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ABSTRACT

Comet chronicles and stories extend back over thousands of years. A common theme has been that comets are a major cause of catastrophe and tragedy here on earth. In addition, both Aristotle and Ptolemy believed that comets were phenomena within the earth's atmosphere, and it wasn't until the 16th century, when Danish astronomer Tycho Brache carried out his research, that comets were found to reside well beyond the orbit of the moon. More than a century later British scientist Edmund Halley placed comets even further out in space by calculating the orbits of a number of them. He also noted that certain comets had been observed to appear in the same orbital patterns three times at regular 75- to 76-year intervals and proposed that the explanation was that these were not three, but one comet--the comet that was later to be named Halley's comet in his honor. Although Comet Halley has receded into the outer solar system, it still regularly reappears and may still generate excitement for students. It is, in effect, a time capsule, binding grandchildren with grandparents, and scientists in one era with scientists of another. This booklet provides teachers with information essential to the study of Halley's comet when this topic is integrated into existing lessons plans. Because this booklet is designed as a teaching supplement for the classroom, the instructional materials are intended for use in the order presented. The first section includes the following chapters: (1) The Ultimate Time Travelers; (2) Touching Humanity; (3) Halley's History; (4) Where Do Comets Come From; (5) What is a Comet; (6) The Halley Fleet; (7) Through the Halls of Time; (8) Other Heavenly Wayfarers; and (9) Touching the Future. Section 2, which includes 43 classroom activities, is presented as a supplement to the first section. Vocabularies listed in section 2 are taken directly from the background information presented in section 1. The classroom activities are suggested for inclusion within a broad course of study or as isolated exercises, and are not labeled by discipline, grade, or ability level. The individual teacher's creativity and ingenuity can facilitate their application to almost any area of study. (KR)

To Catch A Comet...

NASA

To Catch a Comet

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Space Administration EP-252

Acknowledgment

Many individuals have contributed to this book. Teacher In Space Finalist Niki Wenger developed the concept and saw the work through to fruition. Without her dedication and enthusiasm, this book would not have been possible. Special thanks also go to Marchelle Canright, at NASA's Lewis Research Center, for her assistance in the formative stages, and to Malcolm Niedner, at NASA's Goddard Space Flight Center, for his continuing technical guidance. Production of *To Catch A Comet* was made possible by the assistance of the NASA Educational Affairs Division staff. Robert Haynes, Rebecca J. Merck, and Marion Davis edited section 1 of the booklet into its final version, and Pamela Bacon and Muriel M. Thorne provided valuable assistance in compiling the activities in section 2.

Cover Photo: Comet Halley—April 6, 1986. This photograph was taken with a 35-mm camera from on board NASA's Kuiper Airborne Observatory, almost 13 kilometers above New Zealand. (See "The Halley Fleet.")

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Because this booklet is designed as a teaching supplement for the classroom, the material in it is best used in the order it is presented. Vocabularies listed in section 2 are taken directly from background information presented in section 1. Although Comet Halley has receded into the outer solar system, it may still generate excitement for students. It is, in effect, a time capsule, binding grandchildren with grandparents, and scientists of one era with scientists of another. This booklet provides teachers with the information they need to incorporate the study of the comet into their existing lessons.

The Ultimate Time Travelers

For almost as long as comets have crossed the skies, they have both fascinated and terrified humankind. As we near the end of this century, the fear associated with comets has at long last become an historical footnote and a new chapter has begun—a Golden Age—in which comets are among the most important and intensively-studied objects in the universe. These small icy bodies which emit almost no energy of their own and which populate the outer reaches of the solar system in unimaginable numbers, may hold crucial clues to the origin of the solar system, and indeed of life on Earth. It seems almost as if their importance is in inverse proportion to their size. The Golden Age of Comets resulted from not only this increased appreciation of their role in our understanding of the cosmos, but also from the advent of new observational techniques, including measurements from high-flying airplanes, spacecraft in Earth orbit and interplanetary space, and even spacecraft traversing the comet itself!

Giotto's fresco, *Adoration of the Magi*, portrays Halley's Comet as the Star of Bethlehem. Arena Chapel, Padua, Italy.

Two comets in particular, Giacobini-Zinner ("G-Z") and Halley, have achieved (or in the case of Halley, added to its) immortality in the 1980s as a result of being the first such objects to be visited by spacecraft. The findings provided by these missions were truly unique and could not have been obtained in any other way. There is a class of inquiry in cometary science which requires "space truth" for answers, and these missions provided some of them.

