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Halley's Comet Wrap-Up

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COVER: With images like this one, scientists were at last able to take a close look at the nucleus of Halley's Comet. Here sunlight is coming from the left, heating the icy body so that dust and gas jets erupt from its surface. Near the top are bright spots, and below them is a crater-like feature about 1.5 kilometers in diameter. This could be a slump feature formed by the outgassing of nearby jets. Below and right of the "crater" is a bright feature about 400 meters high that some scientists call "the mountain." Image taken by the Halley Multicolor Camera © 1986 Max Planck Institut für Aeronomie, Lindau/Harz, F.R.G., provided by H.J. Reitsema and W.A. Delamere, Ball Aerospace

The naming of comets can, indeed, be a very difficult matter. Traditionally these small, icy solar system bodies were named for their discoverers. But because some people are very persistent (for example, there are four Comets Meier) a particular name is needed for each individual comet. Thus, at discovery a comet is assigned a letter designation based on the order of discovery or recovery in a certain year. So, Comet 1982i was the 9th comet found in 1982. Later, comets are assigned new names based on their perihelion (closest approach to the Sun). 1984 XXIII was the 23rd comet to pass perihelion in 1984. Confused? Here is a poetic attempt to explain.

THE NAMING OF COMETS (With apologies to T. S. Eliot)

BY DAVID H. LEVY

The naming of Comets is a difficult matter,
It isn't just one of your holiday games;
You may think at first I'm mad as a hatter
When I tell you, a comet has THREE DIFFERENT NAMES.
First of all, there's the name that the family use daily,
Such as Whipple, Wilk-Peltier, Wirtanen or Wolf,
Such as Hubble or Humason, Honda, P/Halley—
All of them sensible everyday names.
There are fancier names if you think they sound sweeter,
Some for the gentlemen, some for the dames:
Such as Grigg-Skjellerup, de Kock-Paraskevopoulos,
Schwassmann-Wachmann, Herschel-Rigollet, Tsuchinshan 1,
Churyumov-Solodovnikov, Bappu-Bok-Newkirk—
But all of them sensible everyday names.
But I tell you, a comet needs a name that's particular,
A name that's peculiar, and more dignified,
Else how can he keep up his tail antisolar,
Or spread out emissions, or cherish his pride?
Of names of this kind, I can give you a score.
1910a, '84u, '86b, and such,
Or '65f, '66b, '83d—there's more—
Names that never belong to more than one comet.
But above and beyond there's still one name left over,
And that is the name that at first you can't guess;
The name that no human research can discover—
Until long after the comet's come and it's gone,
Like Nineteen hundred fifty-nine-X—
But the COMET HIMSELF KNOWS, and won't now confess.
When you notice a comet in profound meditation,
The reason, I tell you, is always the same:
His mind is engaged in rapt contemplation
Of the thought, of the thought, of the thought of his name;
His rotational, orbital
Coma-morphological,
Deep and inscrutable singular Name.

David Levy is a member of the International Halley Watch Near Nucleus Studies Network in Tucson, Arizona. In January he discovered his second comet, Levy 1987A, whose name, unfortunately, did not fit into the meter of this poem.

Studying Halley's Comet from Earth and from Space

BY JÜRGEN RAHE

FOR CENTURIES, COMETS HAVE BEEN studied by scientists living and working in many different countries and cooperation has been an essential part of their science. Because comets appear only briefly in our sky and because Earth never stops turning, no one scientist or observatory can hope to make comprehensive observations of any comet. And not all places on Earth are equally good for watching a comet. In the case of Halley's Comet, as it nears the Sun and glows its brightest, it swings "south" of Earth, below the ecliptic (the plane defined by the planets' orbits) and so appears highest in the southern skies. But on its way in and out of the inner solar system, it crosses the ecliptic, and so is best seen from the northern hemisphere.

So, if scientists were to obtain the best possible coverage of Halley's Comet during its 1985-86 apparition, we would have to organize and set up a network of observatories and observers distributed as uniformly as possible around the world. And since several countries were planning to send spacecraft to meet the comet, their observations should be coordinated with those from Earth.

In 1979, Louis D. Friedman, then at NASA's Jet Propulsion Laboratory and now Executive Director of The Planetary Society, proposed a worldwide organization of professional and amateur astronomers, called the International Halley Watch (IHW), to coordinate observations of the comet over the entire apparition. With this effort, researchers could document the global properties and evolution of Halley's Comet in the inner solar system. National and international science groups endorsed the IHW, the American and West German space agencies agreed to fund it and two Lead Centers were established, the Western Hemisphere Office in Pasadena, California and the Eastern Hemisphere Office in Bamberg, Federal Republic of Germany.

The International Halley Watch follows a long tradition of cooperation across national boundaries, beginning in the 16th century. At that time, scientists generally accepted Aristotle's idea that comets were poisonous vapors in Earth's atmosphere. Then, in 1577, Tycho Brahe combined careful position measurements he had made from his observatory on the island of Hven near Copenhagen with those obtained by Hagecius in Prague. With these widely spaced measurements, he determined that the comet displayed a very small parallax. (That is, its position against the star background differed only slightly in the two observations.) He concluded that the comet had to be at least 240 Earth radii away — four times farther from Earth than the Moon, and so well beyond the atmosphere.

By combining observations made in different countries, Brahe clearly demonstrated that comets move in interplanetary space beyond Earth's orbit. While he did not describe correctly the orbits of the planets and the comet, his measurements profoundly changed the scientific view of comets.

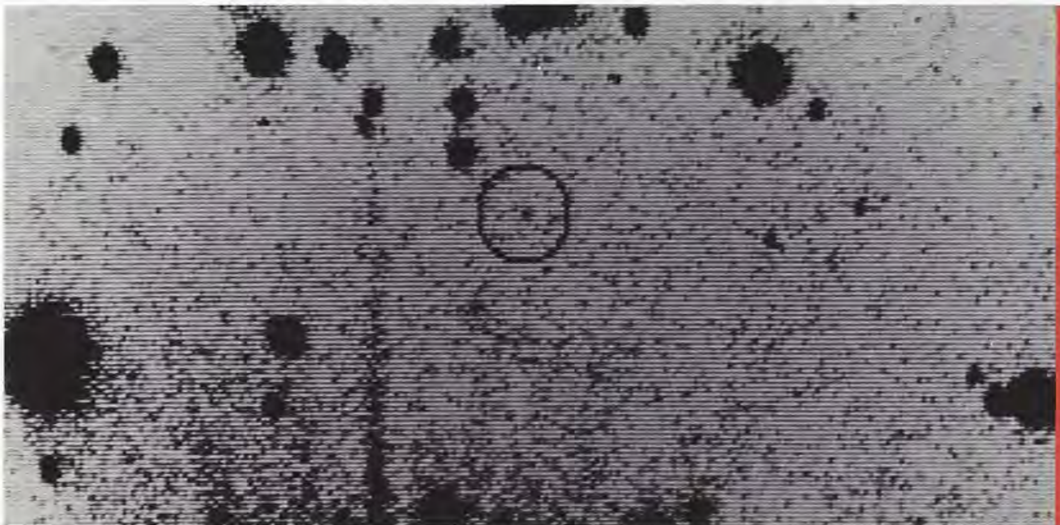
About a century later, in 1687, Isaac Newton described the motion of a comet in Book II of his *Philosophiae Naturalis Principia Mathematica.* Newton collected observations of the Great Comet of 1680 made in different locations in England, France, Germany and North America, and used these measurements to prove that comets move in orbits around the Sun and that they are independent members of the solar system.

In 1835 F. W. Bessel's extensive observations of Halley's Comet clearly showed that single observations provided only a snapshot of the comet and that, for most studies, observing sequences were needed. Realizing this, the Astronomical and Astrophysical Society of America (now the American Astronomical Society) in 1909 created a special Comet Committee to prepare a photographic history of Halley's Comet:

"The ends to be served by these photographs and similar ones obtained elsewhere are conceived by the Committee as follows: to give a permanent record, as continuous as possible, of the phenomena and changes (i) in the tail of the comet, with special reference to outgoing masses; (ii) in the head and nucleus of the comet, particularly as to the formation of envelopes and jets."

The committee had much in its favor — thorough organization and well-defined goals — but it lacked several important ingredients: Although it needed and wanted cooperation from observatories all over the world, it did not have international membership; in addition, it did not have the cooperation of participating observatories in forwarding the material obtained to the committee. Nor did it have adequate funding and staffing to follow up the scientific research that it had inspired. Some of the problems are illustrated by this statement from the committee's 1915 report:

"Subsequent developments have made it



On October 16, 1982, a team of astronomers led by David C. Jewitt and G. Edward Danielson "recovered" Halley's Comet and photographed it on its way back to the inner solar system. This began the most intensive study ever undertaken of a comet, which climaxed in March 1986 with the encounters of Vega 1, Vega 2 and Giotto. The copious data collected are being deposited in the archives of the International Halley Watch. Cometary scientists have years of study ahead of them. Image: California Institute of Technology seem inexpedient to carry out the program above outlined. The photographs obtained at the Lick Observatory and at Cordoba are so numerous and excellent that they must have constituted a large part of the material reproduced and, since these observatories have indicated a purpose to reproduce their own photographs and a similar policy seems to be contemplated elsewhere, the Committee deems it unwise to undertake a duplicate publication, and equally unwise to make one from which this material is omitted."

Systematic, worldwide networks have, however, been established and operated successfully. Examples are the Carte du Ciel (Chart of the Sky) Committee, established in the last century or the networks set up in the last decade which organized observations of an entire rotation of Mars at two-hour intervals, with nearly hourly coverage of the great 1971 dust storm on Mars during the *Mariner 9* mission.

Against this background, the International Halley Watch has became the largest international cooperative program ever undertaken by astronomers. Its scientific objectives are: to characterize the structure, physical processes and chemical nature of the comet's nucleus, atmosphere and tails; and to determine the changes that occur over time and as the comet moves through the solar system.

Internationally selected scientists, the Discipline Specialists, organized worldwide networks of over 1,000 professional astronomers in 51 countries to assure that Halley's Comet was continually monitored by every possible technique and at all wavelengths accessible from the ground. This task required complete longitudinal coverage from around Earth. A network of thousands of amateur astronomers also contributed their observations.

As scientists continue to observe the comet, the data already acquired are being reduced and prepared for inclusion in the Comet Halley Archive, which will eventually hold all ground- and space-gathered data from the 1986 apparition.

From the formation of the IHW, we planned to supply the *Vega* and *Giotto* missions with data to help them target their spacecraft. We also wanted to make sure that the brief, close-up spacecraft "snapshots" of Halley's Comet can be placed into the context with the long-duration Earth-orbital and ground-based observations.

Three space agencies — the European Space Agency (ESA), the Soviet-led consortium Intercosmos and the Japanese Institute of Space and Astronautical Science (ISAS) — sent spacecraft to Halley's Comet. ESA launched *Giotto*, Intercosmos sent *Vegas 1* and *2* and Japan sent *Suisei* and *Sakigake*. Their flyby distances ranged from 600 kilometers for *Giotto* to many hundred thousand kilometers for *Sakigake*. And, after its encounter with Comet Giacobini-Zinner, NASA's International Cometary Explorer (ICE) moved to the vicinity of Halley's Comet and made observations from 30 million kilometers away.

Several scientific experiments on board these spacecraft complemented each other, while others overlapped. For example, the Heidelberg dust particle analyzer was installed on board the two *Vegas* and *Giotto*, allowing researchers to compare data taken at different times. And, having several spacecraft passing through the cometary environment meant that we could make measurements over an extended time.

To coordinate planning and data analysis and to increase the scientific return, in the fall of 1981 the four space agencies formed the Inter-Agency Consultative Group for Space Science (IACG). The IACG coordinated the space missions to Halley's Comet, similary to the way the IHW coordinated the ground-based observations. Agreements to exchange ground-based and space data in real time and to include all ground and space measurements in the Comet Halley Archive are results of the cooperation between the IHW and the IACG.

The Pathfinder project is an important example of the international cooperation triggered by Halley's Comet. Targeting a spacecraft to a comet's nucleus is a difficult problem, since the nucleus is hidden by the gas and dust of the coma. Earth-based IHW observations gave the nucleus' position with an accuracy of about 500 kilometers. After the *Vegas* encountered the comet, Soviet scientists were able to provide ESA with an improved nucleus position so that *Giotto* could fly within 600 kilometers of the nucleus — successfully targeted by spacecraft controllers 144 million kilometers away. NASA's Deep Space Network (DSN) supported this effort by tracking the *Vegas* with Very-Long-Baseline Interferometry (VLBI). Ground-based astronomers and space scientists collaborated on this successful endeavor, independent of political or language barriers.

When Halley's Comet returned in 1985-86, scientists around the world were ready for it. The comet was studied from the ground, from Earth orbit, from Venus orbit, from interplanetary space and from within the comet itself. This unparalleled cooperation triggered by Halley's Comet can serve as a model for future international cooperative programs.

In this special issue of *The Planetary Report* we examine the results of this unprecedented study. D. Asoka Mendis summarizes the most recent findings as they were presented in late October 1986 at an international conference in Heidelberg, Federal Republic of Germany. Mike Belton addresses some of the most fascinating questions asked at that conference — and which astronomers are still asking: How does the nucleus rotate? Does it rotate in 2 or 7 days? Does it wobble more than rotate?

Several cometary experts give us their opinions on the question "What is a comet's nucleus?" Lou Friedman recounts some of the more amusing reactions to this latest apparition of Halley's Comet. Marcia Neugebauer tells us about the implications of the Halley's Comet missions for NASA's proposed Comet Rendezvous Asteroid Flyby (CRAF) mission.

These articles, and many in other publications, demonstrate that a new era in cometary science has begun. The flyby missions and the Earth-based studies are only the beginning. When CRAF sends its first measurements back to Earth, we expect to take another major step forward in our understanding of comets, the solar system and its evolution.

Jürgen Rahe heads the International Halley Watch Eastern Lead Center. He is a co-investigator on Giotto*'s PIA dust experiment and is now working as a planetary astronomer at NASA headquarters.*

On March 21, 1986, Halley's Comet was photographed on its way back to the outer solar system. The comet appeared near the Milky Way in the constellation Sagittarius. Its long, straight plasma tail is still visible, but the faint light from its outermost parts is lost in the glowing bright clouds of the Milky Way.
Photograph: R. Hafner, © European Southern Observatory, 1986

The Science of Comets: A Post-Encounter Assessment

BY D. ASOKA MENDIS

IN 1985 AND 1986, THE INHABITANTS of Earth sent spacecraft probes past two comets — icy bodies from the outer solar system that may carry secrets about the birth of our system. These missions to Comets Giacobini-Zinner and Halley, coordinated with ground-based observations, have greatly increased our knowledge of comets. Careful analyses of the data, with complex theoretical modeling, will lead to a much deeper and more secure understanding of these cosmogonically significant objects. Yet we still have many questions, and much needs to be done to answer them.

