HQ / GRANT / IN-90
54466 - CR
34P.

THE STUDY OF THE PHYSICS OF COMETARY NUCLEI

GRANT NSG-7082

Semiannual Progress Reports Nos. 22-23-24

For the period 1 April 1985 through 30 September 1986

Principal Investigator
Dr. Fred L. Whipple

(NASA-CR-180153) THE STUDY OF THE PHYSICS OF COMETARY NUCLEI Semiannual Progress Report, 1 Apr. 1985 - 30 Sep. 1986 (Smithsonian Astrophysical Observatory) 34 p CSCL 03B G3/90

N87-17594

Unclas 43800

February 1987

Prepared for
National Aeronautics and Space Administration
Washington, D.C. 20546

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

The Smithsonian Astrophysical Observatory
is a member of the
Harvard-Smithsonian Center for Astrophysics

The NASA Technical Officer for this Grant is Mr. David H. Scott
Code E1-4, NASA Headquarters, Washington, D.C. 20546

THE STUDY OF THE PHYSICS OF COMETARY NUCLEI

GRANT NSG-7082

Semiannual Progress Reports Nos. 22-23-24

For the period 1 April 1985 through 30 September 1986

Principal Investigator
Dr. Fred L. Whipple

February 1987

Prepared for
National Aeronautics and Space Administration
Washington, D.C. 20546

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

The Smithsonian Astrophysical Observatory
is a member of the
Harvard-Smithsonian Center for Astrophysics

The NASA Technical Officer for this Grant is Mr. David H. Scott
Code El-4, NASA Headquarters, Washington, D.C. 20546

ON THE ORBITS OF COMETS AND SECONDARIES

The numerical calculations of stability for many possible orbits of a double nucleus for P/Holmes, leading to the surmised collision of a companion nucleus in 1893, showed that the likelihood of such a pre-collision history was quite high. In other words, there were no suggestions resulting from the calculations that the general hypothesis of a double-nucleus collision to account for the double outburst in 1892 and 1893 is not completely tenable. Many orientations of retrograde orbits with periods greater than 73 days separating the two outbursts were indeed stable for hundreds of revolutions integrated numerically. Because of the sparce direct evident concerning the geometry of the outburst, it was not possible to reconstruct details of the orbital motions of the two postulated components before the collision, although certain rather uninteresting restrictions could be set on the orbits.

A number of integrations were made of hypothetical orbits for particles about the asteroid Amphitrite (29) to test for stability. The purpose was to establish more favorable fly-by orbits close to the asteroid for the Galileo missions en-route to Jupiter, reducing the collisional hazard from possible meteoroidal material in orbit about the asteroid. Most of the elongated orbits extending beyond 20,000 km of the asteroids tended to be very unstable. Delay of the Galileo mission thwarted this theoretical effort, although Whipple hopes to return to the problem when it becomes relevant again. The IRAS observation of particulate streams in the orbit of asteroids and comets promises research possibilities of great interest in such studies.

A statistical study was made of the orbits of long-period comets with small original semi-major axes, suggestive of their being relatively new comets, recently perturbed from the great Öpik-Oort Cloud about the Solar System. Comets in such orbits that were observed to be intrinsically faint (34) and split comets of long period (15) exhibit a region of avoidance in the direction of their major axes (lines of apsides). The axes of 45 out of 49 avoid by 75° the ecliptic longitude, $L=4^{\circ}.5$, and ecliptic latitude, $B = +3^{\circ}.0$. The probability of this avoidance is ~ 0.002. The interpretation of this effect in terms of the selective origin of these unstable comets is not yet entirely clear although it probably is connected to disturbances to comet orbits in the Öpik-Oort Cloud by the galactic mass, either by the central mass or by the gradient perpendicular to the plane. In either case, as recently shown by various investigators, the orbits with lines of apsides near the Galactic Pole are not influenced by these attractions. The direction $L = 4^{\circ}.5$, $B= +3^{\circ}.0$ is only 32° from the southern galactic pole. The pole itself is not so effectively avoided by the brighter new comets as is this region by the faint and unstable comets. These facts may be telling us something about the distribution of comets in the Öpik-Oort Cloud, but the message is not yet clear.

Halley's 1986 Apparition

As comet P/Halley approached the Sun during 1985-1986, the attention of the Solar-System scientific community as well as the public began to center more and more on the many aspects of this unique perihelion passage. Consequently, Whipple found his attention more and more diverted to activities related to Halley's comet. This effort included not only purely scientific aspects of consulting and advising on many programs of international import such as the International Halley Watch, the Interagency Consultative Group, the Giotto spacecraft science and many individuals and observatory participants. The effort also included educating the news media, the planetariums and individuals of the public. The truly remarkable cometary space missions demanded scientific attention both in preparation and in interpretation.

The results from the space missions to Halley's comet are partially reported in the two papers in the appendices and in papers in preparation for the great Heidelberg symposium coming in October 1986 so no serious summary is needed here. The main results concerning the nucleus are the extremely low albedo, and moderately well anticipated mass loss, mostly from water ice. These results, combined with the observed non-gravitational forces, lead to a very low calculated mean density, of the order of 0.1 to 0.5 g cm^{-3}, much below the expected value of near unity. A number of suggestions regarding origin concomitant with the Solar-System follow from these and abundance measures and will be reported as the massive information from the P/Halley observations pour in.