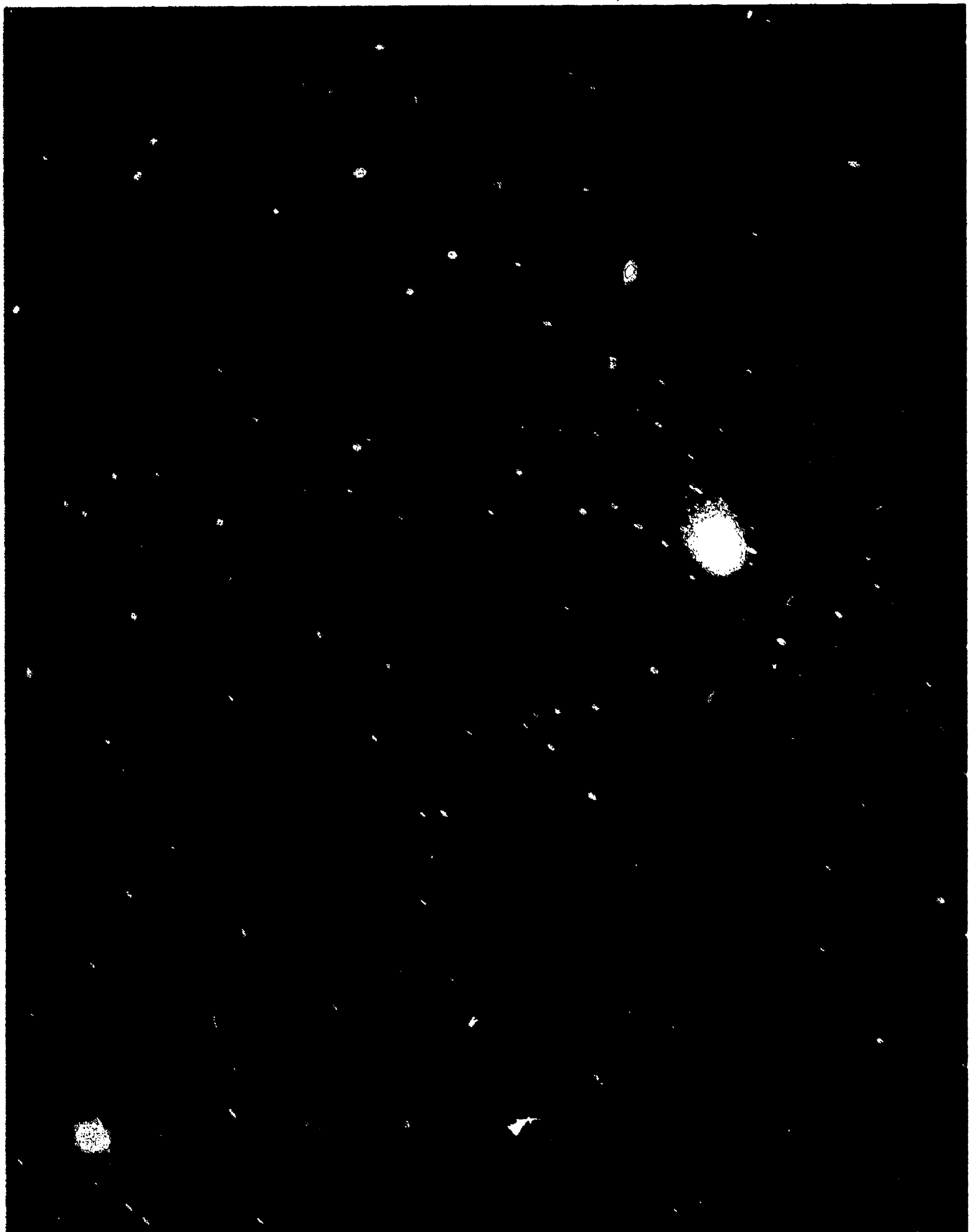
But even with all the data gleaned by the Giacobini-Zinner and Halley campaigns, many more questions remain to be answered by better, more sophisticated missions to other comets. If all goes well, the missions to Halley and G-Z will be seen in historical context as just the start of an exciting new age of cometary exploration—exploration by "going there."

Why is the study of comets so important? Most scientists believe that comets were formed at the same time and out of the same matter as our solar system. Because comets are small and spend most of their time far from the Sun—in "cold storage" so to speak—their composition may have remained essentially unchanged over the eons. This is certainly not the case for Earth, the other planets, and asteroids, which have basked in the Sun's warmth and undergone substantial change over the billions of years the solar system has existed. Comets offer us the best hope of investigating those primordial conditions that existed during the solar system's birth.