The Nucleus

The dominant, but not universal, view that a comet's nucleus is an icy body is by no means new. It dates back at least to Pierre Laplace in the early 19th century. However, about 1860, the meteor showers that periodically streak the night sky were associated with the ancient tracks of individual comets. This idea had such impact that comets became regarded as the densest parts of meteor streams. The model of a comet as a "flying gravel bank" held sway for almost a century.

Then, in 1950, in a seminal paper, Fred Whipple resurrected the idea of a discrete cometary nucleus, with his "icy conglomerate" model wherein the nucleus is an aggregate of meteoritic dust and ices, such as water (H_2O), carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4) and ammonia (NH_3). Whipple did not merely resurrect Laplace's early idea, he modified, and most important, quantified it so that it not only explained the dynamical effects on comets' orbits from things such as erupting gas jets, but also described the essential features of all cometary observations. Whipple's theory became the basis of all later work on the dynamics, physics and chemistry of comets. Thus, he put the subject, which had begun to lose its way over a century ago, firmly back on track.

So, when *Vegas 1* and *2* and *Giotto* detected an icy nucleus in Halley's Comet, it was no surprise. We expected it to have an irregular shape; it was variously described as a potato, peanut or avocado. It is larger than anticipated, with a volume of some 500 cubic kilometers. Halley's nucleus is *very* dark — as black as velvet — and reflects only two to four percent of the sunlight falling on it. This makes it one of the darkest objects in the solar system.

In 1952 Armand Delsemme and Pol Swings significantly advanced our understanding of the nucleus' chemical composition by pointing out that, while water is the dominant ice, all other ices, such as carbon monoxide, would be trapped within the water lattice as "guests," forming what is called a clathrate hydrate. The view that water is the dominant ice is supported both by spacecraft and Earth-based observations. About 80 percent of the cometary material detected by the spacecraft was water, with carbon monoxide the next most abundant ice at about 15 percent. When the comet appoaches the Sun and its ices begin to sublime away, the production of this material varies, which is not surprising since most of the nucleus' activity, in throwing off dust and gas, is associated with discrete jets [see back cover]. These jets erupt mainly on the sun-

TOP: Taken January 20, 1986, this beautiful photograph clearly shows some of Halley's Comet's main components. A bright ball of glowing gas and dust, called the coma, surrounds the comet's nucleus and hides it from Earth-based observers. Ionized gas and dust stream out behind the comet to form tails. The warmth of sunlight releases the gas and dust from the frozen nucleus, in a process scientists predicted but couldn't see until the Vega and Giotto spacecraft flew by the comet.

BOTTOM: The above photograph is here computer-enhanced, with the different colors indicating light intensities.

Photographs: Uwe Fink and colleagues, Lunar and Planetary Laboratory, University of Arizona ward side of the spinning nucleus and reduce or cease activity on its "nightside."

Whipple had anticipated that the nucleus would be covered by a dust mantle. If the mantle were present, the surface temperature would be around 300 degrees Kelvin (27 degrees Celsius) at about one Astronomical Unit from the Sun (an Astronomical Unit is the average distance from Earth to the Sun, about 150 million kilometers). The infrared spectrometer on *Vega 2* measured a surface temperature between 300 and 400 degrees Kelvin (27 and 127 degrees Celsius). While warm dust around the nucleus could have contaminated this measurement, the temperature of an evaporating surface of dirty ice at this distance would be less than 190 degrees Kelvin (−83 degrees Celsius). It is therefore reasonable to assume that what we see is not a bare, icy nucleus, but a surface layer of dark, warm dust.

TABLE 1: *Chemical species identified in cometary spectra before the encounter (tentative identifications in parenthesis).*

Atoms	Molecules	Ions
H	C_2	C^+
O	$^{12}C^{13}C$	Ca^+
C	CH	CO^+
S	CN	CH^+
Na	CO	CN^+
K	CS	N_2^+
Ca	NH	CO_2^+
V	OH	H_2O^+
Mn	C_3	H_2S^+
Fe	NH_2	
Co	(H_2O)	
Ni	HCN	
Cu	CH_3CN	
	S_2	
	HCO	
	NH_3	
	(H_2CO)	
	(NH_4)	

Rotation Period

Some photos of Halley's Comet taken in 1910, when treated by modern image processing, show spiral jets emerging from the nucleus. Recently Zdenek Sekanina and Steve Larson used these jets to determine the nucleus' rotation period (52 hours) and spin axis. Assuming that these spiral jets arise from active regions that turn on at sunrise and off at sunset, Sekanina and Larson have also mapped these regions on the comet's surface. The locations of many of the dust jets seen by the *Vegas* reasonably support their predictions. Sekanina and Larson's deduced spin period is also supported both by the *Vega 1* and *2* observations (53 ±0.5 hours) and by the *Suisei* images showing a period of 52 to 53 hours. This spin period observation is further buttressed by brightness variations seen from Earth.

However, a period of 7.3 days was claimed by researchers using two entirely different observations, one based on the comet's brightness fluctuations and the other based on the extended gaseous radicals CN and C_2 (see box) in spiral jets observed by Mike A'Hearn and several collaborators. The authors believe these substances may be released directly from fine submicron-sized grains, too small to be observed optically. (For a further discussion of the puzzle of the nucleus' rotation, see pages 8-10.)

Cometary Dust

The study of comets' dust tails has a long history, dating back about 150 years. To explain the tail of Halley's Comet in its 1835 apparition, in 1836 F. W. Bessel derived equations for the motion of dust particles emitted from the nucleus and driven away from the Sun by some repulsive force. Much later the postulated force was recognized as the radiation pressure of sunlight.

Two questions about cometary dust concern its chemical composition and physical structure, namely its size distribution, shape, bulk density and light-reflecting properties. Before the Halley's Comet encounters, information about dust composition came mainly from the presence of broad emission bands in the infrared spectrum. Data on the dust's structure came from various lines of investigation, such as studies of dust in the tail, and optical and infrared data. Two less direct sources of information were meteor showers and Brownlee particles collected in Earth's stratosphere, which some believe to be of cometary origin.

The dust composition analyzers on the *Vegas* indicated at least three classes of grains: one of compounds of light elements such as carbon, hydrogen, oxygen and nitrogen (CHON particles), a second similar to certain meteorites enriched in carbon, and a third similar to the second but more enriched in hydrogen.

The small, submicron-sized CHON grains may be the "parents" of the CN and C_2 jets seen around the comet. These observations indicate that the "parents" of some of the observed radicals need not be in the gas phase, but could be dust grains. This new concept has emerged since the Halley's Comet encounters.

Dust detectors on the *Vegas* and *Giotto* found large quantities of very small particles, below 0.1 micron in size. The distribution of the various sizes of particles was very interesting. The smallest particles were detected much farther away than we expected. Scientists have suggested several possibilities for this anomalous spatial distribution. One is that the grains have very unusual electrical properties, another is that larger grains leaving the nucleus get broken up and finally, these electrically charged grains are accelerated in the magnetized plasma environment. If larger grains are broken up far from the nucleus, the question arises "What causes this breakup?" Do the aggregates come apart due to the sublimation of their icy glue? Or are they electrostatically disrupted?

While the spacecraft provided us with much new information about the dust particles, including their elemental abundances and their size and spatial distributions, these data are complemented by Earth-based observations. The infrared observations of the Kuiper Airborne Observatory (KAO) tell us about the large dust grains. On the basis of infrared maps, some have already claimed that Halley's Comet released fewer large particles than Comet Giacobini-Zinner.

RADICALS IN SPACE

In chemistry, a free radical is not someone exercising constitutional rights. Instead the term refers to fragments of molecules, such as those that appear when an ultraviolet photon hits a molecule and breaks it apart. Molecules do not like this and they try to recombine or else dissociate farther, into even smaller bits.

As a result, free radicals are highly reactive and normally do not live long in the laboratory. In Earth's upper atmosphere, however, or in the tenuous coma of a comet, the molecules are so far apart that long times may elapse before they can find a partner and recombine. Meanwhile, sunlight and solar charged particles continue to bombard the thin gas, maintaining an equilibrium population of free radicals.

This is why comet spectroscopists observe a zoo of strange molecules, some electrically neutral and some bearing positive charges, out in the coma. Using theoretical models, they try to determine what were the "parents" of these molecular fragments and thus to determine the chemical composition of the nucleus, whose material is thought to represent the primordial matter of the solar system.

But a comet's coma is a very complicated object. The molecules of ice do not just evaporate and split into free radicals. As the gases fizzle out of the nucleus, they carry dust grains with them. An exciting discovery of the spacecraft encounters with Halley's Comet is that these dust grains themselves may contain (or be coated with) ices whose molecules contribute to the gaseous zoo. And the whole picture is further complicated by electromagnetic interactions with the fast-flowing plasma of the solar wind, to which the comet's coma is a large but tenuous obstacle.

In the accompanying article, we are given a first glimpse of what spacecraft have now told us about these phenomena. Scientists will have happy and productive years ahead as they try to untangle the meanings of these data from humanity's first brief encounters with Comets Giacobini-Zinner and Halley.

—JAMES D. BURKE

Gas: Neutrals and Ions

When Halley's Comet appeared in 1910, comet spectroscopy (the science of detecting atoms and molecules by the colors of light that they emit or absorb) was still in its infancy. Even so, several chemical species, both neutral and ionized (CH, C_2, C_3, CN, Na, CO^+ and N_2^+), were identified in the comet's atmosphere and plasma tail. Advances in spectrophotometric techniques, and the extension of the spectral range into the ultraviolet, infrared and radio regions, have enabled us to detect many more chemical species in later comets. (See Table 1 on page 6.)

At present, the study of cometary atmospheres is the only way to tell the chemical composition of the icy component of the nucleus. However, most of the observed species in Table 1 are radicals, that is, chemically reactive fragments of presumably more stable molecules once stored in the nucleus.

One major discovery of the ion mass spectrometers aboard the International Cometary Explorer (ICE) at Giacobini-Zinner and the *Vegas* and *Giotto* at Halley's Comet was the detection of H_3O^+ as predicted by theoretical studies. This established the general validity of atmosphere/ionosphere models.

Halley's Comet loses its tail in this photograph taken March 21, 1986 from the Palomar Observatory. A sudden instability in the Sun's magnetic field can cause a comet's plasma tail to disconnect from the coma. The comet will quickly regenerate another.
Photograph: Robert P. Thickstan, © 1986 California Institute of Technology

The neutral and ion mass spectrometers on *Giotto* and the *Vegas*, as well as the photon spectrometers on the *Vegas*, detected most species identified earlier, and a number of new ones. The ion mass spectrometers clearly identified the dominant H_3O^+, H_2O^+, OH^+ and O^+ ions of the H_2O group. A clear feature in the spectrum is almost certainly C^+. A composite list of other possible identifications includes CO_2^+, CO^+, CS_2^+, S_2^+, CS^+, S^+, CH^+, Fe^+ and Na^+. Heavier, unidentified ions were also observed. The *Giotto* neutral mass spectrometer also detected the dominant neutral species H_2O, O and OH, and probably also CO_2.

The role that dust played both in the dynamics and the thermodynamics of the atmosphere was appreciated before the return of Halley's Comet. But the important role it also plays in the atmospheric chemistry was overlooked. Some dust grains may be the long-sought parents for some of the observed molecular fragments. Clearly we will have to consider this in future atmospheric modeling.

Solar-Wind Interaction

Since 1951, when Ludwig Biermann used observations of comets' plasma tails to infer the continuous outflow of plasma from the Sun (now called the solar wind), comets have been used to delineate the flow of the solar wind. Dramatic changes in the plasma tail, such as its sudden, total disconnection from the comet's head, have recently been associated with discontinuous changes in the solar wind as it flows past the comet. (See the May/June 1986 *Planetary Report*.)

The large-scale structures of the comet-solar wind interactions observed by the spacecraft at Comets Giacobini-Zinner and Halley were very close to predictions. We were surprised, however, by the high level and large extent of the turbulent motions in the plasma. Besides large variations of the magnetic field strength and plasma parameters over many minutes, a plethora of plasma waves was observed. These have focused our attention on the microphysics of the comet-solar wind interaction. Clearly central to all this activity is the pick-up of heavy cometary ions by the inflowing solar wind. The distributions of the pick-up ions have been measured in several experiments on the various spacecraft.

As a result of all these considerations, the theoretical modeling of the comet-solar wind interaction is moving away from the fluid approach to a more kinetic one (that is, dealing with free particles). While partial models are being developed to explain various aspects, we are still very far from a complete kinetic description of the comet-solar wind interaction.

Wrapping Up

The missions to Comets Giacobini-Zinner and Halley, with the coordinated Earth-based studies, have greatly advanced our knowledge of comets. We are only beginning to appreciate the implications of all the new discoveries. This will, in time, lead to a much deeper understanding of comets and their interaction with solar radiation and the solar wind.

Much remains to be done. While we continue to analyze the existing data and build more elaborate intellectual models to explain them, we should not forget the need for more cometary missions to answer some old questions as well as new ones that arose from the ICE, *Vega* and *Giotto* missions.

Scientists know that determining the chemical composition of a comet's nucleus could lead to far-reaching inferences about the primordial dusty nebula from which comets and the rest of the solar system formed. Knowing a comet's internal structure, perhaps unchanged since birth, could help us understand that event. However, our spacecraft did not see the evaporating surface of Halley's Comet, but a dust mantle insulating the ices underneath. A future mission should sample a comet's subsurface material with a penetrator, as in the proposed Comet Rendezvous Asteroid Flyby (CRAF) mission (see pages 16-17).

We have observed the solar wind interaction with a well-developed atmosphere because the comets were fairly close to the Sun. Comets produce a whole range of atmospheres, from a fledgling one when they are out beyond Mars' orbit, to a dense one when they are close to the Sun. CRAF would enable us to study the interaction of the solar wind with the entire range of atmospheres, as well as with the bare nucleus, which may cause interesting effects such as electrostatic levitation and blow-off of fine surface dust. Halley's Comet has given up some of its mysteries, but it and other comets still hold many for us to explore.

D. Asoka Mendis is a professor in the department of electrical engineering and computer science at the University of California at San Diego. He specializes in the study of solar system physics, and particularly, in cometary physics.

The Wobbling Nucleus of Halley's Comet

BY MICHAEL J. S. BELTON

IN THE FIVE YEARS SINCE HALLEY'S Comet was spotted on its way back to the inner solar system, scientists have collected a rich and varied set of high quality data covering every aspect of the comet's behavior. We have made many exciting discoveries, such as the nucleus' unexpectedly large size and a new class of cometary dust rich in organic material, called CHON (for carbon, hydrogen, oxygen and nitrogen) particles. These discoveries, almost instantaneously, led to major changes in our perception of what comets are like and what they can tell us about nature.