Other Activities

Dr. Whipple received the Kuiper Prize "for major contributions to planetary sciences" given by the American Astronomical Society, Division for Planetary Sciences on October 31, 1985 and the C.W. Bruce Medal of the Astronomical Society of the Pacific on July 15, 1986. At both meetings he responded with discussions of cometary science and Halley's comet.

Among his numerous other public presentations about comets were: "The Nature of Comets" to the workshop on Chemistry and Origin of the Solar System held at NASA's Ames Research Center on May 29, 1985;

A lecture to an international historical conference on Newton and Halley held at the University of California at Los Angeles, August, 11, 1985;

A presentation to the Inter-Agency Consultative Group of space research at Washington, D.C. on September 11, 1985;

Two lectures to the American Philosophical Society at Philadelphia, one on November 15, 1985 and the other on April 26, 1986 (see below, publications in press);

Lecture to the NASA Office of Technology and Space Program Development at the Jet Propulsion Laboratory on June 24, 1986;

Invited to a small luncheon in the White House by the President of the United States on March 26, 1986. Dr. Whipple and five other scientists were able to acquaint the President with the latest developments of cometary and space research;

Whipple has been active in consulting with:

The U.S. National Academy of Sciences Committee on Planetary and Lunar Exploration (COMPLEX);

The International Inter-Agency Consultative Group of the Solar-System space research;

NASA's Comet Rendezvous Science Working Group;

The International Halley Watch;

The European Space Agency's spacecraft to Halley's Comet, Giotto

These activities enabled him to be present in Moscow on March 6-9, 1986, and in Darmstadt, FGR, on March 14, 1986 to receive first hand the results from the Vega and Giotto mission to Halley's Comet.

Publications

"Present Status of the Icy Conglomerate Model" (Center for Astrophysics Preprint Series No. 1996, 1985, Ices in the Solar System, Ed. J. Klinger, D. Benest. A. Dolfus, R. Smolukowski, D. Reidel, 343-366. Also "Der gegeniwärtige Stand des Eiskonglomeratmodells der Kometenkerne", 1985, Die Sterne, Vol.8, 303-314.

COMET P/HOLMES, 1892III- A Case of Duplicity? (Center for Astrophysics Preprint Series No. 1995) 1984, ICARUS, Vol. 60,522-531.

"The Mystery of Comets", 1985, Smithsonian Institution Press, 276p.

"The Giotto Halley Multicolour Camera, with 16-co-authors, 1986, European Space Agency, SP -1077, 149-172.

"First Halley Multicolour Camera imaging results from Giotto, with 17 co-authors, 1986, NATURE 321, 320-329.

In Press: "News from visits to Halley's Comet," tp be published jointly by the American Philosophical Society and the Royal Society of England.Presented in Philadelphia on April 26, 1986 (see appendix).

"A review of Cometary Sciences," to be published by the Royal Society in England, presented at a meeting of the Royal Society in London on May 21, 1986 (see appendix).

Appendices

A Review of Cometary Sciences

Fred L. Whipple
Harvard-Smithsonian Center for Astrophysics

Introduction

This introduction is intended to present a broad elementary description of the phenomena and nature of comets. The reader who wishes to pursue the general subject in more detail is referred to books edited by Delsemme (1977), McDonnell (1978) and Wilkening (1982).

Following the introduction, emphasis centers on the relationship of comets to the interplanetary complex and possibly to asteroids and planets, on the nature of the cometary nucleus and on its possible modes of evolution. Cometary phenomena such as ion tails will largely be ignored as will orbital characteristics, treated in a later paper by Wetherill.

At great solar distances, comets appear as point-like sources of reflected sunlight, observationally indistinguishable from stars except for their motion across the stellar background. As comets approach the Sun, usually well within Jupiter's distance, they develop a hazy coma, sometimes with an apparently starlike central condensation. Because of the limited resolving power of telescopes, this condensation may be several hundred to thousands of kilometers in diameter. More active comets may develop diffuse comas of several tens of thousands of kilometers in diameter and also tails, up to a 100,000,000 km or more in length, directed generally away from the Sun and lagging a few degrees behind the orbital motion about the Sun.

This activity arises entirely from the heart of the comet, its nucleus, an intimate mixture of ices and dust ranging in dimension from less than one kilometer to some tens of kilometers. When the Sun's radiation becomes adequate to produce significant sublimation of the ices, the resultant vapor escapes from sunlit areas on the nucleus carrying with it embedded dust and meteoroidal material. The dust becomes observable as it scatters and reflects sunlight while the gas shines by fluorescence. In this process, the gaseous atom or molecule absorbs a quantum of sunlight and then re-radiates the energy usually in two or more quanta of lower energy, and therefore in redder light than that of the absorbed quantum. No evidence suggests that comets contribute any of the radiation observed, although the warming of extremely cold ices may release a certain amount of energy stored in the form of imperfect crystalline structure in amorphous ices. The Sun is overwhelmingly the prime source of cometary activity and observed radiation.

The fine dust of dimensions in the micrometer (μm) range frequently shows the silicate signature in its infrared reflection spectrum near a wavelength of 10 μm. This dust is forced away from the Sun by light pressure with accelerations rarely exceeding that of solar gravity. Thus, with the proper geometry, we often see such dust tails as relatively stubby, curving at conspicuous angles behind the orbital motion of the comet.