In addition, some scientists believe comets played a role in shaping life on Earth, as they passed through the skies leaving behind atoms and vapors that provided our planet with some of life's essential building blocks.

Comets may also have collided with Earth in times past, throwing great dust clouds into the atmosphere and significantly reducing the sunlight that reached Earth's surface. The resulting sudden drop in temperature could have caused entire species of plants and animals to die out, thus allowing other life forms to evolve.

Halley's is without doubt the most intriguing and endearing of all comets. Because its orbit coincides with the length of an average human lifespan, its arrival every 76 years bridges generations. Bright as far as comets go, its appearance in the year 1301 so captivated the Florentine artist Giotto that he used it as a model for the Star of Bethlehem in his fresco, *Adoration of the Magi*.

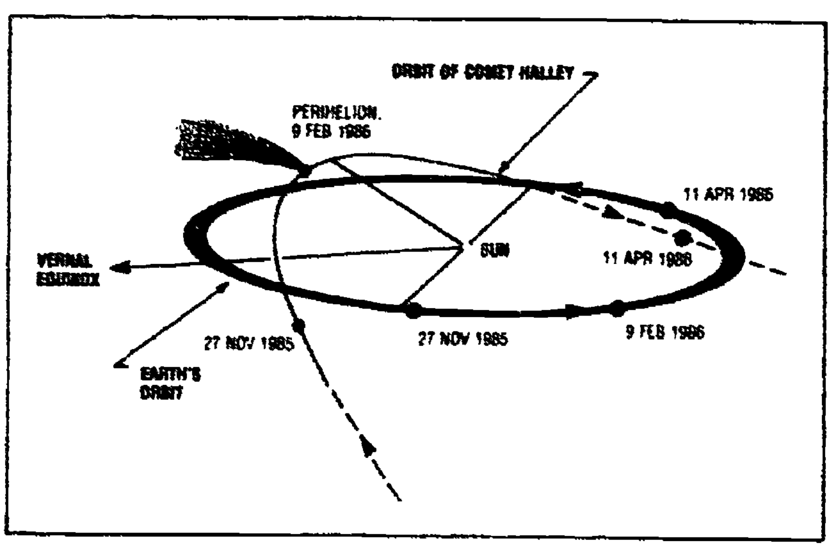


Touching Humanity

Sir Edmund Halley. National Portrait Gallery, London, England.

In 1705, British scientist/astronomer Edmund Halley pulolished his "A Synopsis of the Astronomy of Co nets", a monumental work containing the result for which he is most remembered today. Using accurate observations of cometary positions in the sky made over the previous several hundred years, Halley was able to calculate reasonably accurate orbits *in space* for a number of bright comets. His tools were Kepler's Laws of Planetary Motion and Newton's Law of Universal Gravitation. The former held that planets—and presumably other objects in the solar system—travelled in ellipses around the Sun with orbital periods dependent in a prescribed way on the size of the orbit (a longer period resulting from a larger orbit). Newton's theory that the gravitational force between two bodies was proportional to the product of their masses and inversely proportional to the square of the distance between them, provided the theoretical underpinning for Kepler's Laws.

Halley noticed that three orbits—those of comets sighted in 1531, 1607, and 1682—had nearly identical sizes, shapes, and orientations in space, and that the appearances of these supposedly different comets were separated by about 75-year intervals. He proposed that they were actually the same object returning at regular times, and that this one comet would reappear sometime in 1758–1759. Although Halley was the first to predict the next visit of a comet, he unfortunately died before he could see his prediction fulfilled. When the comet did return as he said it would, first being seen on Christmas Day 1758, it was given Halley's name in his honor.



Halley's retrograde orbit is at an inclination to the orbits of the planets.

Comet Halley completes an orbit roughly every 76 years. As Halley himself realized, the period varies because of gravitational interactions with the planets in the solar system, especially the giant planets Jupiter and Saturn. The comet has returned as soon as 74.42 years (between 1835 and 1910) and as late as 79.25 years (451 to 530). Its arrival in 1986 was 4 days later than predicted.

