

Space missions to comets

Five spacecraft now heading toward an ambitious March 1986 encounter with comet Halley mark the beginning of a new era in cometary research, which promises to modify our understanding of the evolution of the solar system.

Marcia Neugebauer

Comets appear to be the most pristine remnants of the material from which the solar system formed. We wish to know more about these eccentric objects to gain insight into the conditions and processes that prevailed during the solar system's formation and early stages of evolution. Chemical, isotopic and mineralogic studies of comets will tell us about the dynamical and nucleosynthetic processes that operated prior to and during formation of the nebula, and about the original chemistry of the solar system. Studies of the physical properties of comets and of the material of which they are composed will tell us about the agglomeration and accretion of bodies in the outer solar system. The study of comets is also relevant to the evolution of life: Comets may have made substantial contributions to the present atmospheres of Venus, Earth and Mars, and it is possible that either the prebiotic molecules necessary for the evolution of life or the raw materials from which these molecules formed were brought to Earth by comet-like objects. Finally, the study of the interactions between sunlight, plasmas, gas and dust in comets should have applications to processes in a great variety of

astrophysical settings throughout the universe.

Cometary research has increased significantly during the last several years due, in part, to the availability of new ground-based and satellite-borne research tools. Another important factor is anticipation of the return of comet Halley in 1986 and the first close-up explorations of Halley and other comets by spacecraft. Also, debate over the possibility that bombardment of the Earth by comets may be responsible for extinctions of life forms every 26–28 million years has given new impetus to the study of the evolution of cometary orbits. The number of abstracts of research papers on comets printed in *Astronomy and Astrophysics Abstracts* rose from 54 in 1970, to 59 in 1975, to 101 in 1980, to 150 in 1983.

Recent observations confirm, and greatly extend, Fred Whipple's icy-conglomerate, or dirty-snowball, model of comets. In 1950, Whipple suggested that a comet is a kilometer-sized body composed of frozen gases such as water, methane and ammonia, with grains of dust embedded in the ices. As its elliptical orbit brings a comet close to the Sun, solar energy turns the outer layers of ice to gas. The escaping gas drags dust grains out into space with it. A comet is made visible by the interaction of sunlight with the vast cloud of dust and gas that surrounds its relatively tiny nucleus. No comet's nucleus has ever been optically resolved.

I begin this article with a very brief

review of some of the major advances in the understanding of comets already achieved through the application of modern technology. Then I will discuss in somewhat greater detail the expectations for the scientific return from space missions to comets in the 1980s and 1990s.