The composition of cometary comas and tails as observed by optical, infrared, ultraviolet and radio sensors is listed in Table 1. The preliminary results from the missions to Halley's comet reported in subsequent papers of this symposium should add materially to the entries in this Table and to their physical interpretation. Suffice it to say that gas-phase chemistry near the nucleus of a comet in the presence of solar radiation can

make and destroy compounds, primarily of oxygen, carbon, nitrogen and hydrogen in such a fashion as to make detailed deductions about the ices in comets from the data of Table 1 a quite impossible task. From the study of many comets, however, the observed lines and bands of H, O and OH lead to the sum of their abundances as roughly H_2O, indicating that water ice is the major icy component of comets. Carbon compounds, although numerous constitute altogether only perhaps 2 percent of the total mass of the ices, carbon being deficient with respect to oxygen and nitrogen when compared with solar abundances.
The observable dust component varies strikingly from comet to comet, some comets displaying almost none by reflected sunlight in their spectra. Perhaps a third of the mass of an average comet consists of dust and earthy particles.

The molecules in space generally have lifetimes of a number of hours to a few days against the dissociating and ionizing effects of sunlight. Since the gas leaves the surface of the nucleus with a velocity of the order of 0.5 km sec^{-1} at the Earth's distance from the Sun, the coma may, therefore, attain an observed diameter of 30,000 to 100,000 km (2 x 0.5x 86,400). The diameter of the coma may tend to decrease as the comet approaches the Sun because the lifetimes of the species decrease proportionally to the solar radiation while their velocity increases only as its square-root.

Positively charged ions that are formed when solar radiation removes electrons from the various species receive especial treatment in the cometary coma. They become subject to the action of the solar wind. The Sun's high atmosphere blows off about a million tons per second of extremely hot gas at a speed of some 400 km/sec. The gas of this solar wind is thoroughly ionized at temperature of the order of a million degrees. Hence it becomes a plasma, meaning that the ions and electrons that compose it carry with them strong electrical currents and magnetic fields comprising total energies comparable to the total kinetic energy of motion of the ions and electrons. In the rare gases of a comet's coma, these magnetic fields of the solar wind can selectively entrap any electrically charged ions present and carry them along, away from the Sun. In this fashion the solar wind forms the huge nearly straight tails of comets, seen only by fluorescence of the ions present, particularly of carbon monoxide, which by chance is conspicuous in visual light. The main components of the solar wind, hydrogen and helium, constituting 98 percent by mass, are quite invisible because these gases are too hot to radiate. Their electrons have been removed by ionization leaving them radiationally impotent.

The solar wind largely ignores the neutral species in a comet's coma although some cometary atoms or molecules are ionized by charge exchange and then carried into the ion tail. The ionized gases in a comet's tail are so tenuous that the acceleration by the solar wind sometimes exceeds the Sun's gravitational acceleration by as much as a thousand times. These rapid motions and high accelerations in ion tails were mysterious, indeed, until 1950 when the late Ludwig Biermann recognized the function of the solar wind. The solar wind itself was observed directly in the early days of the space age. The plasma theory developed by Hannes Alfven in 1957 is extremely difficult to apply. Hence the direct observations of fields and charged particles in the ion tails of comet P/Giacobini-Zinner by the ICE spacecraft and of Halley's comet by the various space probes are substance for new theoretical developments in plasma physics.

Although comets are being continuously depleted by loss of matter and by perturbation of their orbits by the planets, the supply of comets appears to be maintained by comets disturbed from extremely long orbits because of the attraction of passing stars and the galactic center. This cloud of comets postulated by Öpik (1932) and Oort (1950) is known as the Öpik-Oort Cloud and extends to about a thousand times Pluto's distance from the Sun. Comets attain short-period orbits by the attractions of the planets.

The Interplanetary Complex and Asteroids

The major current contribution of comets to the Solar System is the maintenance of small particulate matter in the interplanetary medium providing the material for the Zodiacal Light and the Gegenschein. The annual meteor streams of the Leonids and Perseids were first associated specifically with their parent comets in the 1860's. Some 15 such associations are now recognized while Elsson-Steel (1986) has recently produced evidence that essentially all sporadic meteors are of cometary origin.

Several lines of evidence point to the ejection of moderate sized masses from the surfaces of comets. Not only do many comets split but active comets such as Halley's for which near nucleus observations are possible, show sharp condensations that must involve ejected coherent pieces. Comet P/Encke shows almost no continuum in its spectrum but its associated Taurid meteors sometimes include fairly bright fireballs. Radar observations of comet IRAS-Araki-Alcock, 1983 VII, in its near Earth passage indicated an accompanying but detached cloud of particles large enough to be conspicuous at a wavelength of 13 cm (Campbell et. al. 1983). Cometary anti-tails, seen when brighter comets are observed as the Earth crosses their orbit planes, arise from sizeable particles lying very close to the planes of the orbits. The difficulties of the Halley comet missions as they crossed the orbit plane of the comet attest to the existence of these sizeable particles.

In view of the various methods now available to study cometary debris including infrared observation from spacecraft such as IRAS, perhaps it is time to re-evaluate the total contribution of comets to particulate material in the interplanetary complex. Several investigators including Delsemme (1976), Röser (1976), Kresàk (1980) and Mukai et al. (1983) doubt that comets can supply the few tons of tons per second (Whipple, 1976) required to maintain the zodical particles, which are largely destroyed by collisions.

There remains a question as to whether the asteroid Phaethon (NO. 3200, 1983 TB), apparently the parent body for the Geminid meteor stream, may be an old comet nucleus. The Geminid stream has a small aphelion distance (just beyond Mars' Orbit) and a near record small perihelion distance of 0.14 AU. The observed color of Phaethon has been in doubt. Tholen (1985) reports that broad-band photoelectric photometry at five wavelengths from 0.3 to 0.9 μm show Phaethon to be slightly bluer than the Sun, inplying a rare F classification, whereas Cochran and Barker (1984) and Belton et al. (1985) find it to be of S-Class on the basis of spectroscopic observations. The S-classification would place Phaethon colorwise among typical asteroids while the F classification would mean it is possibly cometary.

