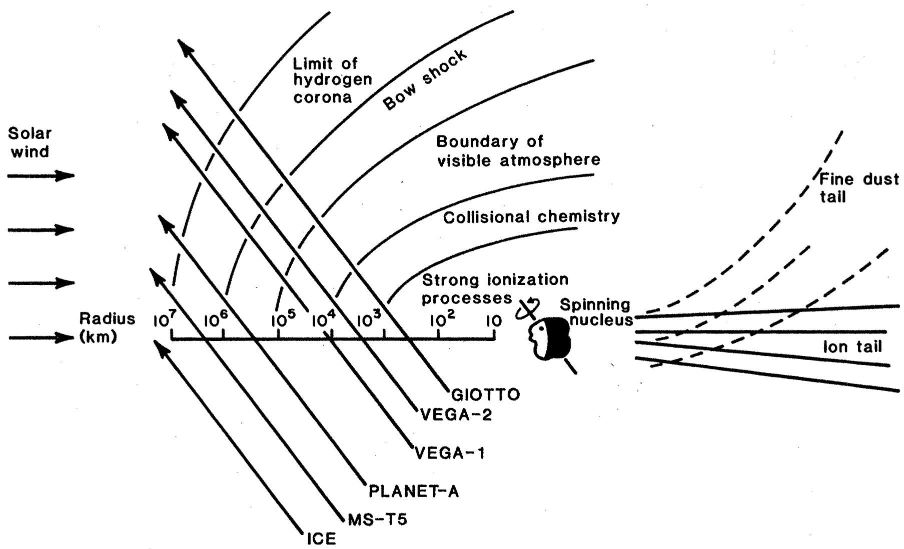


Fig. 6. A logarithmic cartoon of the primary physical domains in P/Halley's atmosphere together with a schematic representation of the trajectories of the various spacecraft comprising the Halley swarm (*1*) that will encounter it. All the spacecraft are currently planned to pass on the sunward side of the nucleus and will not sample the tail regions. NASA's ICE spacecraft will be approximately 0.21 AU upstream of P/Halley in March 1986 to monitor the solar wind conditions; ICE can therefore be considered a member of the Halley swarm. Encounter date for Japan's MS-T5 spacecraft is 8 March 1986; encounter dates for the other spacecraft are given in Table 1.

the substance of the nucleus is very friable (*22*). Only the variability and spectral color at *r* greater than 7 AU are unexplained. The statistics of the reduced magnitudes appear to allow the concept of a slowly rotating nucleus that is spotty or very irregular in shape (or both), but this is weak evidence. Radar echos from the nucleus of comet IRAS-Araki-Alcock in 1983 (*37*) indicate that cometary nuclei can be very irregular, but on the other hand demonstrable activity seen in several comets at these distances indicates that sporadic activity is a viable alternative. Since the P/Halley enterprise has barely begun, I prefer not to beg this question but to wait until the instruments on the Soviet VEGA (Venus-Halley) and European GIOTTO spacecraft provide the definitive answer. The peculiar reflection spectrum near 8 AU and the early infrared color measurements remain enigmatic. The spectral data (*30*) were taken under difficult conditions and are, I believe, unique. No independent data exist with which to cross-check their remarkable properties. They are either highly significant or totally worthless.

Expectations

The climax to the scientific drama that is about to unfold will, without doubt, be the penetration of the GIOTTO probe (*38*) as close as 500 km to the sunlit nucleus and the safe return of its data. However, much will happen before then that is certain to lead to a steady increase in expectations and excitement as time progresses. A calendar of events is shown in Table 1. The International Sun Earth Explorer 3 spacecraft (*39*) will represent the first major event. After being successfully targeted toward P/Giacobini-Zinner in December 1983, it was renamed the International Cometary Explorer (ICE) and became in September 1985 the first spacecraft to enter the atmospheric and tail regions of a comet (*40*). After surviving its passage through the tail of P/Giacobini-Zinner, ICE is now speeding on to join the Japanese spacecraft, MS-T5, in monitoring the upstream solar wind conditions at P/Halley in March 1986.