How close Halley's Comet comes to the Sun and Earth also varies. In 837 A.D. Halley's Comet came to within 4.91 million kilometers of Earth, which sounds far away but is "at arm's length" on the scale of interplanetary space. In 1986, its closest approach was a remote 62.4 million kilometers achieved on April 11. At the aphelion point in its orbit—the farthest distance from the Sun—Halley's Comet is 5.25 billion kilometers away (well beyond the orbit of Neptune) and moves at the relatively slow speed of 3,200 kilometers an hour. In contrast, at perihelion—the closest approach to the Sun (achieved on February 9, 1986)—the comet is only 87.4 million kilometers from the Sun and travels at nearly 195,200 kilometers an hour (about 3,200 kilometers a minute).

Halley's Comet has a retrograde orbit, which means it circles the Sun in an opposite direction from the planets. Its orbital plane is inclined 162 degrees from Earth's orbital plane.

Only several hundred comets are known which have orbits that allow us to view them more than once. Those that do, like Halley's, are called "short period" comets. Halley's has been recorded as far back as 240 B.C. (and perhaps earlier), and its 1985–86 appearance was its thirtieth definitive recorded passage. In contrast, long-period comets may have calculated orbital periods of many thousands of years or more. The traditional demarcation

Bayeux Tapestry. Museum of Queen Matilda, Bayeux, Normandy, France.

line between short- and long-period is an orbital period of 200 years.

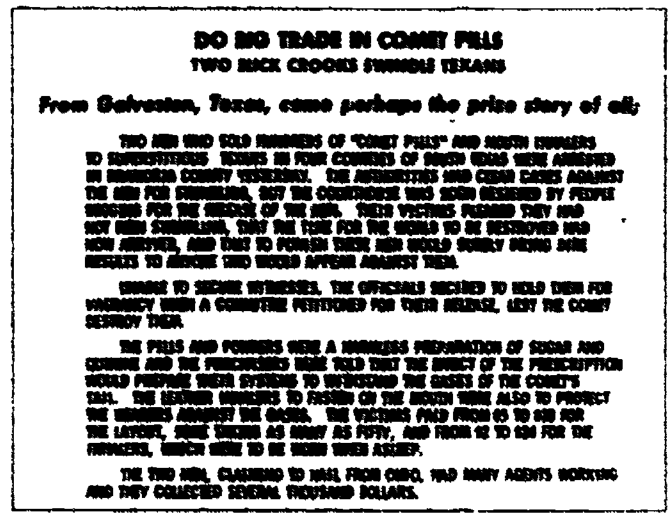
Throughout comet chronicles extending over thousands of years, a common theme emerged that comets are one of the major causes of tragedy and catastrophe on Earth. In part, this superstition derived from the fact that very often a comet was (or had just been) in the sky when something terrible occurred, and it was, therefore, natural for a people to make this association. Add to this their almost ghostly appearance in the sky and the near-complete lack of knowledge concerning their true nature, and one has a perfect formula for superstition and fear. We strive to prescribe an orderly progression for natural phenomena and become anxious when objects like comets seem to appear out of nowhere and then journey to some unknown destination. Even the word disaster comes from the Latin for evil (dis) star (aster).

Comets were so closely tied to the deaths of leaders that when a comet failed to appear at Charlemagne's death, historians made one up and wrote it into the history books.

Both Aristotle and Ptolemy believed comets were phenomena in the Earth's atmosphere. It wasn't until the 16th century, when Danish astronomer Tycho Brahe used accurate observations of a comet's position from two widely separated locations on Earth (the process of "triangulation"), that comets were found to reside well beyond the orbit of the Moon. In other words, they were bona fide celestial objects, and not atmospheric in nature. Even then, comets were thought of as swords or scimitars by some because of their curved shapes, which seemed poised to wield a blow. Such a blow was seen as intended against those most elevated on Earth-royalty and the leaders of nations.

Except for the irrational actions they have occasionally inspired in humans, comets have done little else to harm humanity. For example, such irrational actions might include Nero, who is said to have outwitted Halley's appearance in 66 A.D. by murdering his mother, two wives, and most of his family and by setting the city of Rome on fire. In 1531, the Incas thought the comet was a sign of their Sun God's wrath and began a series of human sacrifices as appeasement. In 1066, William the Conquerer interpreted Halley's appearance as a sign of his impending victory and so led the Norman invasion of Saxon England. When Comet Kohoutek was discovered in 1973, some believed it heralded the end of the world, expected on January 31, 1974.