The Geminid meteoroids themselves are very dense relative to cometary stream meteoroids. Verniani (1967) finds their density to be ∿ 1.0 gm cm^{-3}, about three times the average for those in streams. Whether this high density represents simply the survival of the toughest bodies in short-period orbits so near to the Sun, or whether it represents basically a meteoritic density of carbonaceous chondritic nature remains an open question.

The general question as to whether aging comet nuclei may become indistinguishable from rocky asteroids became an obvious issue with the introduction of the icy conglomerate model for the cometary nucleus. Substantive evidence to settle the question remained elusive until recent years. An important related question concerns the source of the near-Earth asteroids, the Aten-Apollo-Amor groups, in orbits somewhat resembling those of old comets. These bodies have quite finite lifetimes against planetary collisions, measured in tens of millions of years. Aging comets seemed to be a likely renewable source for such kilometer-sized bodies whereas the asteroid belt seemed impotent to renew the supply.

Infrared spectroscopy and photometry have now been applied to a large number of asteroids and also to a few inactive comet nuclei at great solar distances. Photometry alone provides a comparison of the spectral reflectivities of the bodies in question while the addition of diameter measures, either directly or via temperature measures, adds a knowledge of the albedos.

A very thorough study of the superficial appearances of comets compared with the various classes of asteroids has been made by three active contributors to the field, Hartmann, Tholen, and Cruikshank, HTC (1986). Their compilation of cometary albedos (geometric reduced to visual wavelengths) from 13 measures or averages (17 comets in all) leads to a mean value of 0.051 ± 0.001. The values range from 0.01 to 0.13 with σ for one determination of ± 0.037. The scatter may well arise largely from measuring errors and from dusty atmospheres. The mean value is in excellent agreement with the values determined for the nucleus of Halley's comet by the Vega and Giotto space probes, 0.04. The Moon's geometric albedo is 0.115, with a Bond albedo of 0.065. If the typical cometary nucleus scatters and reflects light like the Moon, the Bond albedo of comets would average about 0.02, extremely black indeed!

The distribution of infrared photometric color parameters for comets are restricted on the V-J versus J-K diagram and on the J-H versus H-K diagram (see Hartmann et al, 1985) to regions occupied by asteroids of color classes C, P, and D, particularly class D (see Gradie and Tedesco, 1982, for definition). The C, P and D class asteroids have extremely low albedos and are somewhat reddish. They occupy the outer regions of the asteroid belt, including the Trojans, which move near the Lagrangian points in Jupiter's orbit. Hidalgo, long recognized as an asteroid having an orbit like that of a short-period comet, is, for example, in color class D as are the tiny 1983 SA and 1984 BC, with aphelia also exceeding 5.3 AU. The three comets P/Neujmin 1, P/Arend-Rigaux and P/Schwassmann-Wachmann, 1, are also of color class D, in the Table by HTC. The mysterious Chiron, in a "Chaotic" orbit between Saturn and Uranus, has a similar color, a sub-set of Class C. Thus HTC find that 11 asteroids with orbits suggesting a possibly cometary origin fall in the color classes of D(5), P(1), C(1), and C-like (4).

On the other hand, among 13 Aten-Apollo-Amor objects HTC find only one in the C class (an Aten) and the others in more typical asteroidal color classes. Because meteorites are probably mostly fragments from asteroids in near-Earth orbits, the apparent asteroidal character of these bodies is consistent with the chemical nature of meteorites as compared with Brownlee particles. In his accompanying paper Wetherill elaborates on Wisdom's (1983) theory concerning the chaotic perturbations of the Aten-Apollo-Amor asteroids from the heart of the asteroid belt.

Because of the similarities of the apparent surfaces of the outer asteroids to those of comets and also to some of the icy satellites of the giant planets, HTC support the thesis that ices formed near Jupiter's orbit and beyond during the formation of the Solar System. In their picture Jupiter comets, Saturn comets etc., accreted as building blocks of the outer planets and also contributed to the satellite systems. Because of violent collisional losses near the giants, Jupiter and Saturn, the comets of the Öpik-Oort Cloud may have been derived primarily from the comets near Uranus and Neptune.

Comets to Asteroids? How?

There are at least three obvious circumstances whereby comets could develop into bodies superficially like asteroids and yet another process that might lead to similar results:

a) In their growth comets may have first accreted from rocky material and later added a dusty-ice envelope. Such a comet in a short-period orbit would eventually sublime away its icy envelope and become an inactive asteroidal body.

b) Large comets with radii greater than perhaps

20 km may have accreted from dusty-ice particles but have been heated radioactivity until the volatiles were removed from their cores. When finally exposed, these cores might appear asteroidal. This subject has been discussed by Whipple and Stefanik (1966). Only if the accumulation of comets occurred in a time less than a few million years could radioactive ^{26}Al, if present, have heated the cores of small comets. Otherwise the usual radioactive elements of ^{40}K etc. could have been but only for rather large comets.

c) The coarser meteoritic material in active comets may fall back to the surface, insulate and finally choke off cometary activity even though an icy core remains. Only H_2O ice would probably remain in the core as its temperature would probably have risen to a level that would sublimate more volatile ices or amorphous ices.

d) More speculatively, collisions among comets during their accretion period or even later may have volitalized much of the ice and left large volumes of meteoritic material throughout the cometary bodies. The destructiveness of such collisions has not been studied in detail, being barely suggested by Donn (1963). Possibly, though, such collisions may have returned essentially all of the materials of the comets to the solar (or primitive) nebula. The kinetic energy at a velocity of 2.3 km/sec equals the latent heat of vaporization of extremely cold H_2O ice (11,700 cal/mol). If, for example, comets of the Öpik-Oort cloud were the primary building block of Uranus and Neptune, those we have recovered must have been removed early in the evolution of those planets before large velocities were built up by the growing protoplanets. Or perhaps these have luckily escaped ahead -- on collisions. The nucleus of Halley's comet, incidentally, appears to be a badly battered body.