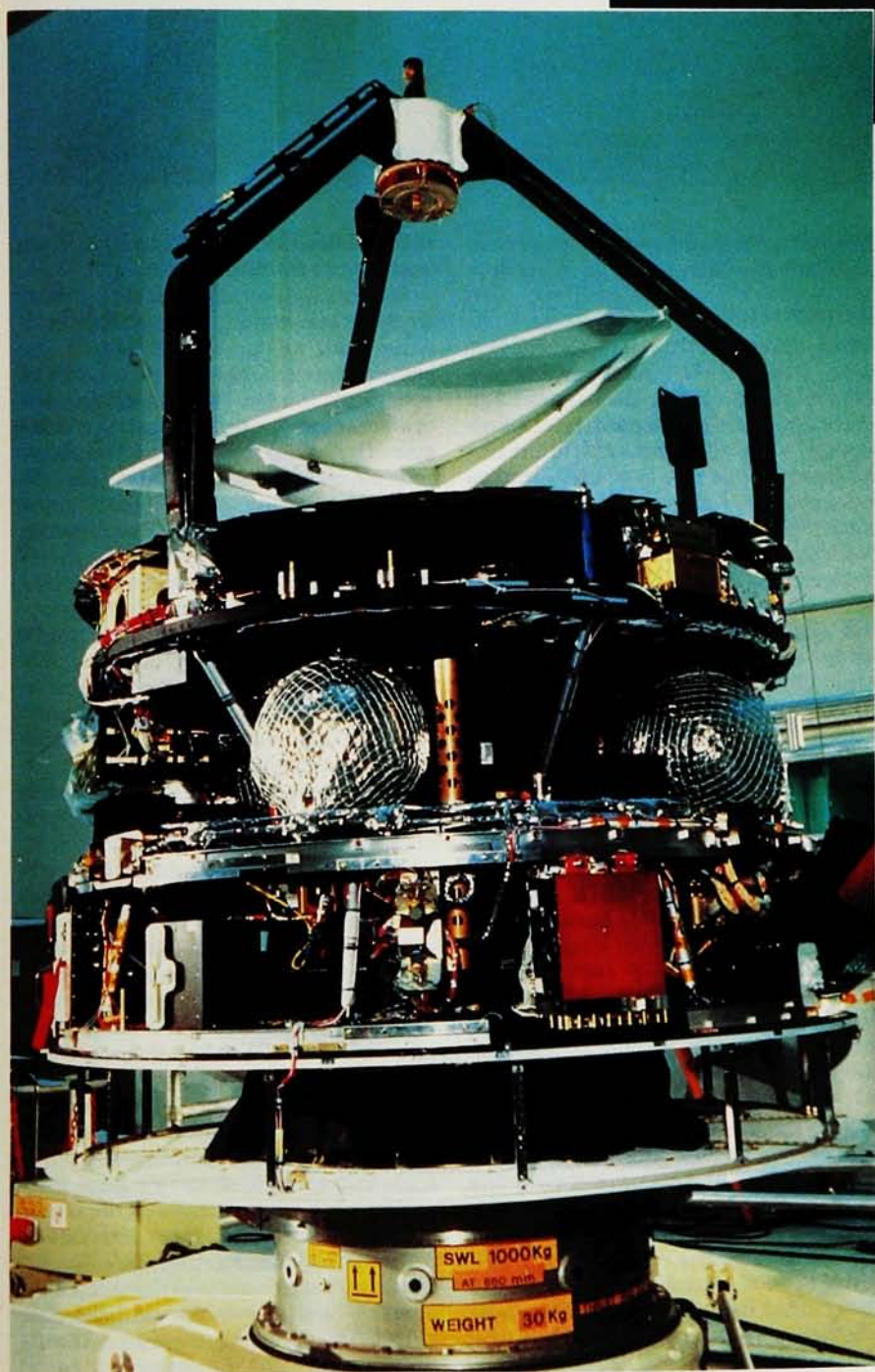
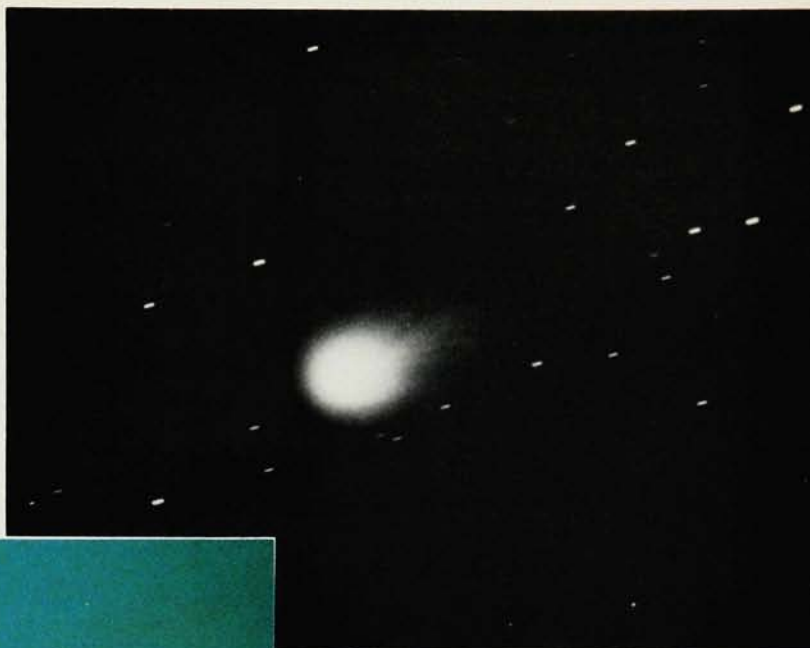
Recent advances

New detectors, and our ability to use them in rockets and spacecraft above Earth's atmosphere, are responsible for much of the recent increase in knowledge about the composition of cometary gas and dust. The 1970 ultraviolet observations of comets by the satellites OAO-2 and OGO-5 confirmed the widely held belief that water is the principal constituent of many comets. The satellite observations of Lyman- α radiation from comet Bennett revealed a roughly circular cloud of atomic hydrogen some 10^7 km in diameter—larger than the Sun. More recent space observations have shown that such hydrogen clouds are a common feature of active comets. The clouds are so extensive because hydrogen atoms carry off much of the energy in the photodissociation of cometary water. The H_2O molecule itself was observed several years later at centimeter wavelengths.

The spectra of comets reveal many ions and molecular fragments, or free radicals, largely through resonance lines in the vacuum ultraviolet. The fragments probably form from stable "parent" molecules by photodissocia-

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Comet Halley, 25 May 1910, 1½ months after perihelion, in a plate taken at Helwan Egypt. (Photo from D. A. Klingensmith and J. Rahe, courtesy of ESA.)