Ultimately, insights from detailed scientific analyses of the various data sets and their subtle relationships will have the most profound effect. Such work will extract whatever there is to be learned about the fundamental chemical and physical processes by which cometary nuclei evolve and, perhaps more significant, the processes that created them four or more billion years ago.

Successful integration of ground and space-based measurements is not simple and will require — mainly because of the unpredictability of the comet's activity — precise knowledge of the rotation of the comet's nucleus. Only when we have a precise timetable, or ephemeris, for the illumination of different parts of the comet's surface, can we expect to relate long-term activity of the comet's atmosphere, as seen from the ground, to active regions on the comet's surface or in its atmosphere as seen by *Vega* and *Giotto*.

Now it has turned out that the rotational state of Halley's Comet's nucleus is probably quite complicated, and possibly is similar to the complex motions seen in a disturbed toy gyroscope or a child's whipping-top — gyrations which have fascinated and confounded people for hundreds of years. This has quite abruptly become a very interesting area of research.

Individual pictures of the nucleus, when they are combined, indicate that Halley's Comet is shaped somewhat like an avocado (*Vega* experimenter Karoly Szego's favorite analogy). The pictures also tell us that the nucleus' length is roughly twice its width.

When a rigid object with a complicated shape spins freely in space, it can execute some peculiar motions. If it spins about its shortest axis, it will be in its lowest energy state and the spin will be regular or "pure." If it spins about some other axis in the object, it will have more energy in the rotational motion and generally (but not always) the spin axis will wobble in a complex way, that is, it is said to nutate. This is because the rotational momentum of the object, fixed by the laws of physics, depends on both the spin axis and the distribution of mass in the object. As a result, the direction of the spin axis is not always the same as the direction of the rotational momentum and, since the latter is fixed, the spin axis must move around as the object rotates.

If, in addition, the object is not spinning freely and finds itself torqued by forces that are coherent over time, the spin may increase or decrease and the spin axis may precess, that is, describe a circular path around a direction associated with the applied forces.

Obeying the Laws

Whatever the motion, the object has to obey all of the usual laws of physics and two of these — that the total energy of the system is conserved, and that, unless acted on by external torques, such as jet reactions, the total rotational momentum is conserved — will help us understand what is going on. We begin by investigating what the most likely state of rotation of the comet's nucleus might be.

Over times as short as a single orbit (75 years for Halley's Comet) the rotational energy and rotational momentum will be little changed by interactions with its environment. The energy is determined by the speed with which it spins and this must remain constant. With this spin we can associate a definite period — the length of a day on the comet. The polar, or spin, axis may move around, but how it moves and its relationship to a fixed direction in space defined by the rotational momentum will be described later.

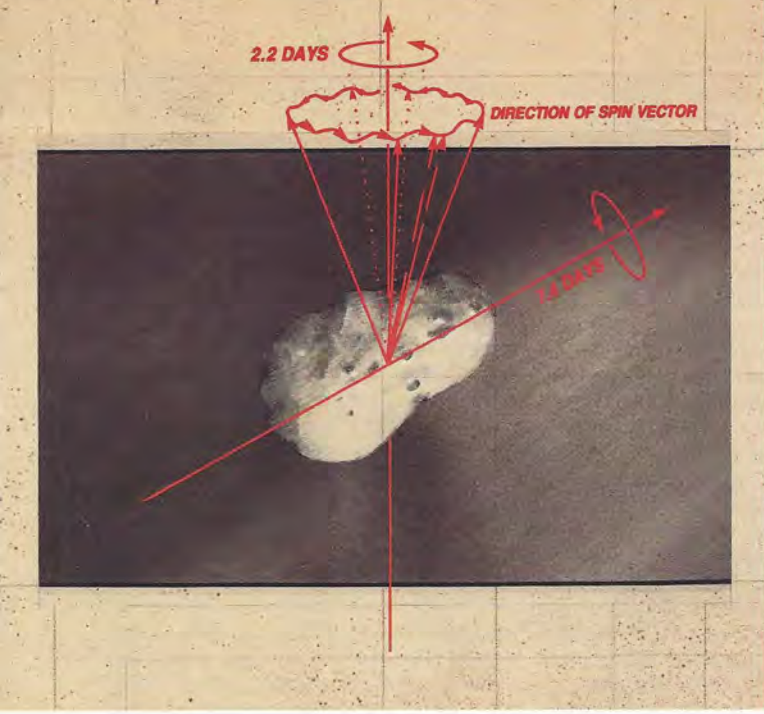
On astronomical timescales, say a hundred million years, it's impossible to conserve the rotational energy, and it is transformed to other energy forms. A small fraction may be lost at each passage through the inner solar system, as intense sunlight heats the comet and sublimed gases and entrained dust flow off into space. Other processes, investigated by planetary scientists interested in asteroids, are also at work: as the object spins it will flex and periodically distort its internal structure. Energy is dissipated through friction and escapes to space as radiated heat. Electrical currents may be induced in the comet as it spins in the interplanetary magnetic field; this too can lead to the dissipation of energy through internal heating.

Long-term conservation of rotational momentum is equally difficult because there are, at each perihelion passage, mechanical torques due to the escaping gas and dust. Gravitational forces, mainly due to the Sun, apply torques to the nucleus and cause its spin axis to precess. However, these precessional motions are very slow (with periods of tens of thousands of years), and I doubt that they are important in the case of Halley's nucleus.

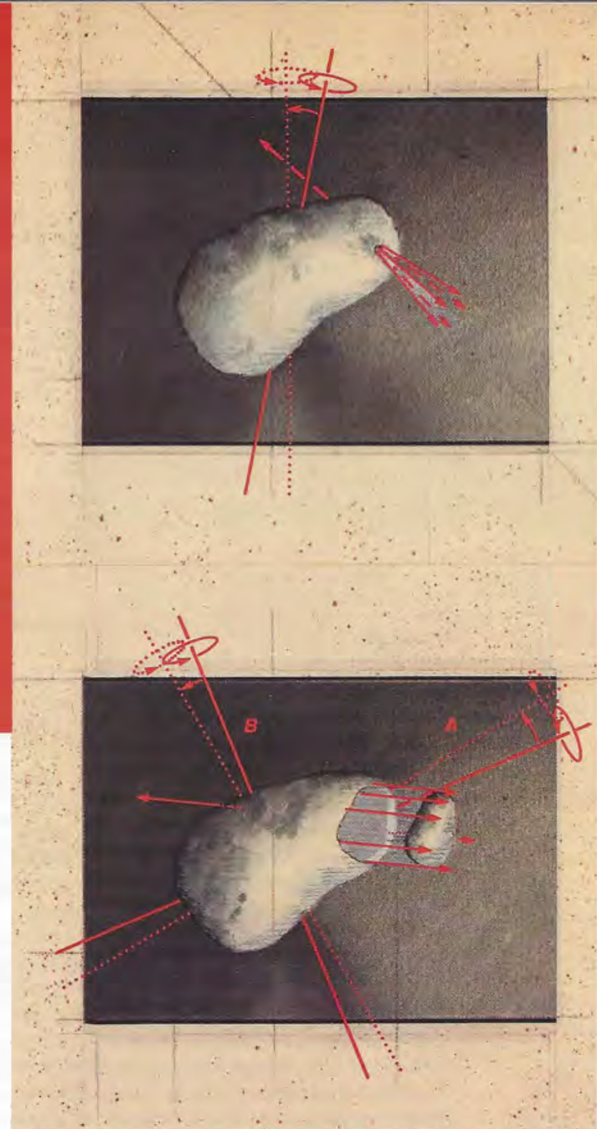
Finally, collisions with other objects in space, as Allan Harris and Joseph Burns have shown, should quite effectively add or subtract to the energy and rotational momentum of asteroids on these timescales. This may also be true for the nuclei of comets.

Detailed studies of the rotational characteristics of many asteroids tell us that they are in their lowest energy spin state, that is, they are spinning about their shortest axes. There are, with few exceptions, such as asteroid 433 Eros, no indications of any complex wobbling or precession in their rotational motion. Asteroids apparently dissipate energy quickly enough (by the

Using information from the Vega imaging system, scientists were able to construct models of the nucleus' shape, which they described variously as a potato, a peanut or an avocado. Here are two im-



As it orbits about the Sun, Halley's Comet moves in some peculiar ways. Shown here are the apparent gyrations of the comet's nucleus. The vertical direction is roughly fixed in space during a single pass by the Sun. The nucleus spins around this axis with a period near 2.2 days. A nodding motion is possibly superimposed on the spin with a period near 3.7 days. The nucleus also seems to roll about its long axis with a period of 7.4 days.



TOP: Jets of gas and dust flowing from the comet's surface are felt by the nucleus as forces and torques. Such activity causes small changes in the comet's motion and, for an irregularly shaped object, will ensure that the comet will wobble. Many small nudges will inexorably add up to a substantial nutation. ABOVE: An irregularly shaped object, such as Halley's Comet, has two axes (A and B) about which it can spin in a stable manner. When a piece comes off the spinning body, the distribution of mass instantaneously changes, shifting the axes. The object finds itself out of balance and begins to wobble or nutate. Over the comet's lifetime, many pieces may break off, adding to the nucleus' nutation. Illustrations: S.A. Smith

internal processes described above) to damp out any wobbling motion resulting from collisions with other objects. According to work done by Joseph Burns and V. Safronov this damping should occur (for something the size of Halley's Comet) in times as short as a few hundred thousand years.

The asteroids are not, however, as fragile and active as comets. Active comets frequently form multiple nuclei, indicating that small pieces have broken off the primary nucleus. When this happens, the nucleus' mass distribution will instantaneously change and cause a small wobble. For a single event this change will be small, but because such events occur quite often (perhaps every few orbits or tens to hundreds of years) there is no time in between events to damp out the induced motion. After hundreds of orbits the wobble may build up, through a random, or "drunkard's" walk, to some sizable value. A quick calculation shows that, in the case of Halley, the spin axis may be disturbed by a modest few tenths of a degree each time. But after a thousand orbits (a mere 76,000 years for Halley's Comet), the net disturbance to the direction of the spin axis could be amplified by more than a factor of ten.

Similarly, at every perihelion passage the cometary nucleus will experience an incessant stream of short-lived (hours-long) torques from the periodic flow of material from active regions. Again we may expect some randomness in these impulses and their accumulative effect may also add up slowly over time, especially if the nucleus is already wobbling.

Nutating Nucleus

With both of the above effects operating, it should come as no surprise that cometary nuclei, particularly of active comets like Halley's, are nutating.

Using pictures of the comet taken in 1910, Zdenek Sekanina and Steve Larson made a rough estimate for Halley's rotation period (about 50 hours) well before the *Vega* and *Giotto* encounters. Unfortunately, uncertainties in this determination, which made use of the repetition of structures in the comet's atmosphere, were unavoidably large and the results, elegant as they were, had to be viewed with considerable caution.

When the comet was recovered in October 1982, ground-based astronomers began work to improve the precision of this estimate. It was thought that fluctuations in the comet's total brightness would show a periodic component.

The prime time to do this work was when the comet was still far from the Sun (beyond the orbit of Jupiter), even though it would be very faint. It would then have no appreciable atmosphere and the light reflected from the rotating nucleus should easily dominate the total brightness. Glimpses of periodicity were noted in the data, but none seemed to make much sense. In three separate investigations different research teams failed to find a convincing periodicity. In retrospect it now seems very evident why — the data were too few and sparsely sampled to stand on their own. In spite of tremendous efforts by the International Halley Watch to obtain the observations, the deficiencies of the data set, caused by too little observing time on large telescopes, overwhelmed the information content.

After the *Vega* and *Giotto* encounters, spacecraft experimenters made their prelim-

ages of the apparent shape, which appear different due to changes in the spacecraft's angle of view and the angle of sunlight falling on the nucleus. Images: Space Research Institute, Moscow

The spiral arms of jets erupting from the nucleus appear in this telescopic image of Halley's Comet. As the nucleus rotates, "hot spots" in the thin, dark crust are alternately exposed to sunlight (on the "dayside") and returned to darkness (on the "nightside"). Heated by solar radiation, these spots periodically emit jets of dust, which curve as the nucleus turns under them, much like water squirting from a rotating lawn sprinkler. Using images like this one, some scientists inferred a rotation rate of 2.2 days for the comet.

Image: Santiago Tapia and Matt Senay, enhanced by Steve Larson, Lunar and Planetary Laboratory, University of Arizona

inary estimates of the shape, size and rotational period of the nucleus. It appeared that the spin axis was aligned roughly parallel to the shortest dimension of the nucleus, giving confidence that the nucleus was in a low energy, pure spin, state of rotation. The dimensions and shape of the nucleus also made it clear that, if it were visible in the distant brightness data, then the brightness fluctuations should reflect its rotation.

Using these results, I went back to the early ground-based brightness data and, in spite of the data's deficiencies, retrieved precise information on the spin rate. The period was either 53.96 or 54.125 hours — it was impossible to be sure which — but the precision of each possibility was better than two minutes — good enough to construct an accurate ephemeris for the rotation. As a check, it was possible to show that the brightness fluctuations had repeated over a year and showed two maxima per full period, as would be expected for an elongated object like Halley's Comet. Based on the data, *Vega 1* and *Giotto* should have seen opposite ends of the nucleus, while *Vega 2* would have seen the illuminated side broadside. Since this was the case, many, including myself, believed (mistakenly) that the nucleus' spin state must be regular with no appreciable nutation or precession.

But then a truly remarkable discovery was announced by Robert Millis and Douglas Schleicher of the Lowell Observatory in Arizona. Brightness data, which they obtained at the Cerro Tololo Inter-American Observatory in Chile near the time of the spacecraft encounters and under the best of circumstances, clearly showed a periodicity — but not with a period near 54 hours. Their period was much longer — some 7.37 days.

Millis and Schleicher very politely proposed that the spacecraft experimenters must have made a mistake in the way they interpreted the encounter images and that 7.37 days was the true spin period. I believe that this is incorrect. In my view, the most likely explanation is that the nucleus is in a state of nutation. That is, as it spins it also wobbles rather badly.

Wobbly Spin

Let us see how we can explain the two (possibly more) basic periods appearing in Halley's Comet's brightness fluctuations. If the comet's mass were distributed in a spherical ball, there would be no preferred direction and the spin axis would always be parallel to the fixed direction defined by the rotational momentum. It would have only one apparent period and this would be the period of spin.

In the next more complicated situation, Halley's Comet might have its mass distributed like a football (or an avocado). In this case, the mass is effectively distributed in the same way about two axes, but in a different way around the third longer axis, the axis of symmetry.

In physics we call this a symmetric top and when it is in its most general state of motion, the outside observer (such as a ground-based astronomer) would discern two periods: one related to an apparent motion of the object about its axis of symmetry, and one related to the apparent motion of the object about a fixed direction in space. Both apparent rotational motions are composed of two parts: one associated with the nutation and the other with components of the spin itself. The first is sometimes referred to as the Euler period after the scientist who first gave a satisfactory mathematical description of the rotational motion of a rigid body, and I associate Millis and Schleicher's 7.37 day result with this period.