The observations of comets produce indirect evidence that the active comets we observe may not have large meteoritic cores, thus weighing against circumstances a) and b). Sekanina (1977), in his study of split comets, finds that the smaller pieces broken from comets move away from their primaries by the action of differential, non-gravitational jet forces radial to the Sun. Their survival times correlate with their non-gravitational forces according to about same logarithmic relationship independent of the survival time or identity of the piece. Thus eighteen pieces broken off from a dozen different comets are somewhat similar in structure. No evidence to date suggests that split comets are inherently different from other comets but, of course, rocky cores may not have split off.

The various members of the Kreutz Sun-grazing family of comets appear to be much alike. They almost certainly are pieces broken tidally from a very large comet in the not-too-distant past. In this case, however, asteroidal inclusions, if present, probably would not have been observed.

Several comets appear to have disintegrated and disappeared while under observation. Sekanina (1984) has described the process for a half dozen, including the most famous, P/Westphal, 1852 IV, that faded out on the way to perihelion as 1913 VI, never to be found again. His descripttion follows: "When discovered, they typically display a prominent, star-like central condensation, but a fading sets in very suddenly and the central condensation disappears usually in a metter of days. At the same time the coma is often (but not always) expanding gradually and becomes progressively elongated. Its surface brightness is decreasing (sometimes with erratic light variations superimposed) until the comet's whole head completely vanishes. The tail can become the brightest part of the object and survive the head."

If these descriptions are truly to be accepted as recording of the death throes of small comets, it is interesting that Sekanina usually finds the remnant dust tails to consist of particles greater than 50 - 100 μm. In contrast, the end of the sun-grazer 1887 I, undoubtedly a broken piece, involved micron and submicron particles, typical of most ordinary comets. Were the initial grains at the very cores of comets typically > 100μm in dimension? In any case these disintegrating comets also tend to support the thesis that active comet cores do not consist of huge meteoritic or rock aggregates.

Half a dozen or so other short-period comets have not been rediscovered even after thorough searches with improved telescopic equipment. Probably they were active for a while and then lay dormant. Thus a few comets seem to have died passively, ceasing to show hazy or central condensations even near perihelion. If discovered now their stellar appearance would cause them to be called asteroids in short period cometary orbits. Marsden (1970) list two such examples and discusses some of the orbital considerations. All of these comets probably have thick layers of meteoritic debris that insulate the ices of their interiors from rapid solar heating. One wonders how many of the Trojan asteroids or those of D, P or C color classes would develop comas and appear cometary if they should collide with sizeable interplanetary bodies.

The high temperatures observed on the inactive surface of the nucleus of Halley's comet demands that this surface be covered with a good insulating material, presumably dust. The evidence that Encke's comet (Whipple and Sekanina, 1979) has one hemisphere that is now mostly inactive supports the hypothesis that accumulated particulate debris covers underlying ices and curtails comet activity.

Many of the larger particles raised by sublimation must fall back to the nucleus. The largest one may never rise from the surface. Many must survive breakage from wasting on slopes and mesa-like elevations, from material falling back, and from thermal stresses of night to day on a rotating nucleus. In fact it seems easier to imagine process to choke off comet activity than to promote it.

All of this evidence is consistent with comets having been formed by the accretion of interstellar type dust at extremely low temperature, the basic material being of the nature described and studied in the laboratory by Greenberg (1984).

Space missions to comets and asteroids are clearly needed to lead to an understanding of the nature and origin of these fundamental building blocks of the Solar System.

Conclusions

Comet contribute most of the particles that produce the Zodiacal Light and intercept the Earth's atmosphere as meteors. The colorimetric and reflective characteristics of comets and the outermost asteroids are so similar as to suggest that some short-period comets finally become inactive, indistinguishable from some asteroids. But this is probably not true for the near-Earth asteroids. The cometary evidence suggests that aging comets may become inactive because they are choked by overlying particulate material that prevents solar heat from sublimating the underlying ices. No strong evidence suggests that pristine cometary cores are intrinsically rocky. Space missions to comets and asteroids are urgently needed.

This study has been supported by the Planetary Geology Program of the U.S. National Aeronautics and Space Administration.

Table 1

Species Observed in Comets.

Coma, Head	H, C, C_2, $^{12}C^{13}C$, C_3,
	CH, CN, CO, CO_2, CS, HCN, HCO, CH_3CN,
	NH, NH_2, NH_3,
	O, OH, H_2O, S, S_2.
(Near Sun)	Na, K, Ca, Cr, Mn,
	Fe, Co, Ni, Cu, V(?), Ti(?).
Ions (tail)	C^+, CH^+, CN^+, CO^+, CO_2^+,
	N_2^+, OH^+, H_2O^+, Ca^+, H_2S^+.
Dust	Silicates and hydrocarbons, mostly dielectrics. (See later papers for additions from Halley comet missions.)