If we were to study history in terms of "Halleys" rather than years (one Halley being 76 ordinary Earth years), we could measure the rise and fall of civilizations and the advance of technology with a scale that coincides with human lifetimes. Each return of the comet would find a different world. In



DO BIG TRADE IN COMET PILLS

TWO BLACK CROOKS SWINDLE TEXANS

From Galveston, Texas, came perhaps the prize story of all:

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"Big Trade in Comet Pills"—One of the big stories during the 1910 visit of Halley's Comet came from Galveston, Texas, in a newspaper article about comet pills.

1910, the prediction that Earth would pass through Comet Halley's "poisonous tail" terrified thousands of people. Some bought gas masks and comet pills to protect themselves against the expected cyanogen gas, others stuffed towels under their doors, while a few even committed suicide rather than face the agony.

During 1986, in almost total contrast, we ventured to meet it, sending satellites and space probes to its vicinity in space. Scientists from many nations worked together to make the most of the scientific opportunity. Perhaps there are some who, even at this enlightened point in the scientific study of comets, will attempt to link the recent appearance of Halley to tragic events. Although the future must tell how the world will react to the next return of Comet Halley, it is still challenging to imagine what the world will be like and how we will greet the return of Comet Halley in 2061.

Halley's History

The following list covers important world events around the time of each recorded appearance of Comet Halley.

1. 240 B.C. First recorded appearance in China. Archimedes is in his forties. Construction of Great Wall of China to begin in 25 years.
2. 164 B.C. Use of gears leads to animal-driven water wheel. Last year Rome recorded 327,032 citizens.
3. 87 B.C. Julius Caesar, at the age of 13, sees Halley's. Athens falls to Rome next year.
4. 12 B.C. Virgil began The Aeneid 8 years ago. First time comet is called an omen of disaster.
5. 66 A.D The Gospel According to St. Mark appeared last year. Jerusulem, attacked by Romans, to fall in 4 years.
6. 141 Chinese astronomers recorded a comet in their skies. Ptolemy is developing his theory that Earth is the center of the universe.
7. 218 Comet appears over China, then over Rome days later. Fearful flaming star precedes Roman emperor Macrinus' death.
8. 295 Roman persecution of Christians to begin in 8 years.
9. 374 Emperor Valentinian to die next year. Books begin to replace scrolls in Europe.
10. 451 Attila and his Huns defeated at Battle of Chalons. Indian astronomer devises mathematical powers and roots.
11. 530 Saxon invaders found kingdom in what is now England. Plague sweeps across Europe.
12. 607 First envoy from Japan arrives in China. Westminster Abbey will be founded in 4 years.
13. 684 Mount Vesuvius erupts. Plague sweeps across China.
14. 760 Bagdad to become seat of Arab Empire in 2 years. Turkish Empire founded.
15. 837 Algebra is invented in Persia. Closest approach of Comet Halley to Earth.

Halley's Comet on May 13, 1910, shown in this photograph with an ion tail disconnection. Note the meteor in the comet's tail to the left of Venus (bright spot), and the trailed lights of Flagstaff, Arizona. Photo: Lowell Observatory.

16. 912 Normans become established in France.

17. 989 Normans to invade England next year. Arabic numbers introduced to E rope.

18. 1066 Battle of Hastings. Frightened by comet, Saxons fall to invading Normans. Earliest representation of the comet is this appearance, noted in the Bayeux Tapestry.

19. 1145 Danube River is bridged. In France, music troubadours heard for the first time.

20. 1222 Genghis Kahn takes comet as a sign he should conquer the world. Cotton introduced to Spain.

21. 1301 Flavio to invent mariner's compass next year. Giotto to use appearance of comet as inspiration for Star of Bethelem in his painting, Adoration of the Magi. (1303–6).

22. 1378 Chaucer is 35 years old.

23. 1456 Athens falls to the Turks. Columbus is 5 years old.

24. 1531 Copernicus is 58 years old; his theory is yet unpublished. Post offices are established in England.

25. 1607 Galileo develops an astronomical telescope. Jamestown is founded.