Giotto spacecraft during integration at the Intespace facility in Toulouse, France. This European Space Agency probe is now heading toward comet Halley. The silver spheres on the main platform are two of the four tanks of hydrazine, the fuel for jets that control trajectory and attitude.

Infrared contour map, superimposed on a visible-light photograph, for the comet IRAS-Araki-Alcock. The 60-micron infrared image shows a dust tail that is much more extensive than the visible tail. The infrared tail is more than 400 000 km long and contains over 15 million kilograms of emitting material, probably in the form of small silicate particles.



tion, photoionization and chemical and charge-exchange reactions. In addition to water, parent molecules detected to date are carbon monoxide and ammonia, observed in the ultraviolet, and cyanide and methylcyanide, observed at radio wavelengths. One can still only surmise the identification and abundances of many other possible parent molecules.

Infrared observations have led to the detection of silicate emission features associated with cometary dust and, recently, to identification of the infrared signature of grains of water-ice in the coma, or atmosphere, of comet Cernis. In 1983 the Infrared Astronomical Satellite found extensive dust trails behind short-period comets with visible tails of much more limited extent.

Within the last five years, astronomers have been able to use Earth-based radar to measure the sizes of the nuclei of several comets. In 1980 such measurements showed the radius of comet Encke to be between 0.4 and 4 km. In 1983 radar observations of comet IRAS-Araki-Alcock, which came within 4.7 million kilometers of Earth, yielded an estimated radius of 3–6 km and gave evidence for the outflow of centimeter-sized solid particles from the comet's nucleus into the coma.

We can expect this accelerating progress in Earth-based observations of comets to continue over at least the next several years, especially with shuttle experiments and the deployment next year of the Hubble Space Telescope (see *PHYSICS TODAY*, November 1984, page 17). Instruments on spacecraft that go to comets to study

them at close range will acquire a qualitatively different type of data.

The comet missions

One spacecraft has already encountered a comet. The International Cometary Explorer flew through the tail of comet Giacobini-Zinner on 11 September 1985. ICE was not originally designed to go to a comet; it was launched in 1978 to measure the solar wind, energetic particles, solar x rays and solar radio bursts as part of a joint program sponsored by the National Aeronautics and Space Administration and the European Space Agency to study solar-terrestrial phenomena. After four years of successful operation, the spacecraft was redirected to make several long, slow loops through the largely unexplored distant regions of the geomagnetic tail, and then sent on its way to Giacobini-Zinner.

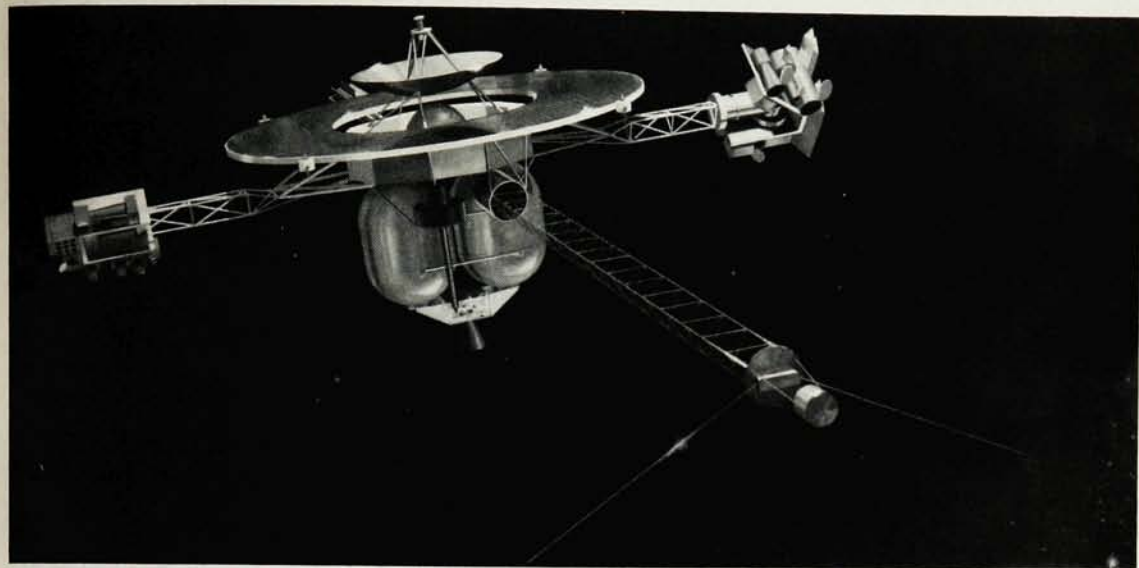
Preliminary results from the encounter fit in with Whipple's "dirty snowball" theory. During the 20 minutes that ICE spent inside Giacobini-Zinner's tail, the spacecraft detected water, carbon monoxide and a small amount of dust. ICE also confirmed the expectation that a comet's ion tail is formed by the draping of the interplanetary magnetic field around the comet's head. Other data from instruments such as the magnetometer and electron detector were more surprising, indicating that the interaction between the solar wind and the cometary plasma is unexpectedly complex and turbulent. ICE did not find the expected clear bow shock such as occurs at Earth and at many other bodies in the solar system, whether or not those bodies have intrinsic magnetic fields. (Louis Lanzer-