Both of these apparent spin periods are constants of the motion; however neither is equal to the "real" spin period, that is, the period of rotation about the spin axis itself.

We can, however, calculate Halley's Comet's true period if we also know the nucleus' mass distribution. We can roughly estimate this from the nucleus' shape as seen in the spacecraft pictures. If the comet is indeed a symmetric top, then this interpretation yields a "true" spin period of about 49 hours, and the polar, or spin, axis will move so that it is inclined about 16 degrees to a fixed direction in space. It will appear to trace out a cone as it moves. The long axis of the nucleus would make an angle of about 78 degrees with the fixed direction, and the component of spin (not the apparent rotation) about the long axis would have a period of about 106 hours. This latter result is interesting because it happens to be almost equal to the interval between the *Vega 2* and *Giotto* encounters. As a consequence, it may be hard to find evidence of this component of the spin in the spacecraft images.

This picture of the comet's rotational motion seems very attractive and may explain most facts as they are now known. Similar results have been announced by other investigators, particularly Jack Lissauer, who was the first to apply Euler's dynamical equations to the problem — in "real" time at the conference when Millis and Schleicher announced their results. However, in my view, it seems unlikely that such a simple situation is the actual state of affairs. There is no good reason why nature should distribute Halley's Comet's mass exactly like that in a symmetric top. It is much more likely that the nucleus will behave like an asymmetric top.

Since the pictures show that the shorter dimensions of the comet's nucleus are not too different, I have looked at the possibility that the comet may rotate as a slightly asymmetric top. In this case a third periodicity should appear which has exactly half the Euler period, 3.7 days. As the spin axis rotates around the fixed axis, it will now "nod" up and down with a period exactly half that of the apparent spin about the long axis. In addition, neither of the apparent periods discussed earlier will be constant but will rapidly modulate about their mean value with the same frequency as the "nodding." The amplitude of these effects is related (in a very complex way) to the comet's internal mass distribution and would be of considerable interest to determine. A periodicity near 3.7 days appears strongly in Millis' and Schleicher's data. They ascribe it to an artifact in the data, but I believe it may originate in the "nodding" motion described above.

The story of the motion of Halley's Comet's nucleus is thus far from complete. It is a hot research topic and we will soon learn much more. We hope to generate an accurate ephemeris so that we can fully understand the relationships between the different kinds of ground-based and spacecraft data. We also urgently need many more brightness observations, made with large telescopes, as Halley's Comet moves away from the Sun and becomes less active. These should begin in the spring of 1987, when the comet once again moves beyond 5 Astronomical Units (1 Astronomical Unit equals the distance from Earth to the Sun, about 150 million kilometers) and we can separate the light of the nucleus from that reflected by the comet's atmosphere.

A great effort will be needed to coordinate these observations. The International Halley Watch, already so successful in organizing observations when the comet was active, still has a challenge before it to see that the needed measurements are made. If they are, we can look forward to having a vivid and correct mental image of Halley's dark, oblong, pock-marked nucleus tumbling away inexorably on its long path toward the cold outer reach of our solar system.

Michael J. S. Belton is an astronomer at the Kitt Peak National Observatory in Tucson, Arizona, specializing in ground-based observations of comets and space-based observations of the outer planets.

WHAT IS IT?

Humans have been watching comets for thousands of years, tracking the glowing apparitions across the sky and attempting to explain what caused the bright comas and the streaming tails. In 1950, Fred Whipple proposed that a small, dusty, icy nucleus lies at a comet's heart, and that effects such as the coma and tails can all be explained using this model. But to test the model, the comet would have to be seen up close.

In 1986, three spacecraft were sent into Halley's Comet to photograph the nucleus and to help answer the question "What is it?" We asked a few of the world's leading comet experts to tackle that question for us. Here are their answers, along with the best close-ups of the nucleus taken by Intercosmos' Vegas and the European Space Agency's Giotto spacecraft.

THE HALLEY NUCLEUS IS THE HOLY GRAIL OF SOLAR system astronomy. Since the space program began nearly 30 years ago, one of its most basic goals has been to understand how our planetary system formed and to find samples of primitive material from the solar nebula. The Halley nucleus is an icy planetesimal, a primitive agglomeration of dust, ice and gas that came together in the solar nebula 4.5 billion years ago. It is the sort of basic building block out of which the planets were made.

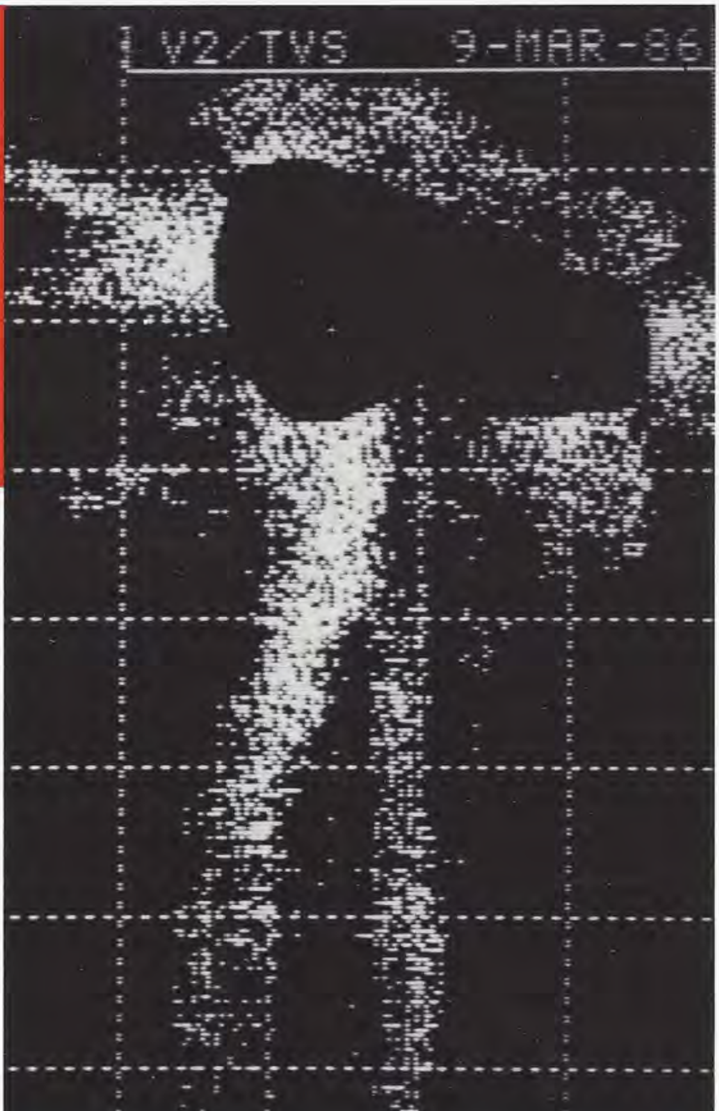
The *Vega* and *Giotto* images are tremendously exciting because, for the first time, we can see something of what the nucleus is like, yet it seems that most decisive details are just beyond the resolution of the best images, or are obscured by the plumes of dust. What we can tell is that the nucleus is a very irregular object, not just because of its very extended, potato-like shape, but also because of the roughness we see along the limb and terminator (the boundary between the sunlit and dark sides), and the 400-meter-high mountain beyond the terminator (in the *Giotto* images) jutting up into the sunlight. It seems that this primordial dirty snowball may actually be an agglomeration of many smaller snowballs stuck together. Because Halley's Comet has been stored in the distant Oort cloud — far from the Sun's heat — for most of its lifetime, the nucleus has never been melted, never bringing all those smaller snowballs together into a single, well-consolidated body.

The surface of the nucleus is divided into active and inactive areas, characterized by either bright dust jets driven by sublimating ices, or a dark crust of presumably carbonaceous materials. This tells us that the surface is not entirely primitive, and that it has evolved due to the comet's repeated passages close to the Sun. What we don't know is whether the pattern of active and inactive areas is constant or is constantly changing.

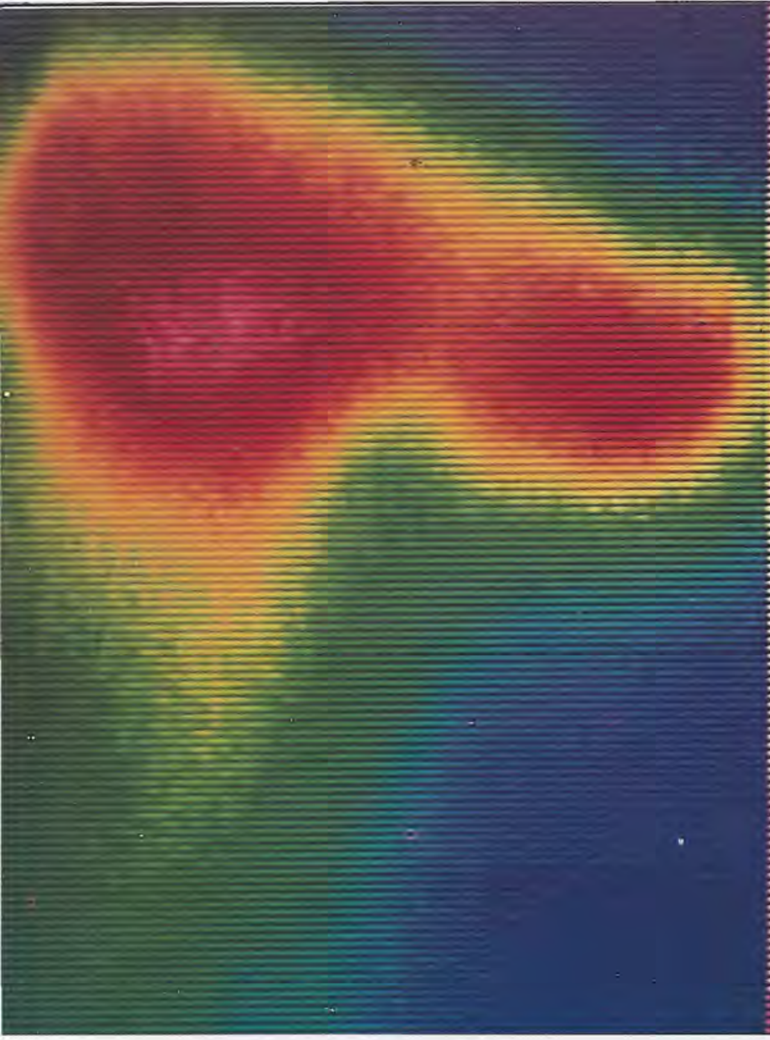
Perhaps the most interesting feature is the apparent "crater" on the surface in the *Giotto* image. At highest resolution, we can see that it is not a traditional impact crater. This matches our expectation, since Halley is a very small target and not likely to have many craters. Most probably, this feature is a dormant active area, the site of a previous outburst from ices buried beneath the carbonaceous crust. And as it rotates farther into the sunlight, it might again burst forth with a massive jet of dust and gas.

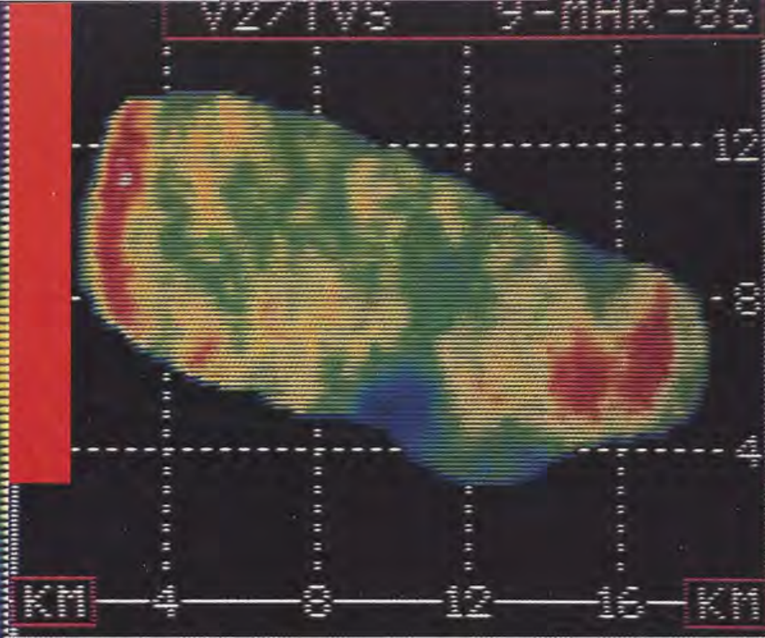
Halley's Comet has given up some of its secrets in the *Giotto* and *Vega* images. But, as in all previous spacecraft missions, we have had some questions answered, and found many new questions to ask. Only future missions to comets, both rendezvous and sample return, will answer those questions.

— *PAUL WEISSMAN, Jet Propulsion Laboratory, Pasadena*



In this near-encounter Vega 2 image, enhanced to show the jets, the nucleus of Halley's Comet appears much as it would to the human eye, for it is one of the blackest things in the solar system.
Image: Institute for Space Research, Moscow





MY NUCLEUS — BASED HALF ON FACTS, HALF ON imagination — looks like this: It is a very dark, irregularly shaped object, with dimensions of 16 x 8 x 8 kilometers. As it was first revealed by the *Vega* spacecraft, its shape is close to that of an avocado, but more irregular. The surface is probably covered by two types of material. The most abundant — covering maybe two-thirds of the nucleus — is thick, impervious to gas and can be heated to 300-400 degrees Kelvin (27-127 degrees Celsius) when the comet is as close to the Sun as our Earth. This surface is criss-crossed by cracks which are the sources of the jets.

There is a big linear feature around the middle of the avocado, uniting many smaller jet sources. This was the most important jet source during the *Vega 2* encounter. There is limited but observable jet activity on the dark side. The emitted material (10 tons per second) demonstrates a cooler core temperature. Water vapor measurements from the Kuiper Airborne Observatory revealed a 30-40 degrees Kelvin (-243 to -233 Celsius) source temperature.

The composition is similar to that of the solar system as a whole. The comet is surrounded by more very light — lighter than cigarette smoke — particles than were anticipated. Many of these dust particles are composed of only carbon, hydrogen, oxygen and nitrogen (CHON particles). The density of the nucleus is very light, about 0.1-0.4 grams per cubic centimeter. The structure is very fluffy.