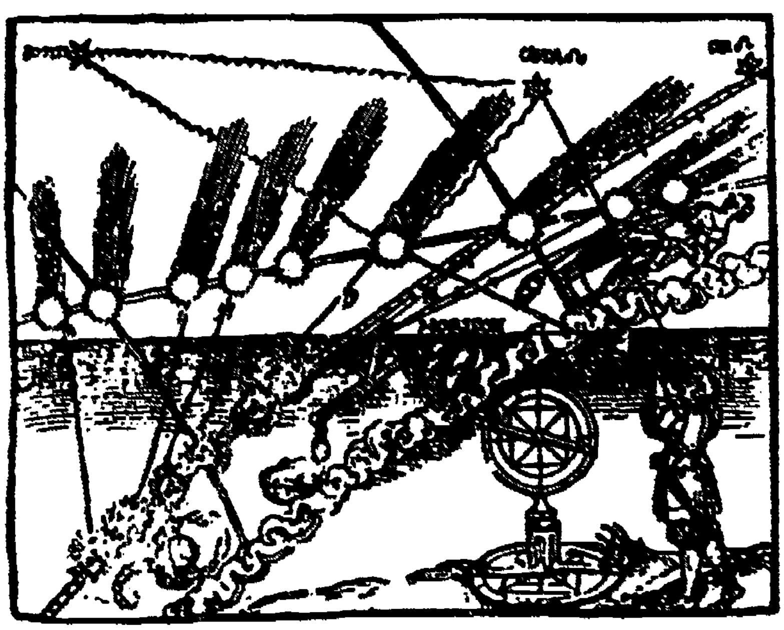
26. 1682 Philadelp^h^ia, Pennsylvania, and Norfolk, Virginia, are founded. Isaac Newton explains tides using theory of gravitation.

27. 1759 James Watt to complete steam engine next year. Return of comet predicted by Edmond Halley; comet given his name in honor.

28. 1835 Cyrus McCormick invented reaper last year. Plague sweeps through Egypt. World population about 1 billion.

29. 1910 Gas masks and comet pills sold to protect people. Boy Scouts of America founded. World population about 2 billion.

30. 1986 Space probes used to observe Comet Halley. World popu'ation about 5 billion.



Great Comet of 1532. Petrus Apianus woodcut.

Where Do Comets Come From?

When humans first looked up and wondered at the night sky, they devised many stories—early theories, really—to explain the bright objects above them. When Edmund Halley showed that comets move in well-determined orbits under the influence of solar gravitation, people began to recognize that comets moved in accordance with well-known physical laws, and hence could not be omens of destruction. Halley's work probably marked the beginning of the scientific method as applied to comets. Nearly a century and a half later, when it was discovered by spectroscopy that many of the elements and molecules in cometary atmospheres and tails are found on Earth and in the Sun, the theory that comets were formed during the birth of the solar system was first proposed.

Twentieth-century scientists have suggested several theories to explain the origin of comets. One landmark and still very current idea was proposed in 1950 by Dutch astronomer Jan Van Oort, who studied the orbits of nineteen long-period comets and concluded *generally* that the long-period comets which visit the inner solar system and are visible from Earth come in from a huge comet "cloud" numbering perhaps a trillion objects. By examining the distribution of aphelion distances (the farthest point on the orbit from the Sun), Oort estimated the size of this cloud to be 100,000 or so astronomical units (or "AU") in diameter (one AU is the distance between Sun and Earth), a size which is about half the distance to the nearest stars and which dwarfs the 40 AU radius orbit of Pluto, the outermost known planet. The periods associated with such huge elliptical orbits are in the tens of thousands, and even millions, of years.

Those nineteen orbits are not typical of comets in the "Oort cloud", however. Oort suggested that the overwhelming majority of comets in the cloud are moving in huge, nearly-circular orbits which do not come close to the inner solar system, and hence they are not visible from Earth. There must be a force which converts some of these orbits into highly-elongated ellipses with perihelion (closest distance to the Sun) inside 5 AU, where we can discover comets. But what is this force? Oort theorized that occasional gravitational encounters of the comet cloud with nearby passing stars in the galaxy might shake loose a relative handful of comets, sending them toward the inner solar system. Modern computer simulations have shown that such a mechanism can indeed bring very distant comets into the inner solar system. Recent refinements on Oort's pioneering idea suggest the presence of a second, or inner Oort Cloud existing beyond the orbit of Neptune and containing 10 to 100 times more comets than the outer cloud.

Oort's model told us where the long-period comets come from today, but perhaps did not completely answer the question "where were comets originally formed, and how did they get into the Oort cloud?" There are two general schools of thought, and both derive from the concept that the solar system was created 4.5 billion years ago from a huge, spinning cloud of interstellar gas and dust. After the initial spherical cloud flattened into a rotating disk, the concentrations of gas and dust would have been large enough for kilometer-size objects called "planetesimals" to condense out of the disk material. When a critical number of these had been created, the planetesimals themselves would have come together gravitationally to form the much larger planets. The Sun, of course, represented the collapse and agglomeration of a huge amount of material near the center of the disk.