otti and Stamatios M. Krimigis discuss bow shocks in their article on page 24.)

Several spacecraft are now en route to Halley's comet, where they will carry out an ambitious set of encounters next March. Two Soviet spacecraft named Vega, an ESA spacecraft named Giotto and two Japanese spacecraft named Sakigake and Suisei will all obtain close-up data. Because Halley moves in a retrograde orbit, traveling around the Sun in a direction nearly opposite to that of the Earth and the spacecraft, all the flybys will occur at a very high relative speed of approximately 70 km/sec and will last only a few hours.

The data obtained by the five Halley spacecraft will be complementary, rather than redundant, because each of the missions has a different emphasis. Giotto will be aimed to penetrate the comet's inner coma on the side facing the Sun, only 500 km from the nucleus. A major emphasis of its experiment package is to measure the properties of the dust, gas and plasma that the spacecraft encounters. The Vega missions will give greater emphasis to remote, spectroscopic observations of the nucleus and coma. The first Vega will be targeted to pass 10 000 km sunward of the nucleus; the second Vega may go closer to the nucleus if the first Vega indicates that it is safe to do so. The Japanese experiments are designed to study the large-scale hydrogen cloud and the outermost region of the interaction of the comet with the solar wind, some 200 000 km from the nucleus. Furthermore, the five spacecraft are timed to arrive a few days apart, which allows the study of time variations. As each spacecraft makes its plunge through the coma of comet

Proposed CRAF spacecraft. The Comet Rendezvous and Asteroid Flyby spacecraft, depicted here by an artist, would join the comet Wild 2 in 1995, after a four-year journey from Earth.



Halley, the other four will monitor the state of the unperturbed solar wind, thus making it possible to determine the dependence of coma properties on solar wind conditions.

The Halley flyby experiments will be supported and complemented by extensive observations from the ground and Earth satellites. International Halley Watch, an organization that involves over 900 professional astronomers from 50 countries and several thousand amateur astronomers, is coordinating the planning of observations and the correlation of the resulting data.

In the mid 1990s, NASA will carry out a comet "rendezvous" mission in which a spacecraft will become a permanent companion of a comet to study it at close range over an extended period of time. Detailed planning for this mission has been underway since 1983. If the mission is approved as part of the 1987 budget, the spacecraft could be launched in March 1991 for a rendezvous with comet Wild 2 in January 1995, when the comet is approximately 5 AU from the Sun. If the project go-ahead is delayed until 1988, a September 1992 launch would allow a rendezvous with comet Tempel 2 in 1996, also near 5 AU. For at least a year after rendezvous, the comet will be relatively inactive. During this phase of the mission, the spacecraft will make many close, slow flybys and then orbit the nucleus at an altitude of perhaps 30 km. Once the comet and spacecraft reach a solar distance of about 3 AU, comet activity will become significant and the spacecraft will move farther away to study the dust, gas and plasma in the comet's atmosphere. Because the spacecraft's initial

trajectory between Earth and the comet Wild 2 passes through the asteroid belt, it will be able to perform a close flyby of an asteroid en route to the comet. Hence the mission name Comet Rendezvous and Asteroid Flyby. In addition to designing the spacecraft and investigating trajectories, NASA has been supporting a substantial program to develop instruments in preparation for the CRAF mission. The scientific payload is scheduled to be selected next April.

We may not see the next stage in cometary exploration until the next century. After a successful rendezvous mission, the next major step in the study of comets will be the collection and return to Earth of still-frozen samples of surface and subsurface cometary material. Only in Earth-based laboratories is it possible to perform sophisticated analyses such as age dating, small-scale stratigraphic studies that may reveal the physical processes involved in the accretion of the nucleus, and microscopic analyses of the structure of the ices and the mixing of the dust and ice.

There is discussion between NASA and the European Space Agency about a potential joint mission in which a spacecraft would fly through the coma of a comet, sweep up samples of gas and dust, and then return the samples to Earth for analysis. There are not yet any definite plans to carry out such a mission.