Events have been quickly unfolding as P/Halley brightened in the fall of 1985. The network of astronomers coordinated by the International Halley Watch are probing the comet with radar to sound the global properties of the nucleus, with spectroscopic instruments at microwave frequencies to detect and characterize parent molecules as they are sublimed from the nucleus, and with optical and infrared telescopes to capture the evolution of the chemistry of its atmosphere and the large-scale, visible manifestation of its interaction with the solar wind. In Earth orbit, the aging International Ultraviolet Explorer spectrographic telescope, which was launched in 1978 and was never expected to be operating for observations of P/Halley, has made spectroscopic measurements of H atoms and OH molecules, directly measuring the rate of production of the major atmospheric constituents.

Only those people who wish to see the comet with their own eyes may be disappointed. The comet will be very difficult to see from the United States because of its distance from Earth and because it will be near superior conjunction with the sun when it attains its brightest phase. Nevertheless a good pair of binoculars should provide satisfactory viewing conditions in late December and early January (*41*).

In late January 1986, during a Space Shuttle flight, a University of Colorado spectrographic and imaging package (*42*) will be released into co-orbit on a SPARTAN carrier spacecraft. For a 48-hour period the system will automatically scan the comet to document its activity and physical state just before its most active period. Also starting in January and continuing through March, instruments of the Earth-orbital Solar Maximum Mission satellite, specialized for work on the solar atmosphere, will be offset from the sun in order to capture further data on the evolving state of the comet (*43*).

Perihelion passage occurs on 9 February 1986, and at this time a clear view of the comet will be prevented by its proximity to the sun in the sky. However it will be visible from the Pioneer Orbiter spacecraft at Venus, whose ultraviolet spectrometer will make spin-scan images of P/Halley's hydrogen corona and other large-scale atmospheric emissions. The comet will also be visible from the Japanese PLANET-A and Soviet VEGA spacecraft at that time, and we can expect to see what the comet looks like courtesy of Japanese and Soviet television.

As March approaches, the Halley swarm will be closing on the comet. Interest and activity will shift to the southern hemisphere, where observing conditions are better from the ground, as well as to Earth orbit. An extended Space Shuttle flight will be launched in the first week of March, carrying a payload of three sensitive astronomical telescopes and a wide-angle camera to capture the changing morphology of the ion-tail structures. A special team of investigators, selected by NASA and known as ASTRO-1, will make spectrographic, photometric, and imaging studies of the comet while it is visible (a few minutes per orbit), and then the principal investigators and their teams will spend the balance of the time on faint, mainly extragalactic, objects.

On 8 March 1986 the encounters will begin. ICE and MS-T5 (Figs. 6 and 7) will be in position upstream of the comet as the first encounter spacecraft, VEGA-1, performs its fly-by at a distance of roughly 10,000 km from the nucleus. Its international payload of 11 experiments (*1, 44*) will send back the first detailed in situ information on the dust, gas, and plasma environment. On board will be the University of Chicago's DUCMA (Dust Counter and Mass Analyzer) experiment (*45*) shown in Fig. 7. Television cameras will return pictures of the nucleus with a resolution of 180 m, which will clearly resolve it and provide precise information about its position in space. As a result of an agreement among the nations taking part in the Halley swarm, a pathfinder program has been planned in which the VEGA project will provide information to the GIOTTO project so that, should it be needed, a last-minute trajectory maneuver can be performed to ensure the best targeting of the European Space Agency spacecraft. The data returned from VEGA-1 may also affect the targeting of VEGA-2, which is due to arrive 3 days later. Its trajectory may be adjusted to move either closer to or farther from the nucleus, depending on the conditions that VEGA-1 reveals.

Japan's PLANET-A will fly by the comet next. Unprotected against damage from dust particles, it will sample the interaction of the comet's atmosphere with the solar wind and also image the large-scale structure of the comet in the ultraviolet from a distance of 200,000 km. The primary goal of PLANET-A, to image the changing morphology of the comet's hydrogen corona for some tens of days while the comet is near perihelion, will be accomplished before the actual encounter takes place.