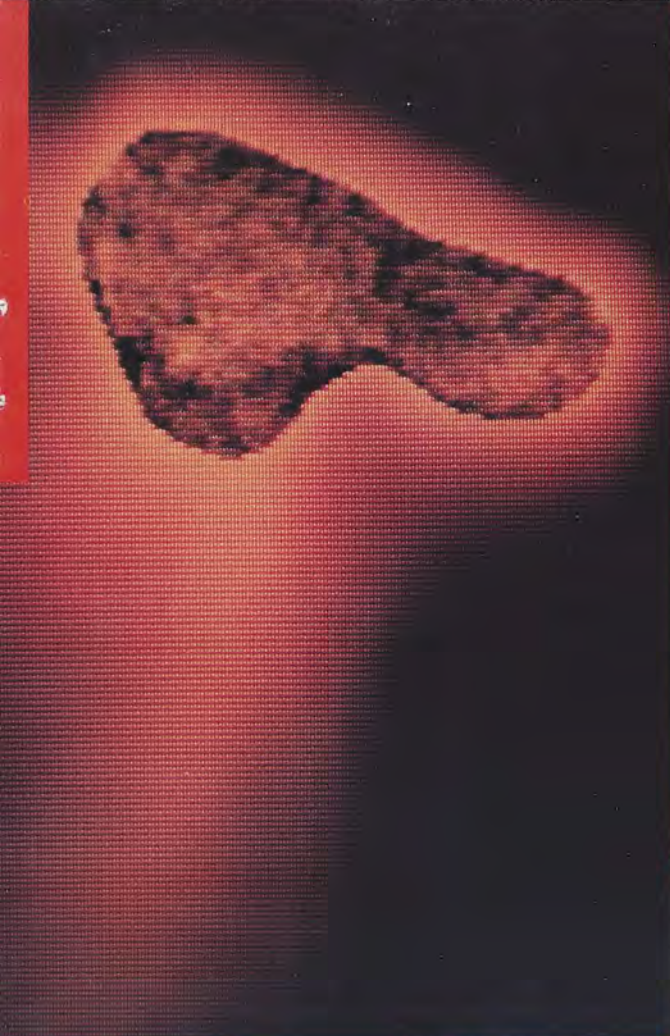
The nucleus' rotation period is about 53-54 hours, but the rotation axis precesses in such a way that the Sun illuminates a different part of the surface at each revolution. This causes the changing coma brightness seen from the ground. — *KAROLY SZEGO, Central Research Institute for Physics, Hungarian Academy of Sciences, Budapest*

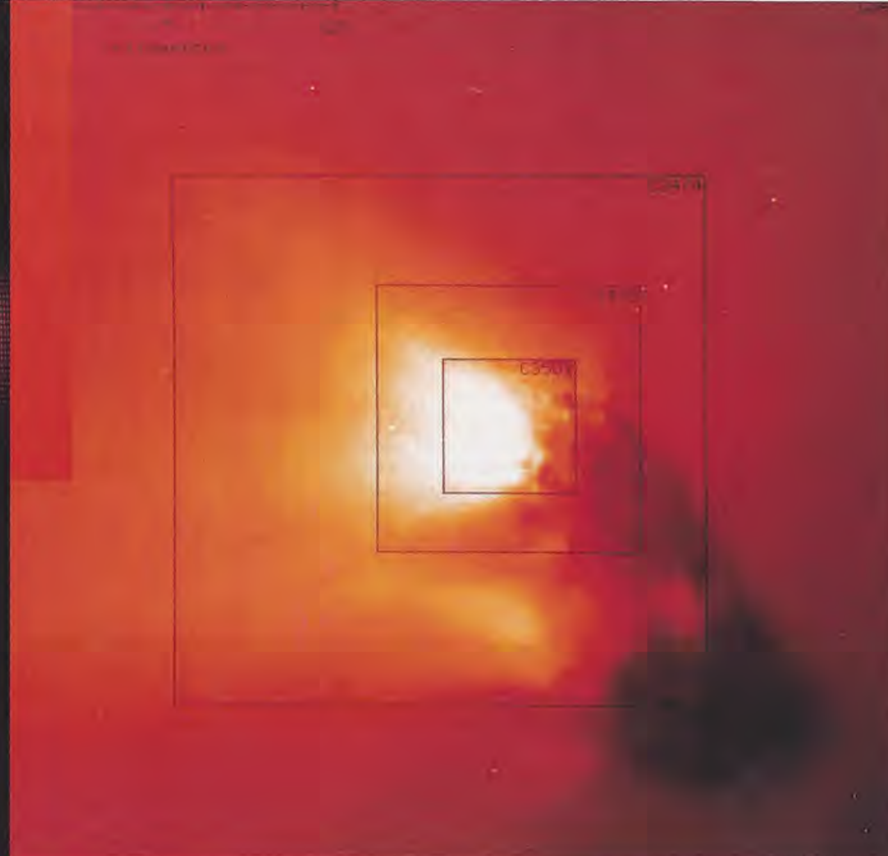
THIS IS A DISTURBED PLANETESIMAL — A SURVIVOR from days of planet formation.

It is a planetesimal in this sense: It is one of the small bodies that formed in the solar nebula, and from which the planets were built. It is like an asteroid, except that it formed farther from the Sun than the main asteroid belt, and hence contained ice as well as rocky material. At its distance from the Sun, the rocky component had two sub-components: ordinary silicate minerals similar to those that formed Earth and the Moon, and very black, carbon-rich minerals, similar to soot, spread among the ice and silicates, making the whole assemblage very black. In the last few years, we have found that this black carbonaceous component, which also contains organic molecules (but not materials as advanced as living organisms!), is the main coloring component of the outer solar system interplanetary bodies, which are all very dark. The black carbonaceous stuff and the ices are native primarily to the outer solar system, which was cold when the planets formed.

It is disturbed in three senses: First, its original orbit was disturbed when it passed close to one of the newly forming giant planets, which kicked it to the outermost solar system (the so-called Oort Cloud), just as the *Voyager* spacecraft were kicked outward when they passed close to Jupiter. Second, it was once again gravitationally disturbed during its long, Oort-cloud orbits around the Sun, causing it to fall toward the Sun into the inner solar system, on the orbit we see today. Third, it is physically disturbed. For perhaps only the one hundredth or five hundredth time in its existence, it is passing closer to the Sun than Earth, where solar heat is sublimating the ices in the surface layers. As the ice turns to gas and expands, it blows off particles of the carbonaceous and silicate dust, along with giant complex molecules and simpler molecules of gas. These materials form the tail and coma, and were sampled at close range by *Giotto* and the *Vegas*.

The object also is a victim of astronomical historical baggage: a Victorian conceptual dichotomy between comets and asteroids, as if they were completely separate species. Probably we will have to recognize a range — or spectrum — of planetesimals, from the rocky types left stranded in the inner solar system and called asteroids, through moderately icy types, to very icy types that were stored in the Oort cloud and later brought in to visit us, called comets. This icy planetesimal is one of the latter group. — *WILLIAM K. HARTMANN, Planetary Science Institute, Tucson, Arizona*





Depending on the spacecraft imaging system and the image processing, the nucleus of Halley's Comet can appear very different in different renderings. Here, at the far left, is a Vega 2 image of the nucleus where the shape is obscured by erupting dust jets. (Colors reflect light intensities, not the actual colors of the nucleus.) Next to it is an image that has been processed to remove the jets. In the center right is a Vega 2 image of a modeled nucleus set within the surrounding dust. At the far right is a false-color Giotto composite image showing bright jets spewing out of the dark nucleus.

Vega images: Institute for Space Research, Moscow; Giotto image: Halley Multicolor Camera, © 1986 Max Planck Institut für Aeronomie, Lindau/Harz, F.R.G.

"WHAT IS IT?" THAT IS THE QUESTION THAT NOT only laymen, but also experts would like an answer to. And I don't think we've got the answer yet.

The cometary nucleus may very well be a conglomeration of ices and dust, à la Fred Whipple. It is clear, mainly from the surface temperature estimates, that what we see visually is mostly the dust — presumably in the form of a crust blanketing the volatile ices underneath. The regions from which the gas and the entrained dust emanate (which correspond to less than 10 percent of the surface, predominantly in the sunward section) are probably associated with cracks or fissures in this thin crust.

Alternately, the surface may not be uniformly covered by such a blanket of dust, due to the irregular shape and/or initial inhomogeneity of the gas-dust mix.

Everything that is presently being said about the internal structure of this object is sheer speculation.
— D. ASOKA MENDIS, University of California at San Diego

AS A RESULT OF THE SPACE MISSIONS TO HALLEY'S Comet in 1986, the nucleus was clearly identified as an irregularly shaped object with dimensions of 16 (± 1) x 8.5 (± 1) x 8.5 (± 1) kilometers. Comparison of *Vega 1* and *Vega 2* images leads to estimation of the rotational period at 53 hours, but really the rotational movement could be more complicated, with some precession and nutation. The direction of rotation coincides with the direction of its orbit (prograde rotation).

The nucleus' low density (about 0.1-0.4 grams per cubic centimeter) implies a friable material. Its substance is a mixture of frozen gases (H_2O, CO_2, CO, HCHO and probably some others) and stony meteoric material. There is also evidence of hydrocarbons.

The nucleus' surface is covered with a thin, porous, refractory mantle with low heat conductivity. Being black, this mantle reflects extremely little light — less than four percent of the Sun's radiation. During the encounters, the surface temperature on the illuminated side reached 360 degrees Kelvin (87 degrees Celsius). Under the crust, the ice is about 200 degrees Kelvin (−73 degrees Celsius). As a result of sublimation, the volatile ices penetrate pores in the mantle, which then cracks and breaks. In the course of this process, dust particles of different sizes are caught, accelerated and blown away with the gas streams. Gas and dust are emitted from the dayside of the nucleus. The gas production was about 30 tons per second (or 10^{30} molecules per second) during the encounters. Dust production was several times lower.

The distribution of the dust is not even — there are many narrow jets. The jets' sources are probably born when the mantle cracks and breaks. The dust outside the nucleus' surface is optically thin, with the exception of certain dust jets that are dense enough to absorb significant amounts of light. Brightness differences on the nucleus' surface were clearly seen during the encounters, and some of them may be connected with its topography. *— G. AVANESOV, V. TARNOPOLSKY, Institute for Space Research, Soviet Academy of Sciences, Moscow*

Halley's Comet was Here!
A Look at Halleymania

BY LOUIS D. FRIEDMAN

HALLEYMANIA WAS EPITOMIZED BY Owen Ryan: "We are very proud to be in a position to create some meaning to that [Halley's Comet] . . . allowing people to buy a symbol of their faith in the future." Mr. Ryan is a salesman, marketing T-shirts, knapsacks, pins, shares in the comet and other commemorative knick-knacks. Hucksterism was only one aspect of Halleymania — perhaps the most lucrative and obvious, but not the most notable or widespread. We can look with skepticism at Ryan's search for meaning, but all those affected by Halleymania — teachers, amateur astronomers, scientists, engineers, writers, filmmakers, impresarios, merchants and occasional doomsayers — had their own reasons for anticipating the comet.

Curiosity was probably the most widespread feeling about Halley's Comet. We had all heard stories of its magnificent 1910 apparition and looked forward to sharing the wonder and excitement our grandparents felt. Millions read articles, watched television, attended lectures, bought memorabilia and looked for the comet in the night sky. Tens of thousands of amateur astronomers took this chance to make serious contributions to the International Halley Watch (see the July/August 1985 *Planetary Report*). Thousands of professional astronomers threw themselves into cometary studies. Hundreds of scientists and engineers took part in spacecraft missions to the comet, and vicariously visited this famous celestial guest.

Cometary Curiosity

The cometary curiosity was dramatically emphasized to me by two invitations to lecture at the Braille Institute in Los Angeles. My audiences were all blind — some remembered seeing Halley's Comet in 1910, and some had never seen the night sky — yet all wanted to know what the comet looked like. Once, while describing why comets are important to understanding the planets, I was interrupted by a 90-year-old who had been blind for 30 years, but who told me, in detail, how the comet looked 76 years ago.

I heard such stories from Halley "two-timers" everywhere, and found them fascinating. People were intensely interested in these accounts of the comet from 1910. At The Planetary Society, we received many letters from elderly people who remembered Halley's Comet, and hoped to live long enough to see it again. I heard stories set in Australia, China, Russia, Scandinavia, the Philippines, Indonesia, South America and across the United States. Many recollections were faulty — wrong season, time of day, year — or simply confused. (There was at least one other bright comet in 1910, and several others in the early 20th century.) But it didn't matter. With its 76-year period, Halley's Comet was seen as a link between generations.

A lot of Halleymania looked to the future, as a mirror image of the interest in the past apparitions. Everywhere mothers and fathers took their children out into the cold night, hoisted them on their shoulders, pointed out the comet, and asked them to remember, in 2061, that they had shared that moment in 1986.

The European Space Agency and The Planetary Society collected children's impressions of the comet to form an archive for the next apparition. Legions of students visited planetariums, museums, observatories and any place they could find information about the comet.

I was privileged to witness one very special visit. Roald Sagdeev, head of the Soviet Institute for Space Research and an Advisor to The Planetary Society, invited a group of Soviet children and students from the Anglo-American School in Moscow to tour the institute during the *Vega* encounters with Halley's Comet. The tour was held in memory of NASA's Teacher-in-Space, S. Christa McAuliffe, and in this remarkable event, nationalities became unimportant. The students heard talks by Academician Sagdeev, Carl Sagan and others working on the cometary encounter. The scientists spoke while live pictures of the comet from the spacecraft played on one video screen, and a tribute to Christa McAuliffe was displayed on the other.

Planetary Society members sent us news clippings about special planetarium shows around the world. Many reported record attendance and sales. Guest speakers on cometary matters were in high demand. Some of my friends on the International Halley Watch gave four or five talks per week. Members of nearly every Kiwanis Club, Boy or Girl Scout troop, retirement center, convention and astronomy club wanted someone to speak to them about the comet. Community and extension colleges offered courses on the comet. Demand so outweighed supply of speakers that some scientists turned down fantastic cruises and tours to exotic places. Yet enough were found to satisfy the demands of people who wanted an excuse to travel to Tahiti and other distant sites.

Comet-watchers traveled almost everywhere to the South, where the viewing was best: the Amazon, Macchu Picchu, the nether parts of Australia, New Zealand, the South Atlantic, the South Pacific, the Black Sea, southern China. Astronauts, astronomers, writers, teachers, engineers, archaeologists and other friends of the comet provided "expert" commentary on tours, and helped people find the comet in the sky.

A friend on a geology field trip in South America was camped out in a remote area at least a half-day's drive from the nearest village. One night around 2:00 a.m., while driving alone on an unpaved mountain road, he rounded a corner and nearly ran into a crowd of about 50 people excitedly pointing to the sky. As he slowly comprehended the Spanish for "There it is!," he realized that he had bumped into a bit of local Halleymania.

Tough Viewing

Just finding the comet in the night sky was the chief disappointment and frustration for many victims of Halleymania. I am not an astronomer and, having been born in New York City and now living in Los Angeles, I can say with little exaggeration that I've hardly seen anything in the night sky. I am a theoretician; I know the stars, planets and comets are there, I can calculate where they should be, but I rarely look up. For me, Halleymania was an excuse to learn some astronomy.