The experiments

Spacecraft on missions to comets will return data from a variety of experiments.

Imaging. The first pictures of a com-

et's nucleus should revolutionize comet study, by taking it from the realm of theoretical modeling to that of observational science. The two Soviet Vega spacecraft and ESA's Giotto spacecraft carry cameras to take pictures of the nucleus of Halley's comet. Each Vega carries a wide-angle and a narrow-angle camera, both with sensitive charge-coupled-device sensors. The electronic output from the CCDs will be analyzed on-board the spacecraft and used to keep the cameras pointed at the comet nucleus for the duration of the flyby. Each picture element in the narrow-angle Vega camera will correspond to an area on the nucleus of $150\text{ m} \times 200\text{ m}$ at the closest approach distance of 10 000 km.

The single CCD camera on Giotto has an even more challenging job because it must find and track the nucleus from a spacecraft that spins at 15 rpm. The microprocessor within the camera must determine the correct camera pointing and exposure without assistance from Earth. The most detailed of the hundreds of four-color pictures obtained by the Giotto camera will have a spatial resolution of approximately 30 m, compared to the estimated 5000-m diameter of the nucleus.

Most models predict that Halley's comet will have an optically thin atmosphere at the time of the spacecraft encounters, with the sunlit nucleus appearing brighter than the gas and dust surrounding it. There are some arguments, however, that the Vega and Giotto cameras may not be able to see Halley's nucleus through the obscuring atmosphere. If this is the case, we would not obtain the first pictures of a comet's nucleus until NASA's Comet

Missions to comets

	International Cometary Explorer	Sakigake and Suisei	Vega 1 and 2	Giotto	Comet Rendezvous and Asteroid Flyby
Agency	NASA-ESA	Japan	Soviet Union	ESA	NASA
Target	Giacobini-Zinner Zinner	Halley	Halley	Halley	Wild 2 or Tempel 2
Mission type	Flyby	Flyby	Flyby	Flyby	Rendezvous
Number of spacecraft	1	2	2	1	1
Date at target	September 1985	March 1986	March 1986	March 1986	1995-1999

Rendezvous and Asteroid Flyby Mission in the mid-1990s.

Even if the imaging experiments on the Halley spacecraft are highly successful, many important imaging tasks will remain for the proposed CRAF mission. Because the rendezvous spacecraft would spend such a long time very close to the nucleus, it will be able to map nearly the entire nucleus with a spatial resolution of 50 cm, under various lighting conditions and varying levels of cometary activity. All told, CRAF will obtain tens of thousands of pictures.

Spectroscopy. Combined spatial and spectral mapping is an important technique for studying physical and chemical processes in the coma and for studying the thermal and mineralogical properties of the surface of the nucleus. Spacecraft can map the distribution of chemical species in the coma as a function of distance from the nucleus, with a spatial resolution that cannot be achieved from Earth; such maps will help sort out many of the physical and chemical processes in the coma. The Japanese Suisei spacecraft carries a Lyman- α spectrophotometer to map the distribution of atomic hydrogen both at the time of encounter and near the time when comet Halley passes through perihelion and cannot be observed from Earth. The Giotto spacecraft carries a spectrophotometer to monitor the brightness of the coma, to measure polarization in emission lines of CO^+ , OH, CN and C_2 and to study dust by recording intensity in four bands in which there is little emission from gases. By taking the differences of successive brightness measurements along the track of the spacecraft, this instrument can achieve a spatial resolution of 100 km. One of the spectrometers on each Vega spacecraft will obtain images and high-resolution spectra of the coma over the wavelength range 120 nm to 1800 nm. It will map the coma with a spatial

resolution of 15 minutes by 6 minutes of arc. Its goals are to determine the coma's chemical composition, the velocities of various gas molecules and the spectrum and polarization of light scattered from dust. This instrument can also obtain a spectrum of the nucleus, although it cannot resolve the nucleus spatially.

Spectral maps made from visual and near-infrared radiation reflected from the nucleus will show the distribution of mineral phases of ices, silicates, oxides, sulfides, carbonates and other surface material. Longer infrared wavelengths will give thermal maps. Each Vega spacecraft carries an additional experiment capable of mapping the nucleus at infrared wavelengths of 7-14 microns, with a spatial resolution of 2.4 km at the 10 000-km distance of closest approach. Two other channels of this instrument will operate in a nonimaging mode, with a 1-degree field of view, to identify minerals through reflectance measurements in the 2.5-5-micron band, and to analyze the thermal properties of the nucleus and dust through emission measurements in the 6-12-micron band.