VEGA-2, which has instrumentation similar to that of VEGA-1, will penetrate the comet's atmosphere on 9 March 1986 to take a second sample of the changing cometary environment. Finally, just hours before its encounter, GIOTTO will turn on its payload of ten instruments (*38*) and, on 13 March 1986, will attempt to penetrate as close as 500 km to the nucleus by flying at 68 km sec^{-1} through the dusty atmosphere almost directly into the heart of the comet. If it is successful, it will provide the highest resolution views of the nucleus and details about the atmospheric dust, structure, and composition that are totally unavailable by any other means.

Future Prospects

While GIOTTO's passage into the comet may be the climax of the series of events described above, it will certainly not be an ending. If comets are truly the relatively unevolved relics of the primitive solar nebula that we suspect them to be, the result of the Halley swarm, the International Halley Watch, and the other associated research programs will be to elevate this suspicion to detailed knowledge on the most firm scientific basis: observational fact. Unexpected

Table 1. P/Halley: calendar of events.

Date	Event
January 1986 (through March)	Earth-orbital observations by Solar Maximum Mission spacecraft.
20 January 1986	Comet lost in sun's glare.
22 to 29 January 1986	Space Shuttle SPARTAN Earth-orbital observations.
9 February 1986	Comet at closest approach to sun; observations of comet scheduled by Pioneer spacecraft in orbit around Venus; PLANET-A and VEGA imaging.
26 February 1986	Comet emerging from the glare of the sun.
March 1986	ICE and MS-T5 spacecraft upstream of P/Halley.
6 March 1986	VEGA-1 encounter; ASTRO-1 Earth-orbital mission.
8 March 1986	PLANET-A encounter.
9 March 1986	VEGA-2 encounter.
13 March 1986	GIOTTO encounter.
11 April 1986	Comet closest to Earth (0.42 AU) on outbound leg of orbit.