I found out what the Pleiades are, I made out constellations, I saw planets move across the sky. I discovered that most people are like me: They don't know how to find things in the sky. On one tour, some people came without their glasses and complained that they couldn't see the comet. On the Planetary Society cruise, we had a terrible time convincing people that the deck lights had to be turned off; we couldn't see the comet from a brightly lit area.

Despite all advance warnings, many people were distraught not to see a long, bright tail. Because it was at its brightest on the opposite side of the Sun from Earth, the comet appeared dim in this apparition. Most people I went out with — whether at home in the mountains near Los Angeles or on comet-watching tours — needed

ILLUSTRATION: S.A. SMITH

about 30 to 60 minutes to find the comet for the first time. It took me longer. But after I learned a little about the sky, I could find it in two minutes. Once the comet was found, most reactions were, at best, subdued. And in many large groups, a sizable fraction seemed content to give up and never see it!

But there were a few great moments. I spent nearly an hour with a 90-year-old woman, trying to teach her to use binoculars and where to look for the comet. Finally she exclaimed, "My God, it looks just like it did in 1910!" My most thrilling memory is of seeing the tail extended through the Milky Way. For several people on the Society's cruise, the best part was seeing the changing position of the comet on successive nights, and realizing that its motion through the solar system is very different from other objects'. (A beautiful demonstration of this can be seen in the IMAX movie "Sacred Site," made near Ayers Rock in central Australia during the Halley apparition.)

Many people now describe the comet-watching as a bust. But I've noticed that description comes from those who didn't really try to see it. Those who climbed a mountain, hiked through the desert, sought out some remote rural area, took an ocean cruise, or simply went as far south as possible, I have not heard complain.

Media Coverage

Television around the world featured Halley's Comet. The Planetary Society was given a videotape of a Soviet special, featuring their *Vega* spacecraft. It was replete with computer graphics, scenes from 1910, scientists at work and Halleymania. Coinciding with the *Giotto* encounter, the French aired "The Night of the Comet," an 11-hour live production of mostly rock music, celebrating the comet and the opening of La Villette, a new Paris exhibition hall. Responding to enormous public interest, each Japanese network ran a comet special. Asahi Broadcasting based their show on the Planetary Society special produced by John Wilhelm and WETA-TV.

Our Emmy-nominated special, "Comet Halley — Here It Comes Again," shared the Public Broadcasting System airwaves with a *Nova* show on the comet. The British and most European networks each produced at least one major show and provided special coverage of viewing conditions. The Canadian Broadcasting Corporation produced major television and radio specials about the comet. In the United States, ABC-TV broadcast a series of comet briefs featuring Society President Carl Sagan. Through Society arrangements, they provided live coverage of the *Vega* encounters from Moscow and the *Giotto* encounter from Darmstadt in the Federal Republic of Germany. Local stations provided varied Halley programming, ranging from spots on weather reports to major news features.

In discussing news reports, people like to recount major errors. A colleague in England sent me a notice of "Wally's Comet Discovered." My favorite mistake ran in the prestigious International Herald Tribune on the morning after a *Vega* encounter. Alongside a well-written article on the encounter, they ran a 1910 photograph of the comet, with a caption explaining that it was what *Vega* saw.

Other byproducts of Halleymania, created to satisfy enormous public curiosity, were telephone hotlines. There were at least 25 in various countries. Phone lines at planetariums and other institutions were so busy that many had to set up recorded information messages. Many astronomy clubs, museums, colleges and even the Jet Propulsion Laboratory set up local lines. The Planetary Society-ABC-TV Information line was an 800 number available across the United States. (Unfortunately, as interest waned in March 1986, ABC tired of the comet and closed the line.) People in the International Halley Watch set up lines around the world; Arizona State University ran an innovative computer network that recorded worldwide reports on observations almost as soon as they were made.

Comet newsletters — sometimes obscure — sprang up to provide information. The Planetary Society helped distribute "The International Halley Watch Amateur Observer's Bulletin" to amateur astronomers who hoped to contribute to the extraordinary worldwide efforts to study the comet. A New Jersey publication called the "Halley Watch" was apparently a one-man effort.

A Japanese Halley's Comet society claimed a membership of 100,000. In Britain, several societies were organized for the occasion, including a Halley's Comet Society of 5,000 founding members representing only "distinguished people in all walks of life." The British didn't quite claim ownership of the comet, but you could tell that, since it was named for an Englishman, they felt that way.

My hope that Halleymania would inspire new education about astronomy and space science was largely fulfilled. Based on anecdotal reports, most teachers used their students' interest in the comet to build up their science curricula. Despite some people's disappointment in the comet's appearance, many people, including me, learned to use a telescope. Telescope sales were the greatest commercial manifestation of Halleymania, although many people, organizations and publications (including *The Planetary Report*) warned that, for general viewing, the comet would best be seen with binoculars. There was some flim-flam and most who bought telescopes were disappointed.

Scientists suffered their own Halleymania: international conferences, scores of publications, trips to everywhere, payloads in space and innumerable toasts to Edmund Halley and his comet. In 1981, after drinking such a champagne toast at 8:00 a.m. on a Sunday morning in Washington with a group of misguided but well-placed people who had influenced the new administration to give up on a NASA comet mission and "invest" in a privately funded effort, I vowed to forego all toasts to the comet. I kept that vow until September 1986 at the Heidelberg conference summarizing results from *Vega*, *Giotto* and the International Halley Watch.

Best Legacy

The spacecraft missions were the *pièces de résistance* of the comet experience. These extraordinary international efforts were the best legacy of Halleymania. Only the enormous drawing power of the comet enabled people like Roald Sagdeev in the Soviet Union, Jacques Blamont and Roger Bonnet in Europe, and many others, to break down institutional and political barriers to join together exploring the comet.

Twelve years ago Carl Sagan wrote, "Centuries hence, when the political problems of today will seem as important as those of the Thirty Years' War appear now to us, this generation will be remembered as the first to take steps off its home planet into the solar system." In 1986 we made humanity's first visit to Halley's Comet; that will be a legacy to the next generation. For all of us who participated in Halleymania, it's enough.

Louis Friedman is the founder of the International Halley Watch and is Executive Director of The Planetary Society.

The Next Step in Exploring Comets

BY MARCIA NEUGEBAUER

"COMETS APPEAR TO BE Rosetta Stones" declared a recent headline in *Science* magazine. Most scientists studying the data on Halley's Comet gathered by spacecraft and ground-based instruments would agree with this assessment. We now believe, even more firmly than we did before the Halley experience, that comets hold the key to understanding the origin of our solar system — they are the most primitive material left from the interstellar cloud that gave birth to the solar system.

A question naturally arises: "What next?" Will thorough analyses of the new data reveal most of what comets have to tell us about our solar system's origin? Will we then understand the astrophysical processes within interstellar clouds? Probably not — the observations of Halley's Comet not only left some important questions unanswered, but raised many new ones as well.

Example: The *Giotto* images of the comet's nucleus showed that gas and dust spewed out in jets from only a few regions while the rest of the body was covered with a dark crust. What is this dark crust? Is it made of dust particles that have fallen back to the surface, or is it a porous, pumice-like material from which the volatile (easily evaporated) material has boiled off? And how do the active regions differ from the rest of the comet?

Example: The *Vega*, *Giotto* and ground-based data all showed that much of the cometary dust was made of organic (carbon-based) material. For instance, we found grains made of carbon, hydrogen, oxygen and nitrogen (CHON particles). How were these elements combined into molecules? Does the organic material include amino acids or other biogenically important molecules that might tell us a great deal about the origin of life on Earth and about the universality of life in the cosmos? Because we observed only the gases and dust out in the comet's coma, where the ejected materials have already been broken up, we did not detect the "parent molecules" from which the coma materials originated. Many of these parent molecules making up the cometary ices and most of the refractory (high-melting-point) minerals remain unidentified. Furthermore, we know very little about the physical structure of the dust grains.

Example: Both Comets Halley and Giacobini-Zinner (visited in 1985 by the International Cometary Explorer, see the May/June 1985 and May/June 1986 *Planetary Reports*) were surrounded by huge regions of energetic (fast-moving) particles in a plasma, that is, a gas whose atoms are largely ionized. Since these discoveries, plasma theorists have proposed a mechanism, called "second-order Fermi acceleration," for accelerating cometary ions to the energies observed. Still they must test this and other hypotheses about the behavior of cometary plasmas under a greater variety of conditions in the solar wind (the supersonic plasma flow emitted by the Sun) and over a much greater range of cometary activity levels before these hypotheses can be applied to other astrophysical plasmas.

Thus, it's not surprising that comet scientists are actively planning future comet missions at the same time that they are analyzing their data from Halley's Comet.

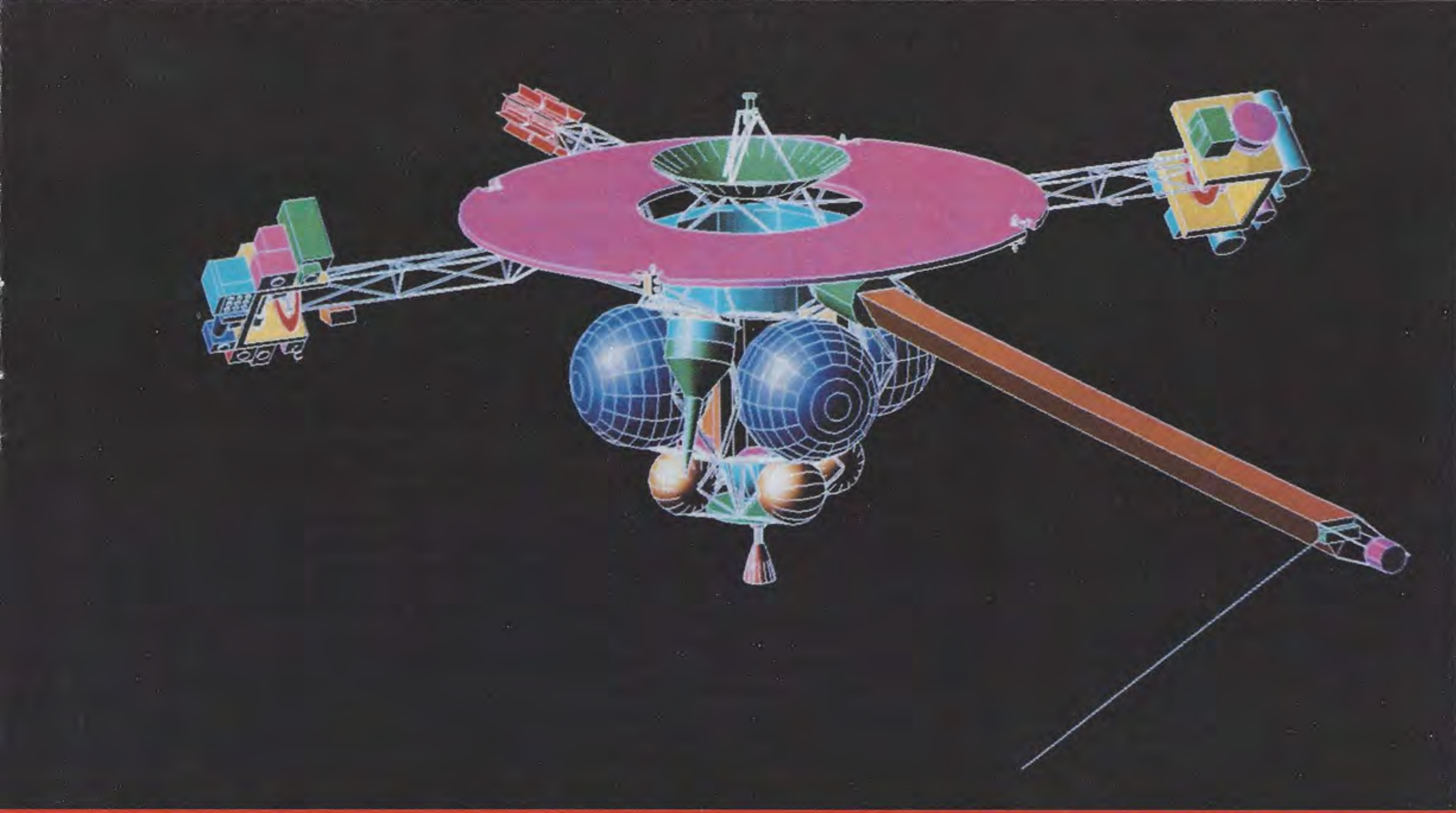
New Comet Studies

The next generation of missions to comets will involve rendezvous and sample-return missions. In a rendezvous mission, the trajectory of the spacecraft is exactly matched to the orbit of the comet, so the spacecraft doesn't simply fly by its target. The comet and the spacecraft will travel about the Sun together indefinitely. This is the principal objective of the Comet Rendezvous Asteroid Flyby mission, called CRAF for short. This past October, NASA picked the scientific experiments to be flown on CRAF. These instruments, combined with the rendezvous trajectory, will substantially advance our understanding of comets.

According to current plans, CRAF will be launched in early 1993 by a *Titan IV-Centaur G* launch vehicle. After a gravitational assist from a swingby near Venus, followed by another from Earth, CRAF will head for the comet named Tempel 2. En route to Tempel 2, CRAF will pass through the asteroid belt

The Infrared Astronomical Satellite (IRAS) detected a trail of dust left behind by Comet Tempel 2 in its track around the Sun. The trail probably extends all the way around the comet's orbit.

Image: JPL/NASA

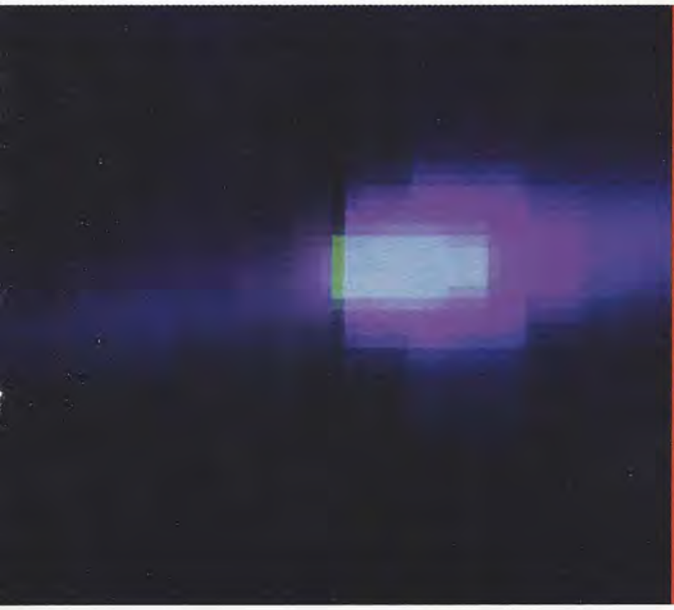


The Comet Rendezvous Asteroid Flyby (CRAF) spacecraft will be the first of a new generation of spacecraft called the Mariner Mark II. These low-cost spacecraft are designed to undertake several different missions with only minor modifications. The CRAF configuration is seen here, as drawn by a computer. Image: JPL/NASA

and will fly close to a large asteroid named 46 Hestia. It will take pictures of Hestia with details as small as 100 meters, measure its mass and density and map it in the infrared to determine the distribution of minerals on its surface.