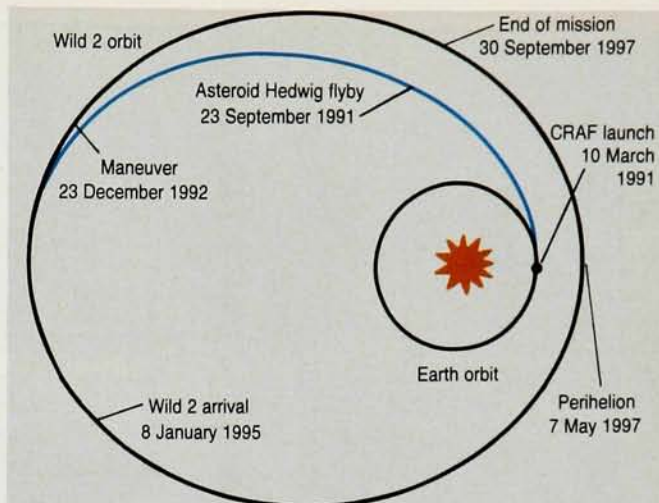
NASA has appointed a team of scientists to develop a visual and infrared mapping spectrometer for use on the Comet Rendezvous and Asteroid Flyby Mission. This instrument will be an upgraded version of the near-infrared mapping spectrometer to be flown on the Galileo mission to Jupiter. The spectrometer's multiplexed detector array, with 64 Si and 256 InSb detector elements, has already been built and used at ground-based observatories. When the spacecraft is in a 30-km orbit around the comet nucleus, the visual and infrared mapping spectrometer will be able to map the distribution of ices and nonvolatile minerals on the surface with a spatial resolution of 10 m. When the comet is near perihelion, 1.6 AU from the Sun, the spectrometer will map the distributions of such

molecules as CH_4 , CO, CO_2 and H_2O in the inner coma. Although the visual and infrared mapping spectrometer doesn't have the spectral range to map either ultraviolet emission lines in the coma or thermal emissions from the nucleus, NASA may select additional instruments to do so. The ultraviolet spectrophotometers and far-infrared thermal radiometers required to make such measurements have flown on Earth satellites or on earlier planetary missions and would require only minor adaptations for the Comet Rendezvous and Asteroid Flyby Mission.

Mass and density. A slow, close spacecraft trajectory is required to measure the very weak gravitational field of a comet's nucleus. A spacecraft in a 50-km orbit about the nucleus of a comet with a diameter of 3 km and a density of 1 gm/cm^3 —a nucleus of moderate size—can determine the mass to an accuracy of better than 0.1% in only two revolutions. With even closer orbits around the nucleus, it should be possible to detect large-scale nonspherical distributions of mass as well as local concentrations of mass. Measurement of the average density is limited by the accuracy of the volume measurement, which depends on the complexity of the structure. A spacecraft measurement will probably tell us the density to within less than 10%. A density measurement might shed light on such properties as the ratio of rock to ice and the degree of compaction of the ice.

Penetrator. NASA is supporting the development of an experiment that would go below the surface of a comet's nucleus. A variety of sensors would be located near the tip of a meter-long penetrator shaped like a thumbtack or a golf tee. The CRAF spacecraft would release the device, which would then accelerate into the nucleus under the power of a small solid-propellant rocket. The technology for this does not have to be developed from scratch; scientific studies of the arctic ice cap,

Orbits and trajectory for the proposed CRAF mission to comet Wild 2. The Earth and comet orbits are drawn to scale. (After a diagram from Jet Propulsion Laboratory.)



using penetrators launched from airplanes, have been going on for about a decade. The comet penetrator that is under study would pierce the outer 30–100 cm of the nucleus, depending on the surface strength of the nucleus. Batteries would power the instruments for about a week. The penetrator would send its data to the main spacecraft, hovering overhead, which would relay the data to Earth. Among the instruments being studied and tested for inclusion in such a penetrator are temperature probes, an accelerometer for determining the surface strength and the depth of penetration, and a miniature gamma-ray spectrometer and an alpha-backscatter detector for determining the elemental composition of the material surrounding the penetrator.

Gas, plasma and fields. Each spacecraft in the comet fleet heading toward Halley carries an array of instruments for measuring the properties of the gas, plasma and electromagnetic fields along its flight path. Most of the instruments for the comet missions evolved directly from similar particle and field instruments on earlier Earth satellites and planetary spacecraft.