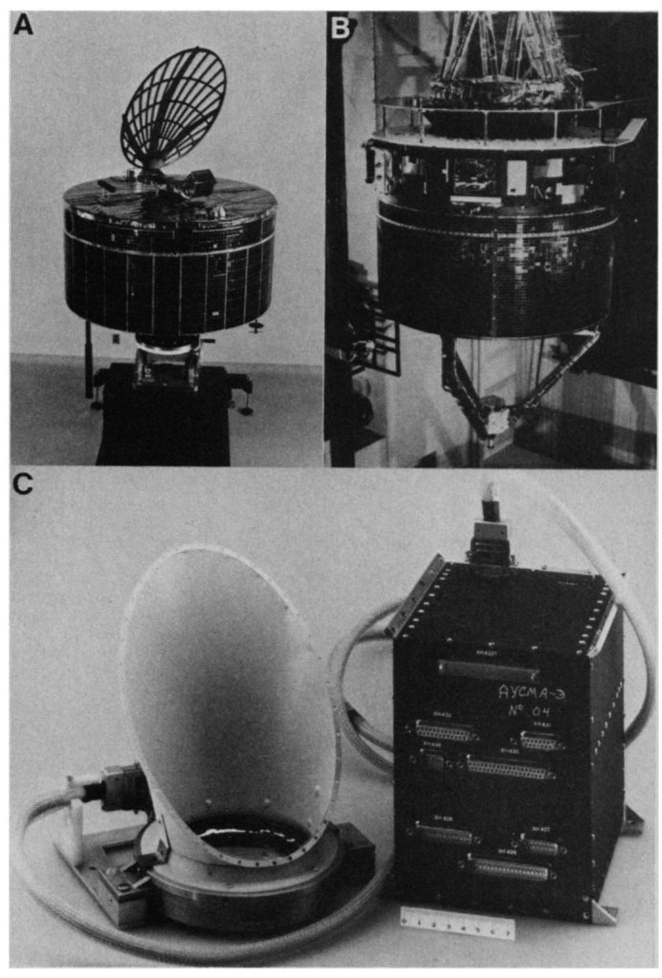


Fig. 7. (A) The Japanese MS-T5 test spacecraft (*50*). The antenna at the top (diameter, 80 cm) is mechanically despun to point at Earth on this 142-kg spin-stabilized spacecraft. It was launched from Kagoshima Space Center on 7 January 1985 and will arrive at P/Halley on 8 March 1986. The PLANET-A spacecraft (see text) is similar. (B) The European Space Agency's GIOTTO spacecraft (*38*), designed to carry ten experiments to as close as 500 km of the nucleus. The instruments and spacecraft are protected from high-velocity dust impacts (at 68 km sec^{-1}) by the dual-sheet bumper shield. GIOTTO was launched from Kourou, French Guiana, in early July 1985 on an Ariane launch vehicle and will arrive at the comet on 13 March 1986. To the right, projecting from the spacecraft, can be seen the outline of the Particulate Impact Analyzer built at the Max-Planck-Institut für Kernphysik (*51*) which is designed to accomplish time-of-flight mass spectrometry on individual cometary dust particles. (C) The University of Chicago's DUCMA instrument (*45*), which is included in the scientific payload of the Soviet VEGA spacecraft. It is reported that this instrument is sending back data and is operating normally at this time.

discoveries may be made, many old problems may be solved, and new problems may be posed. As a result, the study of the chemistry and physics of comets should become one of the most active frontiers in solar system research and exploration. In the future, we can expect that a detailed exploration of comets and asteroids by spacecraft will become an essential and logical next step in the U.S. program of planetary exploration. Already this potential has been recognized at NASA, and the agency is considering a Comet Rendezvous/Asteroid Flyby (CRAF) mission to comet P/Wild 2 in the early 1990's (*46*). This mission will make possible a study of the detailed isotopic, atomic, and molecular chemistry and the physical structure of the nucleus at very close range, and possibly by direct contact, over most of an orbital period while the activity of the comet evolves. Its success should enable planetary science to take another great step forward toward a detailed resolution of one of the central questions about our planet: Whence did it come?