In the more prevalent view of comet formation, the Oort cloud of comets was created when kilometer-size planetesimals in the Uranus-Neptune zone were gravitationally ejected by the newly-formed Uranus and Neptune into the Oort cloud. Thus, comets represent those planetesimals between the orbits of Uranus and Neptune which did not condense into those two planets, but were simply ejected by them into near-interstellar space.

The other view is that comets were actually formed at the distances of the current Oort cloud, out of the very outermost material of the initial spherical cloud of gas and dust (the so-called "solar nebula"). The major problem with this theory is that at such vast distances from the Sun, the density of dust and gas in the solar nebula would have been so low as to virtually preclude condensation into kilometer-sized objects.

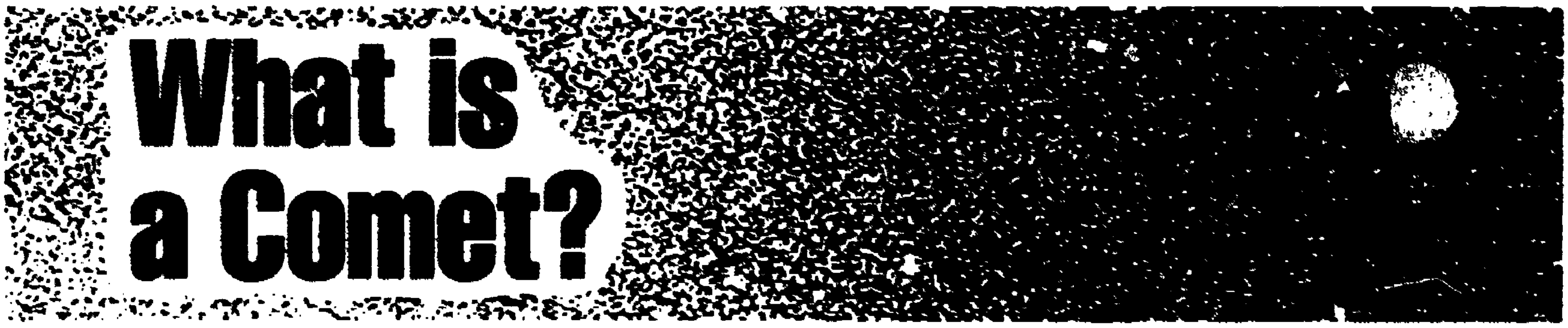
Any successful model of comets must explain the existence of comets like Halley's, whose periods are not long, and whose aphelion distances are not in the Oort cloud, but inside the planetary system. If all comets originally resided in the cloud (after ejection by Uranus and Neptune, that is), what force converted some of their orbits to relatively small ellipses like Halley's? The answer is gravitational inter-

The Oort Comet Cloud. When a star comes close enough (insets at right), comets in the cloud "fall" into the inner solar system. Courtesy of *Sky and Telescope* magazine.

actions with the giant planets Jupiter and Saturn. After stellar encounters convert some of the circular orbits in the Oort cloud to huge, highly-elongated ellipses (with perihelia in the inner solar system), Jupiter and Saturn have enough mass to further change the orbit if the comet passes close to either of them. The result of repeated interactions with these planets can be a very small orbital ellipse (and short period) such as Halley's. But just the opposite is also possible: comets can be hurled "slingshot style" out of the solar system by a close pass with Jupiter if the geometry of the interaction is just right.

Eventually comets die. After thousands of passes around the Sun, they either disintegrate, evaporate, or become inert. This latter situation probably results from the formation of a thick encrustation of dust and other nonvolatile material which prevents the maintenance of an atmosphere and tail. When this happens, the comet continues its orbit around the Sun, but now it resembles a sponge-like asteroid.

Orientation of Halley's orbit to planets in our solar system.

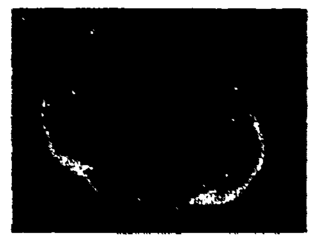


What is a Comet?