Both Giotto and the Vegas carry neutral-mass spectrometers to measure the abundances of various gases encountered by the spacecraft. The Giotto instrument has two analyzers. The first obtains a mass spectrum over the range 1–86 daltons. The second is sensitive to masses of 36 daltons or less: it also measures the speeds of the molecules. The Giotto mass spectrometer will obtain a complete mass spectrum every 1.5 seconds, which corresponds to spatial resolution of 100 km. This instrument can also measure the mass spectrum of ions. The Vega neutral mass spectrometer has one sensor for the range 1–36 daltons, and another that can detect molecules as heavy as 130 daltons but with poorer mass resolution.

On the Halley Flyby Missions, the high speed of the spacecraft relative to the comet allows the use of molecular-beam techniques for the study of gases. Discrimination against low-speed gas will minimize contamination by material released from the spacecraft or from the walls of the mass spectrometer itself. For the rendezvous mission, the speed of the gas relative to the spacecraft will be the 0.5–1.0 km/sec outflow speed of the gas from the nucleus. This low speed will make it necessary to take special precautions for chemical cleanliness. Fortunately, for much of the rendezvous mission the densities of the cometary gases are expected to be orders of magnitude greater than the densities of the most troublesome background gases— H_2 , H_2O , CO_2 , CO and CH_4 .

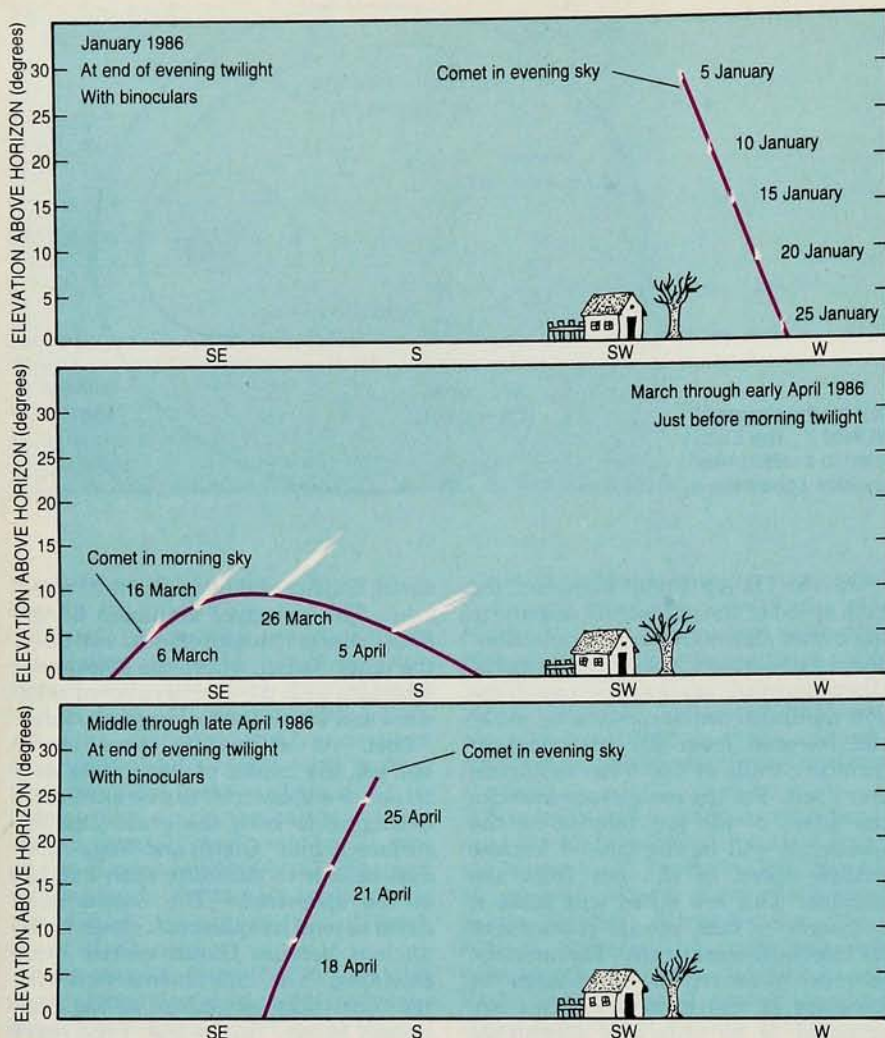
There is much synergism between the several comet missions in the observations of plasma ions, electrons, magnetic fields and waves. The instruments on the International Cometary Explorer mapped the plasma properties across the tail approximately 8000 km downstream of a moderately active comet. At Halley, which will be quite active in March 1986, the Japanese spacecraft will observe the initial deceleration of the solar wind as it encounters the cometary plasma. The Soviet spacecraft will observe the solar wind in a region where the wind has already picked up a substantial number of cometary ions, has passed through a bow shock or an interaction region and is in the process of stagnating with the convected magnetic field lines piling up and draping over the cometary ionosphere. Giotto may penetrate into the ionosphere proper. Plasma observations by instruments on the Comet Rendezvous and Asteroid Flyby Mission will show how the interactions with the solar wind change in response to changing cometary activity, ranging from quiet to moderate, and in response to varying solar wind

speed, density and magnetic field direction. The principal emphasis of the CRAF plasma measurements will be on the inner region, where the ionosphere interacts with the already slowed solar wind and where the tail begins to form.