NEWS FROM VISITS TO HALLEY'S COMET

Fred L. Whipple
Smithsonian Astrophysical Observatory

I am indeed honored and pleased to participate in this joint meeting with the Royal Society, which has survived since about 12 years before Halley first observed the comet that carries his name. The Philosophical Society was formed later by about one revolution of the comet, some fifteen years before its recovery in 1758 as predicted by Halley. At the current apparition a unique and truly remarkable event has occurred. Three spacecraft have visited the comet, passing dangerously close, well within the coma or major dust and gas envelope surrounding the nucleus (Fig. 1). My major interest has been in the nature of this discrete nucleus which I postulated many years ago to be an icy conglomerate mixture of fine dust embedded in a mixture of various ices, water ice probably being the most prevalent.

SUMMARY

For the first time in history spacecraft have invaded the coma of a great comet and survived to send back pictures of the nucleus and a host of scientific data. This is a preliminary report about the first images of the hither-to unexplored nucleus of a great comet. The nucleus is larger and blacker than expected and provides clues about the origin of comets and of the solar system.

Recently, within the interval from March 6 to March 14, two USSR spacecraft, the Vegas, two Japanese spacecraft and the Giotto mission of the European Space Agency passed by the nucleus of Halley's comet.* This concentration in time was, in fact, unfortunate because Halley's comet typically reaches its maximum brightness approximately a month after it passes closest to the Sun, at perihelion (9 February 1986),

*Preliminary scientific reports from all the experiments in these missions are contained in *Nature* 321:259-366 (15-21 May) 1986.

At that time it emits gas and dust at the maximum rate as induced by the sublimation of the ices heated by solar radiation. The dust and small particles presented a serious hazard to the spacecraft which were passing through the dust at speeds of some seventy or more kilometers per second. The reason for the concentration of the missions at the most dangerous time was, however, a practical one. A severely limited amount of energy was available for propelling the spacecraft. Hence they perforce moved close to the Earth's orbit and necessarily met the comet near the time when it crossed the plane. This, by chance, occurred near the time of maximum activity. The extremely high relative velocities of the encounters were similarly caused by the fact that Halley's comet itself is moving almost in the reverse direction around the Sun from that of the Earth in its orbit. Thus the missions met the comet nearly head on (Fig.2).

It was my privilege to be present in Moscow at the Mission Center to observe the telemetric reports from two Vega spacecraft on March 6 and on March 9. An unusual amount of international cooperation was involved in these visits, which was sponsored by an Inter Agency-Consultative Group (IACG) and the International Halley Watch. In this country the IACG was supported by the National Academy of Sciences, the International Halley Watch by the Jet Propulsion Laboratory of the National Aeronautics and Space Administration. This international scientific comradeship was largely made possible by the activities of Dr. Roald Sagdeev of the USSR Academy of Science. International press, radio, and TX representatives were welcomed.

The images of the comet were displayed on large screen television projections in beautiful false colors to show variation in brightness from the center of the nucleus region throughout the observable areas of the comet. The comet itself was, in fact, almost uniformly white with a very slight reddish tinge, there being almost no color effects caused by differential scattering of sunlight by the various gases. The first *Vega* approached within 9,000 kilometers of the nucleus of the comet. The eroding effect of the dust, like that on an automobile windshield in a violent dust storm, was so serious as to reduce the electric power of the solar panels by about 45 percent. An even greater loss was experienced by the second *Vega* on March 9 that passed within about 8,000 kilometers of the nucleus. In the latter case several of the ten experiments aboard the spacecraft were partially incapacitated by the passing dust.

These first images show what was seen in Halley's comet first by the great mathematician and astronomer Fredrich Wilhelm Bessel in 1835. Very near the nucleus the jets are directed *towards* the Sun, whereas, in the normal less resolved images we see a curtain of light around the nucleus stretching off in the opposite direction from the Sun. A fountain effect occurs on the sunny side. The motion is reversed by the pressure of sunlight on the dust particles coming out from the nucleus and by the pressure on the positively charged ions of the gases by the solar wind blowing away from the Sun and by the comet at some 400 kilometers per second. These pressures produce cometary tails. Otherwise the images obtained by the first *Vega* spacecraft were very difficult to interpret and rather confusing at the time. Figure 3 (a,b) shows the nucleus before the closest approach to the comet with the Sun to the left in the top images. Two bright spots or rays are evident. If you happened to be watching the live television and were confused as to what you were seeing at the time, so was I. At minimum distance (Fig.3,c) the Sun was in back of the spacecraft. In these images the scale should be stretched vertically so that the comet image is very nearly a circle. The dimension here is about 20 kilometers across the picture. Figure 3,d shows the image with the Sun to the right after closest approach. What part of these images represented the nucleus? The interpretations were so difficult that for the first day or two after *Vega* 1, I wondered whether we might indeed have been seeing a double comet: two components orbiting about each other.

Three days later as I watched *Vega* 2 approaching the comet, I was very unhappy because the presentations showed some very large images of the huge coma and not the nucleus of the comet. I learned afterwards that there had been some malfunction in the microprocessor of the spacecraft controlling the pointing of the camera. In a last minute desperation action the engineers ordered the starfinder to set on the comet. Being intended *only* as a finder it pointed the camera some three minutes of arc away from the actual center of the comet nucleus. The exposure of the camera was set by the intensity of the light where the camera was pointed, in this case out at a faint part of the coma. Hence the images were over-exposed and gave no real information about the nucleus. By a happy coincidence the turning of the spacecraft at nearest passage was so rapid that the camera could not keep up. Thus by luck the proper light levels were acquired for two exposures at the nearest approach. (Fig. 4.)