References and Notes

1. The term "Halley swarm" was coined by J. Blamont [for example, in *Cometary Exploration*, T. Gombosi, Ed. (Hungarian Academy of Sciences, Budapest, 1982), vol. 3, p. 127]. Earlier, some had referred to the five P/Halley spacecraft as an "armada." However, when the fate of the famous Spanish expedition in 1588 was pointed out the term was quickly dropped.
2. F. L. Whipple, *Astrophys. J.* **111**, 375 (1950); *ibid.* **113**, 464 (1951).
3. L. Kresak, *Bull. Astron. Inst. Czech.* **32**, 321 (1981).
4. D. K. Yeomans, in *Cometary Astrometry: Proceedings of the ESO Workshop*, D. K. Yeomans, R. M. West, R. S. Harrington, B. G. Marsden, Eds. (Jet Propulsion Laboratory, Pasadena, Calif., 1984), pp. 167–175; *Astron. J.* **82**, 435 (1984); D. K. Yeomans and T. Kiang, *Mon. Not. R. Astron. Soc.* **197**, 633 (1981); D. W. Hughes, *ibid.* **213**, 103 (1985); R. P. Broughton, *J. R. Astron. Soc. Can.* **73**, 24 (1979); I. Ferrin, *Astron. Astrophys.* **135**, L7 (1984).
5. E. Everhart, in *The Study of Comets: Proceedings of the Twenty-fifth IAU Colloquium*, B. Donn, M. Mumma, W. Jackson, M. A'Hearn, R. Harrington, Eds. [NASA-SP 393 (1976)], p. 445.
6. Ho Peng Yoke, *Vistas Astron.* **6**, 127 (1962).
7. P. R. Weissman, in *Comets*, L. L. Wilkening, Ed. (Univ. of Arizona Press, Tucson, 1982), pp. 637–658.
8. Several articles on different aspects of the cometary nucleus can be found in L. L. Wilkening, Ed., *Comets* (Univ. of Arizona Press, Tucson, 1982).
9. The fact that periodic comets that come close to the sun eject large amounts of material at each perihelion passage indicates that their surfaces evolve. Whether their interiors have substantially changed since their formation is really unknown. B. Donn and J. Rahe discuss ideas on the interior structure [in *Comets*, L. L. Wilkening, Ed. (Univ. of Arizona Press, Tucson, 1982), pp. 203–226]. Up-to-date discussions of surface processes that may occur are given by F. P. Fanale and J. R. Salvail [*Icarus* **60**, 476 (1984)] and by G. Herman and M. Podolak [*ibid.* **61**, 256 (1985); *ibid.*, p. 267].
10. The origin of comets and of the solar system has been discussed widely. Introductory material and references to earlier work can be found in (*8*). See also W. M. Irvine [in *Cometary Exploration*, T. Gombosi, Ed. (Hungarian Academy of Science, Budapest, 1982), vol. 1, pp. 3–12] for a discussion of the origin of their chemistry.
11. D. C. Jewitt, G. E. Danielson, J. E. Gunn, J. A. Westphal, M. Schmidt, B. A. Zimmerman, *IAU Circ. 3737*.
12. S. Djorgovski and H. Spinrad, *IAU Circ. 3996*.
13. R. M. West and H. Pedersen, *Astron. Astrophys.* **121**, L11 (1983).
14. D. Jewitt and G. E. Danielson, *Icarus* **60**, 435 (1984).
15. The observations are an eclectic mix of data made through many different kinds of filters, under different observing conditions, and with different observing techniques and photometric apertures. In order to construct Fig. 3 I have reduced the data to total visual magnitudes using solar color indices and ignored other potential problems. As a result, the light curve in Fig. 3 must be considered as only a rough approximation to reality. The sources of the data are: R. M. West and H. Pedersen, *Astron. Astrophys.* **138**, L9 (1984); O. LeFevre, J. Lecacheux, G. Mathez, G. Lelievre, J. Baudrand, J. P. Lemonnier, *ibid.*, p. L1; H. Pedersen, *IHW Electronic Bulletin Board* (1984); M. Belton and H. Butcher, *Nature (London)* **298**, 249 (1982); *IAU Circ. 3776*; S. Wyckoff, R. M. Wagner, P. A. Wehinger, D. G. Schleicher, M. C. Festou, *Nature (London)* **316**, 241 (1985); *IAU Circ. 4029*; E. Barker and C. P. Opal, private communication; J. Miller and R. Goodrich, private communication; M. J. S. Belton, H. Spinrad, P. A. Wehinger, S. Wyckoff, *IAU Circ. 3934*; S. F. Green, J. Zarnecki, C. M. Birkett, personal communication; D. P. Cruikshank, W. K. Hartmann, D. J. Tholen, *Nature (London)* **315**, 122 (1985); D. Jewitt and G. E. Danielson, *Icarus* **60**, 435 (1984); H. Spinrad, P. A. Wehinger, M. Belton, private communication; T. Seki, *IAU Circ. 3996*; S. Djorgovski and H. Spinrad, *ibid.* G. K. Nazarchuk, *IHW Newsletter 7* (18 June 1985); S. I. Gerasimenko, N. N. Kiselev, G. P. Chernova, *ibid.* (18 June 1985); D. P. Cruikshank, C. Chapman, J. Pasachoff, H. Hammel, private communication; S. Edberg *et al.*, *IHW Electronic Bulletin Board* (1985). See also (*16*).
16. M. Hanner and A. Tokunaga, *IAU Circ. 4034*; C. M. Birkett and S. Green, *IAU Circ. 4025*.
17. The model is similar to that of R. L. Newburn [*Adv. Space Res.* **2** (No. 12), 111 (1983)] and includes the scattered light contribution of the nucleus, C_2 fluorescence, and scattering by dust. It assumes a rotating water-ice sphere. Calculations of H_2O sublimation were provided by P. Weissman (private communication). The dust liberation was assumed to be directly proportional to the sublimation rate. The model was normalized to agree with the observed reduced magnitude of the comet beyond 7 AU and with the brightness of the comet at perihelion in 1910 (*49*). P. Melroy worked out the numerics of the model (unpublished).
18. M. S. Hanner, in *Cometary Exploration*, T. Gombosi, Ed. (Hungarian Academy of Science, Budapest, 1982), vol. 2, pp. 1–22.
19. P. R. Weissman and H. H. Kieffer, *Icarus* **47**, 302 (1981); *Adv. Space Res.* **4** (No. 9), 221 (1984).
20. S. M. Larson and Z. Sekanina *Astron. J.* **89**, 571 (1984); *ibid.* **90**, 823 (1985); Z. Sekanina and S. M. Larson, *ibid.* **89**, 1408 (1984); S. M. Larson, private communication.
21. M. S. Hanner, *Adv. Space Res.* **4** (No. 9), 189 (1984).
22. M. Horanyi *et al.*, *Astrophys. J.* **278**, 449 (1984).
23. J. Lecacheux *et al.*, *IAU Circ. 3928*; *IAU Circ. 3943*; *IAU Circ. 3957*. Variability is discussed by B. Sicardy *et al.*, *Astron. Astrophys.* **121**, L4 (1983); O. LeFevre *et al.*, *ibid.* **138**, L1 (1984); R. M. West and H. Pedersen, *ibid.*, p. L9; see also (*14*).