CRAF would then move on to rendezvous with Tempel 2 in October 1996, when the comet is at its farthest point from the Sun, and so at its least active. After measuring the mass of the comet's nucleus in a series of slow flybys, the spacecraft can be put in a leisurely orbit around the comet, making a complete circuit in tens of days. It can hover over points of interest or carry out other maneuvers in the comet's weak gravity.

CRAF's cameras will map the entire surface, resolving details smaller than one meter. The comet's density will be measured with an accuracy of 10 percent or better. From such data, we can learn about how solid bodies, such as comets, accumulated during the formation of the solar system and about how they have "weathered" since then.



By superimposing several maps of Tempel 2's infrared emission, obtained by IRAS, scientists constructed this "picture" of the comet. The tail appears to the right; to the left is a thin band of dust left behind by the comet.

Image: JPL/NASA

A visual/infrared spectrometer will map the minerals and ices on the surface, while an infrared radiometer maps the surface temperature. Comet modelers can use these data to learn about the temperature and pressure in the regions where comets formed — perhaps an interstellar cloud or the fringes of the solar system. We will also learn how the comet absorbs sunlight, and how the Sun's energy generates the coma and tail that we see from Earth.

We will use the first maps of the comet's topography and temperature to decide where to land the penetrator experiment. The penetrator will carry an array of instruments with a week's worth of batteries to study the comet's crust and the material beneath it. Accelerometers will determine the depth of penetration and the strength of the surface material and the layers beneath it. In the penetrator's tip, buried about a meter below the surface, will be a gamma-ray spectrometer to measure the relative abundances of carbon and all important heavier elements. A set of temperature probes will measure the rate at which heat works its way from the surface down into the nucleus.

A small sample of material taken near the bottom of the penetrator's hole will be sealed in a container and heated in a controlled way. Pressure and temperature measurements taken during the heating will tell us more about the nature of the ices: At what temperature do they change from ice to liquid, and how much heat does this require? Does the heating set off any chemical reactions? How much gas comes out of the ice at each temperature? At several stages during the heating, the gases will pass through a gas chromatograph to identify what molecules are present. These data will tell us about the conditions that formed the comet's ices and about the physical and chemical processes in protostellar clouds.

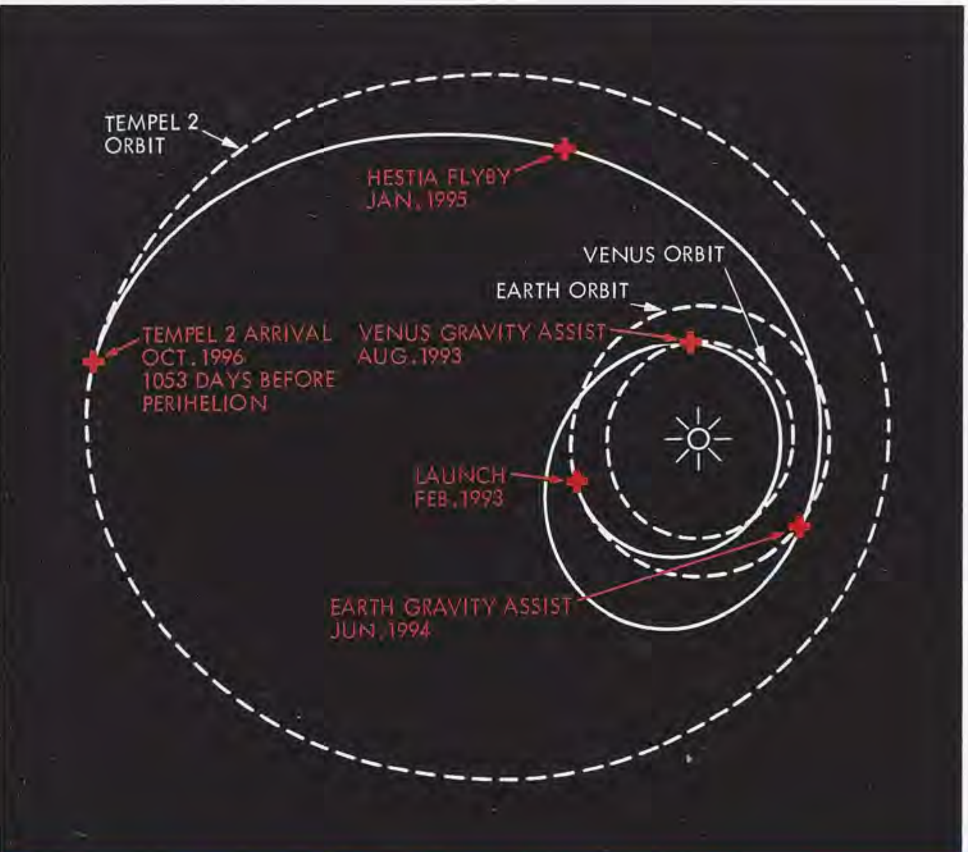
As the comet and the spacecraft approach the Sun, the comet's activity will increase. CRAF's instruments will measure the dust, gas and plasma coming off the comet. The spacecraft will explore the coma and move tens of thousands of kilometers down the comet's tail to collect dust samples and to map the ever-changing interaction between the comet's gases and the solar wind. The mass spectrometer will tell us what gases emerge from the comet at different distances from the Sun and what chemical reactions occur in the coma. This instrument will also concentrate and analyze heavy organic molecules.

A battery of instruments will focus on solid grains in the coma. One will gently knock off ions from dust grains and then analyze the ions with a mass spectrometer that can measure abundances of chemical isotopes as well as atoms and molecules. The differences from one grain to another may tell us about the histories of the different materials making up the solar system.

A miniature scanning electron microscope will take pictures of the structure and arrangement of mineral phases in individual grains. Another instrument will use x-ray fluorescence to measure the elemental composition of dust samples. The same samples will also be heated, and the gases which escape at different temperatures will pass through a set of gas chromatograph columns to search for different molecules, including heavy organics.

Still another dust detector will monitor the impact rate of dust grains and measure their velocities. Sudden bursts of dust from the comet could damage the instruments, therefore this instrument will be used to warn other instruments so their protective covers can be closed.

The Federal Republic of Germany will supply one of the dust experiments and the propulsion subsystem needed to rendezvous with Comet Tempel 2.



If the mission remains on schedule, CRAF will be launched from Earth in February 1993, get a gravity assist from Venus in August 1993, get another boost from Earth in June 1994, fly by the asteroid Hestia in January 1995, and rendezvous with Comet Tempel 2 in October 1996. Chart: JPL/NASA

Future Plans

NASA is developing a new generation of planetary spacecraft, named *Mariner Mark II*, for CRAF and other missions to study main-belt asteroids and the outer planets. The *Mariner Mark II*'s will be easy to reconfigure from one mission to the next. They will use several new technologies to increase reliability and to decrease costs.

Perhaps the ultimate comet mission would bring back to Earth a well-preserved, still frozen, deep core sample of a comet for analysis with instruments too large and complex to send into space. Both NASA and the European Space Agency (ESA) have such a Comet Nucleus Sample Return mission in their long-range plans. The return of a pristine cometary sample is one of four major program elements, called cornerstone missions, identified by ESA. NASA's Solar System Exploration Committee has similarly recommended a sample-return mission as part of its Core Program of planetary exploration. A joint NASA-ESA science working group is planning such a mission. The data from CRAF will be enormously valuable to the mission design.

It would be extremely difficult and expensive to return a well-preserved nucleus sample with the launch vehicles now available, so both ESA and NASA's Goddard Space Flight Center are studying easier missions to retrieve samples of cometary dust and gas. These simpler and less expensive missions would fly through a comet's coma at many kilometers per second. During its flyby, the spacecraft would expose a sample-collection surface, seal it up and return to Earth.

However, the sample would be very small and its properties would be altered by high-speed impact with the collector. Although potentially important for understanding the composition of cometary dust, these missions would not address most problems concerning comets' nuclei. Neither NASA nor ESA now plans to undertake this type of mission.

Thus, the hopes of the cometary science community are tied to CRAF. NASA is supporting the necessary planning and development activities. But the spacecraft and its instruments cannot be built until the project has been officially approved. Congress must approve funds for CRAF in early 1988 if we are to rendezvous with a comet before the end of this century.

Marcia Neugebauer is a senior research scientist at the Jet Propulsion Laboratory in Pasadena. She is Project Scientist for CRAF and a member of the Giotto *ion mass spectrometer team.*

News & Reviews

by Clark R. Chapman

It has been well over a year since that terrible morning when the space shuttle *Challenger* disintegrated in the Florida sky. Still, the American space program remains in disarray as we grope toward regaining our stairway to the heavens. The question confronting us is whether we can learn from the history of our mistakes, or must we repeat our errors time and time again.

It's easy to see where we went wrong. The essential problem with the shuttle program was aptly explained just before the *Challenger* accident by James Van Allen in a *Scientific American* article which I reviewed in this column a year ago. An even more cogent history of the shuttle's beginnings, by John Lodgson, appeared last spring in *Science* and was also reviewed here. Members of The Planetary Society have all been keenly aware of NASA's misguided priorities, since planetary exploration has "taken it on the chin" more than almost any other part of the space program. (That trend continues with President Reagan's latest budget proposal for fiscal year 1988: Solar system exploration is one of the few NASA programs slated for a further decline.) As we face an uncertain future in space, these history lessons bear repeating because of the disquieting signs that they remain unlearned.

The astronauts need not have died in vain. An eloquent recapitulation of the shuttle's early and most recent history has been written by James Fallows. He examines the President's latest space proposal — the "Orient Express" space plane — and finds that it looks depressingly familiar. His essay in the December 18th issue of *The New York Review of Books* reviews three works, including the report of the Rogers Commission on the *Challenger* accident.

Many NASA-watchers have noted parallels between development of the shuttle and the early phases of the space station. Fallows says little about the station — NASA's prime goal after we get flying again — instead he emphasizes the less familiar, would-be space plane. Once again, military goals threaten to become paramount as the budget-starved space agency turns to the Department of Defense for most of the bucks. NASA would pay only about 20 percent.

But then, according to Stephen Korthals-Altes, whose book *The Aerospace Plane: Technological Feasibility and Policy Implications* Fallows reviews, the Air Force estimate of $3 billion in development costs for the space plane is less than 20 percent of the likely costs of over $17 billion. Korthals-Altes, a young engineer and cost analyst at the Massachusetts Institute of Technology, presents his own readable, nicely illustrated synopsis as the cover story of the January issue of *Technology Review*, MIT's popular science magazine.

"The technological challenges have been downplayed, the development costs are grossly underestimated, and the utility of the aircraft is vastly exaggerated," writes Korthals-Altes. The initial project concept, since President Reagan first proposed it in his State of the Union address a year ago, reminds us of the space station, and of the shuttle before that.

James Fallows has outlined a five-stage process typical of huge military procurements. First, there is the "Vegematic promise" ("It slices, it dices!" and does practically everything under the Sun.) The space plane would "combine the vantage point of a reconnaissance satellite with the maneuverability of an SR-71 (a high-altitude, high-speed aircraft), deliver the ordnance of a bomber with the speed of an ICBM, launch payloads into orbit with the ease of a DC-9, and whisk civilian passengers across oceans in a few hours.

As Korthals-Altes notes, "perhaps the most important lesson of the shuttle is that a space vehicle designed to perform many functions is optimal for none." We, who were promised that a low-Earth-orbit transfer vehicle (the shuttle) would be ideal for launching planetary missions, can bitterly acknowledge Fallows' first stage. He reminds us that it was originally touted that the shuttle would carry four vehicles per year to planetary exploration. He concludes that "so far it has carried none."

Stage 2 is "the rosy prospect." The numerous flights per year would so reduce commercial launch costs that space would triumph on Wall Street. Korthals-Altes quotes a French Aerospatiale official, still smarting from the financial failures of the *Concorde*, that "our American friends are daydreaming" about the viability of the "Orient Express."

The *Technology Review* article also documents enormous technical hurdles that must be overcome with the scramjet engine if the space plane is to work. "The technical leap" is Fallows' third stage; remember the required breakthroughs for the shuttle's main engines and its heat-resistant tiles? Next comes "the unpleasant surprise" stage, the 2.8 person-days *per tile* for installation and the "unexpected" repair or replacement of all three of *Challenger's* main engines after its maiden flight.

The last stage, of course, is "collapse of the house of cards." Not only were the hopes and dreams of America's schoolchildren sunk beneath the Atlantic, along with the bodies of seven astronauts and fragments of one-quarter of our main launch fleet, but "major scientific, commercial and military programs are delayed at least two years," Fallows writes. As I write these words, only two months after Fallows' essay appeared, further delays seem certain.

Will NASA Ever Visit a Comet?

NASA's shortsightedness continues to delay progress on space science and planetary exploration. (See, for example, Mitch Waldrop's report "A Crisis in Space Research" in the January 23 issue of *Science*.) In its November 1986 issue, *Astronomy* magazine's cover story asked "Why Can't We Explore a Comet?" Donald Frederick Robertson explains how NASA had planned, until a year ago, to explore Comet Wild 2. He laments that the mysterious celestial visitor will swing back out of the inner solar system unexplored by the delayed Comet Rendezvous Asteroid Flyby (CRAF) mission (see pages 16-18).

Robertson quotes NASA about the "probable" new start for CRAF in 1988, which would send CRAF instead to Comet Tempel 2. But NASA backtracks almost faster than *Astronomy* can roll off the presses. Despite frequent promises over the past year by NASA officials, the President's 1988 budget proposal does *not* have a new start for CRAF. The next launch opportunity wouldn't get CRAF to a comet until after the turn of the century! Some pundits believe that NASA's Solar System Exploration Division may cancel all outer planet exploration (including suggested missions to Saturn's moon Titan, comets and asteroids) if Congress cannot be persuaded to reverse the administration's shortsightedness.

NASA officials themselves recognize that the space agency is losing its capacity for leadership in space, not only in the international arena but even among the executive branch agencies in Washington. Craig Covault, writing in the February 2nd issue of the aerospace trade journal *Aviation Week & Space Technology*, documents some recent heavy-handed actions by the Departments of Defense, Transporation and the Treasury; various federal agencies seem to be trying to commandeer NASA's responsibility. NASA's plans for launch vehicles are being compromised, and recent international negotiations concerning the space station broke down due to Department of Defense interference.