Two bright centers show in the image of *Vega* 2 some 8000 kilometers away with the Sun in back of the spacecraft. A large bright ray extends below. The separation of the centers is roughly 8 kilometers. Very thorough analysis will be required to delimit the edges of the nucleus in these pictures. Note that the dimensions seem to depend upon the level of the exposure. What we are seeing are one or two very bright rays coming from the nucleus of the comet, mostly dust illuminated by sunlight, the brightest ray extending below in Figure 4.

Five days later at Darmstadt in West Germany I was privileged to see the results coming in from the European Space Agency's Giotto Mission. The Giotto spacecraft was given that name be cause of the famous painting of the Nativity scene made in 1305 by the Italian painter Giotto. He depicted a comet that was probably Halley's, which he could have seen in 1301. The star seen by the Wise Men in the biblical account could not have been Halley's comet because it passed perihelion in 12 B.C.

Between the *Vega* 2 and Giotto missions there occurred a remarkable example of international scientific cooperation. The scientists wished to fly the Giotto spacecraft within about 500 kilometers of the nucleus of Halley's comet. Relevant is the surprising fact of current space lore that we can track craft through space with an uncertainty of perhaps 50 kilometers, but our observations of astronomical bodies, particularly of comets, are generally uncertain by some two or more hundred kilometers. The Giotto spacecraft, which aimed to miss the comet nucleus by 500 kilometers, might have passed the comet much more closely than expected and been destroyed by the surrounding particles. Thus OPERATION PATHFINDER was set up. Its purpose: to utilize the observations of the nucleus of Halley's comet made by the two *Vega* spacecraft to locate it precisely in space, and thereby enable the Giotto mission to be directed with much greater precision. The resultant uncertainty in the miss distance from the spacecraft to the nucleus of Halley's comet was estimated to be 40 kilometers. Between March 9 and March 14 a slight correction was made in the motion of the Giotto mission aiming it to miss the comet by 540 kilometers, reducing the probability that the nearest approach would be much less than the desired 500 kilometers. The achieved miss distance, in fact, was 605 kilometers, showing that the actual error in the space position was about 1.5 times the estimated value, an extraordinarily good result.

Although this successful operation appears simple in retrospect, it actually involved a large number of great radio antennas located around the planet and operated by many different countries.

It also involved detailed advanced planning, excellent communications as well as rapid and accurate calculations made by computing centers in two continents. The success of the PATHFINDER OPERATION and the nature of the images of the cometary nucleus as seen by the *Vega* spacecraft had already given us one important scientific result about which a number of us had speculated for at least three decades. The diffuseness of the apparent center of a comet and the poor resolution of such images as seen through our tremulous atmosphere had made us uncertain as to whether the center of brightness neasured for a comet was actually the same, to astronomical accuracy, as the direction to the center of gravity or to the true nucleus of a comet. The *Vega* images showed clearly that we were seeing jets from the nucleus of a comet and that the center of the brightest of these jets fell somewhere on the nucleus. Therefore, well within the astronomical accuracy, the center of light represented the center of the mass of the nucleus, as a result of great significance in the interpretation of the calcuted orbits of comets.

As we first watched the images of Halley's comet from the Giotto spacecraft at several tens of thousands of kilometers from the nucleus, we saw two bright rays much as the *Vegas* had shown. But we also saw a mysterious dark patch opposite to the Sun (from the two bright rays, Fig. 5). In real time things were happening rapidly. Very quickly we passed through the images shown in Figures 6-9 until the spacecraft reached some 1800 kilometers from the nucleus, at which time the telemetering suddenly stopped! Apparently a tiny particle, perhaps the mass of a grain of rice striking the spacecraft at some 70 kilometers per second, was able to displace the antenna that carried the radio images back to Earth. Some 32 minutes later the telemetering was resumed but by that time the spacecraft had passed far beyond Halley's comet, perhaps to return near the Earth about 1990.

We immediately realized that the dark region shown near the bright rays on the nucleus was in fact the silhouette of the nucleus itself, seen against the background of sunlight scattered by the surrounding dust. In other words, we saw for the first time the silhouette of the nucleus of a comet from which we could discern the bright dust rays ejected from a very few active areas. The Giotto mission had been lucky! The dust level near the nucleus of Halley's comet was lower than when the *Vegas* had gone by. As a consequence, the higher intensity of the scattered light in the *Vega* pictures obscured the limb of the nucleus so that rather subtle analysis has been required to ascertain the true shape. We had seen only the rays emanating from the nucleus, but not the nucleus itself. The last images taken at $\sim$ 1800 kilometers from the nucleus has a width of 3.2 kilometers and shows details of the bright ray system and a filamentary structure near the bright limb of the nucleus. Is this a series of craters somewhat smaller than 1 kilometer in diameter? Are the bright somewhat circular regions only sources of dust illuminated by sunlight, or are they brighter regions on the surface of the nucleus? The topography of this part of the nucleus is yet uncertain. The ray seen near the center in Fig. 6 may be a "mountain" peak a few hundred meters in height illuminated in the morning sunlight, but that too is somewhat speculative. We can be sure, however, that the irregularities along the nearly straight edge of the nucleus do represent topographical features, suggesting a fairly rough surface.