Dust. At a relative speed of 70 km/sec, the impact of dust grains on a sensor or a spacecraft can be extremely damaging to both the grain and the surface it hits. Giotto and Vega carry dust shields to minimize such hazards to the spacecraft. The Giotto team dares to send its spacecraft closer to the nucleus because Giotto carries more shielding. The instruments that analyze dust take advantage of the high impact speed. Giotto and Vega carry acoustic sensors to analyze dust impacts, and other instruments to measure the amount of plasma created in a single impact. The plasma sensors can detect individual particles with masses as small as 10^{-18} grams.

Another instrument, developed in West Germany and flown on both the Vega and Giotto missions, determines the elemental composition of the impacting grains by using a time-of-flight ion spectrometer to analyze the composition of the plasma clouds produced by the impacts. An American experiment on the Vega spacecraft detects dust particles, and determines their masses, by measuring the charge pulse created when the particles punch into or through a sheet of polarized polymer polyvinylidene fluoride with conducting electrodes on each face. (See *PHYSICS TODAY*, March 1985, page 113.)

For the CRAF the spacecraft velocity will be so low that the relative speed between the spacecraft and the dust equals the speed imparted to the grains by the drag of cometary gas. Impact speeds will probably be substantially less than 1 km/sec. It should thus be possible to collect and analyze undamaged grains. NASA's comet rendezvous science working group has recommended the inclusion of three types of



Where to look to see Halley's comet. These guides are exact for viewers in the Northern Hemisphere, 40° north latitude. The comet will spend February 1986 behind the Sun.

molecules or minerals on the surfaces of the two nuclei and in the gases and dust grains that escape from them. We may have isotopic abundances for a few of the more abundant elements.

From these data we may be able to find answers to many questions about the origin and evolution of the solar system. Among these questions are the following:

- ▶ What do the isotopic abundances of cometary material tell us about the source of the material from which comets formed?
- ▶ Are the present molecules and dust grains in comets the same as those known to exist in interstellar clouds, or are they products of the solar system?
- ▶ What conditions, such as temperature, composition, density and the presence of ionizing agents were necessary for the formation of the molecules and grains?
- ▶ Is the chemical composition of comets consistent with their being a significant source of volatiles for the atmosphere of Venus, Earth and Mars?
- ▶ What biogenic elements or compounds could have been brought to Earth by comets?

We will also have data on plasma phenomena at three comets with different levels of activity, and under various solar-wind conditions; from such data we can deduce the principal ionization, acceleration and other interaction processes that occur in this type of astrophysical setting.

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dust sensors on the CRAF mission:

- ▶ A dust counter, or flux monitor, to measure the flux of grains as a function of their size, mass and perhaps also their velocity. NASA is funding development of a sensitive microbalance with this capability. An alternative method of measuring the flux of dust would be to analyze light scattered from individual grains. Whatever the type of detector selected, other instruments on the spacecraft would use the information on the instantaneous dust flux to close shutters or to take other protective steps in the event of a potentially harmful onslaught of dust.
- ▶ A dust-particle analyzer to determine the morphology and mineralogy of individual dust grains. Development work is well along on a miniature scanning electron microscope for this application.
- ▶ An instrument to determine the elemental and molecular compositions of bulk samples of dust. There are many well-proven techniques for doing this, including alpha backscattering, x-ray fluorescence and secondary-ion mass spectrometry. One could also pyrolyze samples of dust and use a mass

spectrometer or gas chromatograph to analyze the gases that evolve.

What we'll know by 1998

Where will our knowledge of comets stand in 1998 if the experiments described above have all been successful?

Most importantly, we will have detailed pictures of the nuclei of two comets, from which we can deduce such parameters as their sizes, shapes, spin rates and how they are put together. For the rendezvous comet, we will also know the average density and gross arrangement of mass within the nucleus. We will have maps of the surface topographies and their relation to the distribution of minerals and ices. We will know how the escape of gas and dust from the comets is related to these surface features and how it varies with the influx of solar radiation. We will know the elemental composition of the gas and dust emitted from the nuclei of two different comets. If a penetrator is included on the CRAF mission, we will also know the elemental composition at one point below the surface of one comet's nucleus. We will know how these elements have combined into