In an editorial in the same issue entitled "NASA Under Seige," *Aviation Week* calls for renewed independence by NASA. It is encouraging that NASA officials are now vocally seeking to re-establish the space agency's preeminence in formulating and implementing United States space policy. However, if NASA is to succeed in recovering from the *Challenger* tragedy, there must emerge a more lofty and long-range goal in space than the military-oriented goals that are now threatening to dominate our country's approach to space. To establish such visionary goals and give NASA the go-ahead to pursue them requires leadership from the very top of the administration.

Clark R. Chapman is beginning work on two new popular books about space.

World Watch

by Louis D. Friedman

WASHINGTON — "I am writing to inform you that the President's Fiscal Year 1988 budget reflects a delay in the launch of the Mars Observer mission from the present launch date of 1990 to 1992."

This sentence opened a letter from NASA Administrator James Fletcher to the four congressional committees responsible for the space program. It was written on January 2, three months after a previous NASA attempt to delay the mission had failed — due, in part, to strong action by Planetary Society members. On January 5, the new budget was released:

Space shuttle – $1,229 million (up 22 percent)
Space transportation operations – $1,885 million (up 2 percent)
Space communications – $949 million (up 10 percent)
Construction of facilities – $196 million (up 18 percent)
Civil service manpower – $1,598 million (up 9 percent)
Space station – $767 million (up 82 percent)
Space transportation research and development – $569 million (up 15 percent)
Aeronautics and space technology – $691 million (up 17 percent)
Tracking and data – $18 million (up 6 percent)
Commercial programs – $54 million (up 32 percent)
Safety and reliability – $16 million (up 77 percent)
Physics and astronomy – $567 million (up 3 percent)
Life sciences – $74 million (up 3 percent)
Space applications – $559 million (up 3 percent)
PLANETARY EXPLORATION – $307 million (down 14 percent)

TOTAL – $9,481 million (up 12 percent)

Every area — except planetary exploration — received a major increase. In the planetary exploration budget, the Mars Observer was delayed two years, and the Comet Rendezvous and Asteroid Flyby (CRAF) was put on hold. No new Mars initiative was proposed. And there was no mention of space at all in the President's State of the Union address.

Congress has begun consideration of the proposed budget. Extensive questioning about the NASA program is expected and public interest in planetary exploration could force reconsideration of these priorities. The congressional committees acting on the NASA budget are:

— Senate Committee on Commerce, Science and Transportation, Washington, DC 20510
Senator Ernest Hollings, Chairman
— NASA authorizing subcommittee, Senator Don Riegel, Chairman

— Senate Appropriations Committee, Washington, DC 20510
Senator John Stennis, Chairman
— NASA appropriations subcommittee, Senator William Proxmire, Chairman

— House Committee on Science and Technology, Washington, DC 20515
Representative Robert Roe, Chairman

— House Committee on Appropriations, Washington DC 20515
Representative Jamie Whitten, Chairman
— NASA appropriations subcommittee, Representative Edward Boland, Chairman

WASHINGTON — NASA's launch schedule for major scientific missions currently stands as follows:

- Hubble Space Telescope to Earth orbit, November 1988 on the space shuttle
- *Magellan* to Venus orbit, April 1989 on the space shuttle
- *Galileo* to Jupiter, November 1989 on the space shuttle with the Inertial Upper Stage, with possible postponement to 1991 if *Ulysses* is launched in 1989.
- *Ulysses* European mission to solar orbit, scheduled for October 1990 on the space shuttle with the Inertial Upper Stage, but could move up to November 1989. (The congressional Appropriations Committees have recommended delay to 1991 with launch by a *Titan/Centaur.*)
- Mars Observer to Mars orbit, August 1990 (however, NASA is seeking a two year delay, saying there is no room on the shuttle manifest, largely because of military payloads).

Space shuttle flights are scheduled to resume on February 18, 1988. If, as seems increasingly likely, this date slips, the above-mentioned launch dates are all unlikely. The first flight will launch a tracking and data relay satellite. This satellite will provide a crucial communications link for these future space missions.

ROME — On November 7, 1986, Pope John Paul II met with the leaders of the Inter-Agency Consulting Group (IACG) to receive a report about the Halley's Comet encounters of 1986. The world's four leading space agencies had formed IACG to coordinate the mission activities. The agency leaders were: Roald Sagdeev, Intercosmos (USSR); Roger Bonnet, European Space Agency; M. Oda, Institute of Space and Astronautical Sciences (Japan); and Burt Edelson, NASA. International Halley Watch leaders Ray Newburn and Jürgen Rahe joined them.

In meeting the group, the Pope said:

"I wish to commend this splendid initiative which brings you together and which seeks to foster ever more effective international cooperation in the space sciences. It is indeed a kind of celebration of scientific cooperation, a celebration which can offer hope to men and women of science, as well as to all people of good will, as they seek to identify those areas of knowledge and concern which unite the human family rather than divide it. The participation of the Vatican Observatory serves to illustrate the desire of the Church to encourage these worthy endeavors and to contribute, as far as possible, to the realization of the noble goal of harmonious human coexistence, in the achieving of which science can play an active and vital part . . . .

"There is yet another way, one that we commemorate today, namely, that collaboration in a scientific endeavor which transcends all national boundaries and requires knowledge and dedication to science and technology by men and women of many nations, races and creeds. Last week, in commemorating the Fiftieth Anniversary of the Pontifical Academy of Science, I spoke of the great esteem which the Church has for scientists, not only for their intellectual prowess, but also for their moral character, their intellectual honesty and objectivity, their self-disciplined search for truth, their desire to serve mankind and their respect for the mysteries of the universe which they explore . . . .

"I hope and pray that all of the scientists and engineers in your space agencies will continue to work together in your exploration and thus merit to be called peacemakers, in addition to your other worthy titles . . . .

"I also wish you to know how much I appreciate your field of science, and how much I admire the contribution that you are making to it. Your science opens up to man so many of the wonders of the universe and leads him in a new and deeper way to be aware of its greatness. Your scientific research and discoveries are likewise capable of becoming effective instruments for a more profound understanding of man, for whose well-being the whole adventure of science is conducted . . . ."

Louis Friedman is the Executive Director of The Planetary Society.

SOCIETY Notes

UPCOMING SOCIETY EVENTS

March 16-20 — Annual Lunar and Planetary Science Conference, in Houston Texas. The Planetary Society will sponsor a public session on the evening of March 16, with V. Barsukov and V. Moroz from the Soviet Union, and Harold Masursky and Bruce Murray, Society Vice President, from the United States. Their topic will be planning the exploration of Mars.

July 18-22 — Case for Mars III: Strategies for Exploration, in Boulder, Colorado. Public sessions are planned.

August 21-23 — The Pacific Nations Conference, Planetary Society sessions, in Kona, Hawaii.

KUDOS TO . . .

Teinya Prusinski and Linda Low of Chicago, who spent many hours planning and organizing a brunch featuring astronaut Kathryn Sullivan, who spoke on "Challenges Ahead: Our Future in Space." The enthusiasm of our Chicago membership remains among the highest in the United States, thanks, in part, to these two members.

HAWAII CALLS THE PLANETARY SOCIETY — ALOHA

You have the rare opportunity to attend a Planetary Society open forum with Sally Ride, Society Advisor, Astronaut and Special Assistant to the NASA Administrator. The Society's Board of Directors will also hold an open discussion of Society plans for the International Space Year, 1992 and the organization of international membership activities. The occasion is the Pacific Nations Conference, organized by the University of Hawaii and the government of Japan, to help plan the International Space Year, which will be modeled on the International Geophysical Year (IGY) of 1957.

The Pacific Nations Conference will be held August 19-21, 1987 in Kona, Hawaii and will be chaired by United States Senator Spark Matsunaga (D-HI) and Japanese Minister of Economic Planning Tetsuo Kondo. The conference itself will be limited to invited attendees, but The Planetary Society will hold several public sessions for our members August 21-23.

On the evening of the 21st, Dr. Ride will give the keynote address at a Society session, followed by commentary from the Society directors. On the 22nd, the Board of Directors will hold their open meeting. A field trip to the active Hawaiian volcanos, a lecture on volcanos in the solar system and a nighttime sky party will round out the weekend program.

We will give more details of the conference and of a special Society travel package in the next issue of *The Planetary Report*. After March 1, you may also call our Information Lines, 818/793-4328 from east of the Mississippi, and 818/793-4294 from west of the Mississippi. We hope that many of our members will be able to attend this exciting conference.

MARS CONTEST DEADLINE EXTENDED

The fourth annual Mars Student Contest deadline has been extended to May 1, 1987; the winner will be selected by May 30, 1987. College and high school students are eligible to enter the contest, which encourages student participation in research and development for future exploration of Mars.

This year's contest has two categories: In the first, students will design an international Mars mission; in the second, students will analyze the social, political and economic assets and liabilities of an international mission to Mars. The winner in each category will receive $750.00 and an all-expenses-paid trip to the Case for Mars III conference to be held in Boulder, Colorado in July, 1987.

For more information, write to the Mars Institute at the Society offices.

A CHALLENGE TO ALL MEMBERS

The Library Outreach Program — made possible by Nick Pavlica's gift to fund library subscriptions to *The Planetary Report* — has spontaneously spawned a new membership program. Several members have given gift subscriptions to their local school and community libraries. One of those members, Regina Mitchell of Holbrook, Massachusetts has issued a challenge to all 100,000 members:

"After reading in the July/August issue of Nick Pavlica's grant to have 1,000 libraries receive *Planetary Report* subscriptions, I was thrilled — truly a fantastic idea!

"There remains, however, a lot of uncovered territory. I would like to challenge personally all of my fellow members to do as I did — donate subscriptions to your local libraries!

"Let us make *The Planetary Report* available to everyone. How better to share the excitement and knowledge that The Planetary Society offers. Then watch us grow!"

Ms. Mitchell gave subscriptions to Holbrook High School and the Holbrook Public Library. If you accept her challenge, you can give subscriptions at our educational discount rate of $12.00 per year for *school and community libraries, and teachers who have the magazine sent to their classrooms.* Fill in and mail the coupon below.

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The Solar System in Pictures and Books

NEW LASER PRINTS!

JUPITER

(#322)

On February 13, 1979, *Voyager 1* imaged Jupiter's southern hemisphere. Passing in front of the planet are the two inner Galilean satellites, sulfurous Io (on the left in front of the Great Red Spot) and icy Europa (right).

MARS

(#323)

Taken by the *Viking* Orbiter, this image captures the geological diversity of the martian landscape as the spacecraft looks across the cratered surface to the cloud-streaked horizon.

SATURN

(#333)

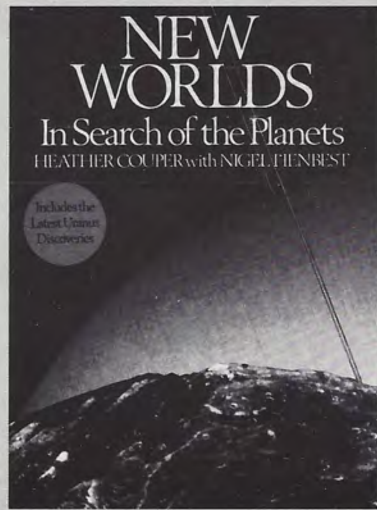
On November 16, 1980, four days and 5.3 million kilometers after its encounter, *Voyager 1* looked back at Saturn and observed the planet and its rings from this unique perspective.

URANUS

(#337)

On its way to Neptune, *Voyager 2* turned one last time to Uranus and imaged the sunlit crescent of the planet. Methane in Uranus' atmosphere absorbs red light, giving this planet its blue-green color.

NEW BOOKS!



NEW WORLDS

(#137)

This profusely illustrated book presents both historical and modern theories about the planets and the creation of the solar system. Authors Heather Couper and Nigel Henbest examine each planet, and include the recent *Voyager 2* results from Uranus.

THE CASE FOR MARS (not pictured)

(#159)

After numerous requests, this book has been reprinted and is again offered to our members. Drawn from papers presented at the 1981 Case for Mars Conference, cosponsored by The Planetary Society, this book covers mission strategy, life support, surface activities and other topics that will have to be addressed before we set out for Mars.

NEW VIDEOTAPE!

URANUS — I WILL SEE SUCH THINGS

(VHS #450, BETA #451)

William Herschel discovered Uranus in 1781, but the planet remained a mysterious dot in astronomers' telescopes until, in January 1986, it was visited by *Voyager 2*. The spacecraft found a world tipped on its side, surrounded with a shimmering glow of ultraviolet light, and orbited by strange and ancient moons. This entertaining and informative videotape examines the mysterious and distant world, Uranus.

Order Form

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145	**Pioneering the Space Frontier** by the National Commission on Space. 211 pages.	$12.00
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155	**Rings — Discoveries from Galileo to Voyager** by James Elliot and Richard Kerr. 209 pages.	$16.00
159	**The Case for Mars** edited by Penelope J. Boston. 314 pages. **Soft Cover** REPRINT	$18.00
160	**The Case for Mars II** edited by Christopher P. McKay. 700 pages. **Soft Cover**	$26.00
165	**The Grand Tour: A Traveler's Guide to the Solar System** by Ron Miller and William K. Hartmann. 192 pages.	$ 9.00
170	**The Mars One Crew Manual** by Kerry Mark Joëls. 156 pages.	$10.00
175	**The Mars Project** by Senator Spark Matsunaga. 215 pages.	$15.00
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187	**To Utopia and Back — The Search for Life in the Solar System** by Norman H. Horowitz. 168 pages.	$11.00
190	**Voyager: The Story of a Space Mission** by Margaret Poynter and Arthur C. Lane. 152 pages.	$ 8.00
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440 VHS / 441 BETA	**Universe** (30 min. videotape)	$30.00
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Other Items

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510	**Back issues** of THE PLANETARY REPORT – Each volume contains six issues. (Vol. 1, #5 & 6; Vol. 2, #1 & 6; Vol. 3, #1 & 2 and Vol. 4, #6 have been sold out.) Specify the issues you are ordering by volume and number. **each**	$ 2.00
515	**Bookmark** — blue with logo (6" x 2", 2 for $2.00)	$ 1.50
520	**Calendar for 1987**	$ 7.00
530	**"I Love Mars, That's Why I Joined The Planetary Society" T-Shirt** — burnt orange **S M L XL**	$ 8.00
535	**Mars Model** by Don Dixon and Rick Sternbach	$65.00
540	**Men's T-Shirt** — white with blue logo. **S M L XL**	$ 9.00
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COMETARY ENCOUNTER — Because a thick coma surrounds a comet's nucleus as it nears the Sun, it is impossible for Earth-based telescopes to see into the heart of a comet when it is at its most active. If we are to expand our understanding of comets beyond the data gathered by the Vegas and Giotto, more spacecraft will have to visit comets. In this painting, a Giotto-like craft approaches a comet spewing jets of dust.

Space artist Don Dixon is now at work on a series of paintings depicting the exploration of Mars. He recently created the covers for several science fiction books published by Ballantine, Warner and Berkley Books.

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