The length of the nucleus is well defined from the dark edge at the bottom of the pictures to somewhat beyond the bright spot near the top, some 15 kilometers (see Fig. 10). The width is much less certain. From photometric cross sections of the nucleus I formed a suggestion that the maximum width is some 8 or 9 kilometers.

These images coupled with compositional data validate completely my original concept that the heart of a comet is truly a dirty snowball. Finding the dimensions adds another important piece of information that confirms recent infrared measures showing the nucleus of a comet to be a very black object. With the knowledge of the actual dimensions of the nucleus of Halley's comet coupled with its brightness out at some 10 times the Earth's distance from the Sun before the ices had become activated by Sun light, we can calculate the reflectivity of the nucleus (*albedo*). It turns out to be about 1/3 that of the Moon seen in the full phase. If the angular scattering of sunlight by the nucleus of the comet is similar to that by the Moon, the total light reflected from the surface of the nucleus adds up to only about 2 percent of the incident light. In other words, the cometary nucleus is blacker than coal, blacker than charcoal and probably comparable to black velvet observed from a direction where the sheen does not show.

The result coupled with the dust measures reported in subsequent papers has great significance in visualizing the origin of comets. Comets appear to contain very fine hydrocarbon dust particles such as are abundant in intersteller molecular clouds, one of which constituted the great nebula that collapsed to form the solar system some 4.5 billion years ago. Halley's comet ejects a great deal of extremely fine dust, not measured previously because the dimensions are too small to scatter sunlight significantly. In a somewhat porous solid made up of such fine dust the rays of sunlight scatter down into the material and are largely lost before they can find their way out again, thus making the cometary material so extremely black.

The Giotto images tell us nothing about the three dimensional shape and the rotation of the nucleus because they are all taken from nearly the same direction. It is not certain whether the true shape can be determined well by intercomparison with the *Vega* images, but an all-out effort will certainly be made. The 52-hour rotation period found by Zdenek Sekanina and Steven M. Larson from the 1910 photographs have been confirmed by the Japanese spacecraft and from the *Vega* images. The spin is in the sense of the orbital revolution about the Sun as I predicted in 1950. Whether the pole has shifted any in these 76 years is yet to be determined.

This short preliminary report on the images of Halley's comet can provide only a taste of the many results to be expected from 10 scientific experiments on each of the three missions that went close to the comet and the additional experiments on the two Japanese spacecraft that approached it only at a minimum distance of 750,000 kilometers. The imaging definitely shows that there is a discrete nucleus of dimensions not far from expectations, although a bit larger. And the nucleus is extremely black giving us a clue as to its probable origin from the accumulation of tiny interstellar dust particles containing carbon, immersed in an icy matrix. The nucleus appears to be badly battered, suggesting that it accumulated by colliding with other comet nuclei.

The many results to come from the other experiments will deepen our knowledge of comets, their origin and, to some extent, our own origins. Next is needed an extended rendezvous mission in which a spacecraft hovers around a comet for months or even years to observe details of the processes and composition. And eventually we must bring back samples for the subtle analysis possible only in great laboratories.

I am very indebted to the International Halley Watch for enabling me to observe the live results from the *Vega* spacecraft as received

in Moscow and to the National Aeronautics and Space Administration supported research on the imaging camera of the Giotto Mission by Ball Aerospace of Boulder, Colorado. In addition, I congratulate my seventeen colleagues who are responsible for the design, construction and operation of the Giotto camera on a magnificent result. I mention specifically the Project Scientist of the Giotto team, Rudeger Reinhard, the chief engineer of the Imaging Team, Wilhelm Schmidt and the principal investigator of the Imaging Team, Horse Uwe Keller whose energy and scientific and engineering acumen were a major factor in the success of the camera. Sadly, a famous member of the Team, Ludwig Biermann, did not survive to see the culmination of this experiment.

My research has been partially supported by a grant from the Planetary Division of the National Aeronautics and Space Administration.

CAPTIONS

Fig. 1 Six million kilometers of the head and tail of Halley's Comet 9 January 1986, (Taken at the Calar Alto Observatory in Southern Spain,) courtesy Dr. Kurt Kirkle of Max Planck Institut fur Astronomie, Heidelberg.

Fig. 2 Inner part of orbit of Halley's Comet tilted 18^{0} in reverse direction from Earth's orbit (outer projection) and the Giotto orbit (inner projection).

Fig. 3. Vega I images of nuclear region of Halley's comet, 6 March 1986

a) Before nearest approach, Sun left.
b) Just before closest approach, Sun left
c) At closest approach, Sun in back of observer
d) After closest approach, Sun right

Fig. 4. Vega 2 image of nuclear region of Halley's comet, 9 March 1986. Sun in back of observer. Width of picture about 15 kilometers

Fig. 5. Giotto image of Halley comet nucleus, 19 March 1986 at distance of 25,660 kilometers

Fig. 6. Same as Fig. 5 at distance of 18,300 kilometers. Width of picture 30 kilometers

Fig. 7. Same as Fig. 5 at distance of 7100 kilometers Width of picture 12 kilometers

Fig. 8. Same as Fig.5 at distance of 4600 kilometers Width of picture 7.7 kilometers

Fig. 9. Same as Fig. 5 at distance of 2800 kilometers. Width of picture 4.6 kilometers. Sun at left and 29^{0} beyond level of picture

Fig. 10. Outline of Halley comet nucleus from Giotto images. Dotted outline is estimated. Various jets of sun-illuminated dust are indicated.