23a. K. Meech, personal communication.

24. F. L. Whipple, *Astron. J.* **85**, 305 (1980); C. Froeschle, J. Klinger, H. Rickman, in *Asteroids, Comets, Meteors*, C.-I. Lagerkvist and H. Rickman, Eds. (Univ. of Uppsala Press, Sweden, 1983), p. 215.
25. J. Klinger, in *Asteroids, Comets, Meteors*, C.-I. Lagerkvist and H. Rickman, Eds. (Univ. of Uppsala Press, Sweden, 1983), p. 205.
26. S. Wyckoff *et al.*, *Nature (London)* **316**, 241 (1985).
27. C. Birkett, S. Green, A. Longmore, J. Zarnecki, *IAU Circ. 4025*.
28. D. P. Cruikshank, W. K. Hartmann, D. J. Tholen, *Nature (London)* **315**, 122 (1985).
29. M. Hanner and A. Tokunaga, *IAU Circ. 4034*.
30. M. J. S. Belton, H. Spinrad, P. Wehinger, D. K. Yeomans, *Bull. Am. Astron. Soc.* **16**, 636 (1984). The very first spectrum was obtained by S. Djorgovski and H. Spinrad in October 1983.
31. P. D. Feldman, *Science* **219**, 347 (1983).
32. H. Spinrad, private communication.
33. T. A. Morley, *GIOTTO Study Note 54* (1985).
34. M. J. S. Belton and H. Butcher, *Nature (London)* **289**, 249 (1982).
35. M. A'Hearn, presentation to the Astronomical Society of the Pacific, Flagstaff, Ariz. (1985).
36. A third possibility for the high albedo is that the H_2O production rates at perihelion, inferred from the 1910 data and on which the analysis partially depends, are too low by a large factor. If this is true, then the estimated albedo would decrease almost in proportion to the increase in the estimated value of the production rate.
37. R. M. Goldstein, R. J. Jurgens, Z. Sekanina, *Astron. J.* **89**, 1745 (1984).
38. R. Reinhard, *Adv. Space Res.* **2** (No. 12), 97 (1983).
39. F. L. Scarf, E. J. Smith, R. W. Farquhar, in *Cometary Exploration*, T. Gombosi, Ed. (Hungarian Academy of Science, Budapest, 1982), vol. 3, p. 225.
40. R. Kerr, *Science* **230**, 51 (1985).
41. D. K. Yeomans, *The Halley Watch Handbook* (Publ. 400-911/81, Jet Propulsion Laboratory, Pasadena, Calif., 1981).
42. C. A. Barth, S. A. Stern, A. I. F. Stewart, *IHW Newsletter 6* (1 January 1985).
43. K. J. Frost, B. E. Woodgate, L. L. House, *IHW Newsletter 5* (1 September 1984).
44. R. Z. Sagdeev *et al.*, *Adv. Space Res.* **2** (No. 12), 83 (1982).
45. M. A. Perkins, J. A. Simpson, A. J. Tuzzolino, *Nucl. Instrum. Methods*, in press.
46. *Report of the Comet Rendezvous Science Working Group* [NASA technical memorandum 87564 (1985)].
47. W.-H. Ip, in *Cometary Exploration*, T. I. Gombosi, Ed. (Hungarian Academy of Sciences, Budapest, 1982), vol. 1, p. 281.
48. M. J. S. Belton, H. Spinrad, P. Wehinger, unpublished data.
49. C. S. Morris and D. W. E. Green, *Astron. J.* **87**, 918 (1982).
50. K. Hirao, H. Matsuo, K. Uesugi, *IHW Newsletter 5* (1 September 1984). Photograph courtesy of N. Hara, National Space Development Agency of Japan.
51. J. Kissell, private communication.

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