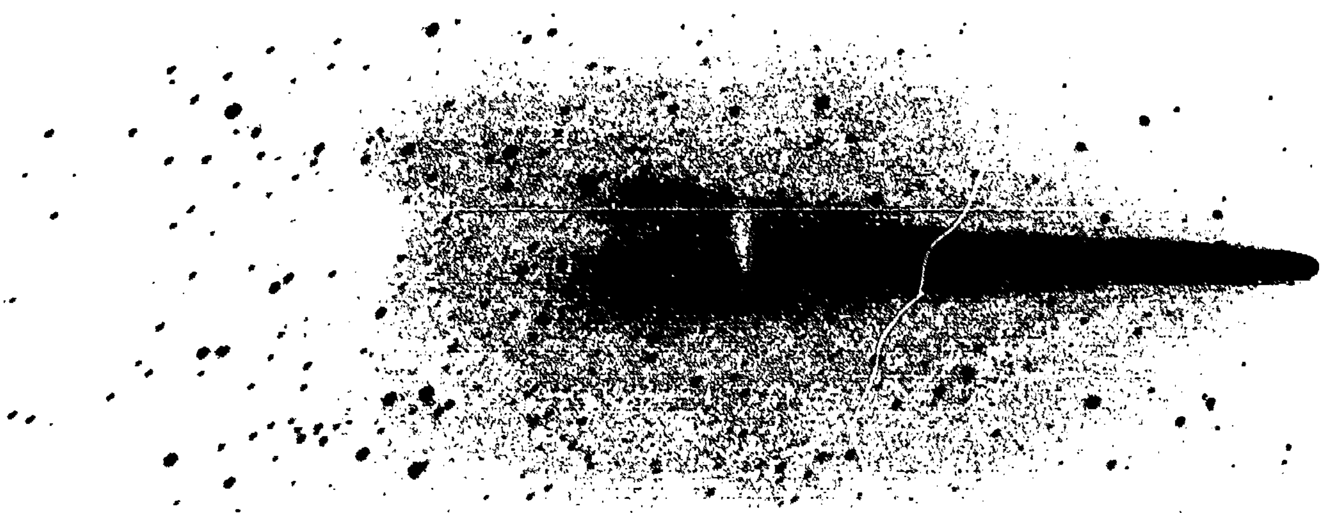
It is a remarkable coincidence that the first modern idea on the structure of comets came in the same year as Oort's hypothesis, 1950. The pioneer was the American astronomer Fred L. Whipple, who addressed the fundamental question of the ultimate *source* of material seen in cometary atmospheres and tails. As comets near the Sun from the cold outer reaches of the solar system, it is an observational fact that they produce an atmosphere, or "coma", which is approximately one hundred thousand kilometers across, followed by the formation of a tail or tails which can be tens of millions of kilometers long. Unfortunately, the coma's brightness completely hides the central source of its material when the comet is close enough to Earth to be studied. The problem when the comet is distant and does not yet possess an obscuring coma is that the central source is too faint and small to be studied in detail from the Earth. Is there a tiny solid nucleus which produces the coma and tails, or is the source of material a compact swarm of individual particles? Whipple tried to come to grips with such seemingly simple questions, and the theory he put forth has survived the test of time.

Over the huge majority of its orbital arc, Whipple reasoned that a comet is a small (several kilometers wide), cold, and inert chunk of ice embedded with dust grains and perhaps rocks. He pictured comets as dirty snowballs. In addition to hydrogen- and oxygen-bearing molecules, spectra of cometary comae had shown carbon- and nitrogen-bearing species, and Whipple therefore knew that there had to be several kinds of ice, not just water ice, in his nuclei. Water ice might be the dominant component, but carbon monoxide, carbon dioxide, methane, and ammonia ices, were also possibilities in smaller amounts. In Whipple's model, the dust grains are trapped in the icy lattice and are released by the evaporating ices as the comet approaches the Sun and grows warmer. It is this outstreaming "dusty gas" which forms the coma and ultimately the tails of comets. Because of the extremely low pressure of the coma gases, the melting ice bypasses the liquid phase altogether, changing from a solid to a gas in one step called "sublimation."

Whipple's theory explained two observed facts very well. First, the concentration of ices into a solid body, as opposed to a particle swarm, was consistent with the longevity of the short-period comets (such as Halley and Encke, each of which had been seen for many returns), for the amount of material sublimated away during each orbital pass should only be meters deep. The second fact had to do with the observed tendency of some comets to have an orbital period which changed with time. If the nucleus of a comet were to rotate, then the maximum sublimation on the sunlit hemisphere should be in the "afternoon sector" as a result of thermal inertia, and the resulting uneven release of gas across the face of the nucleus would create a "rocket effect" which could, in principle, change the orbital period ever so slightly with time. When Whipple worked



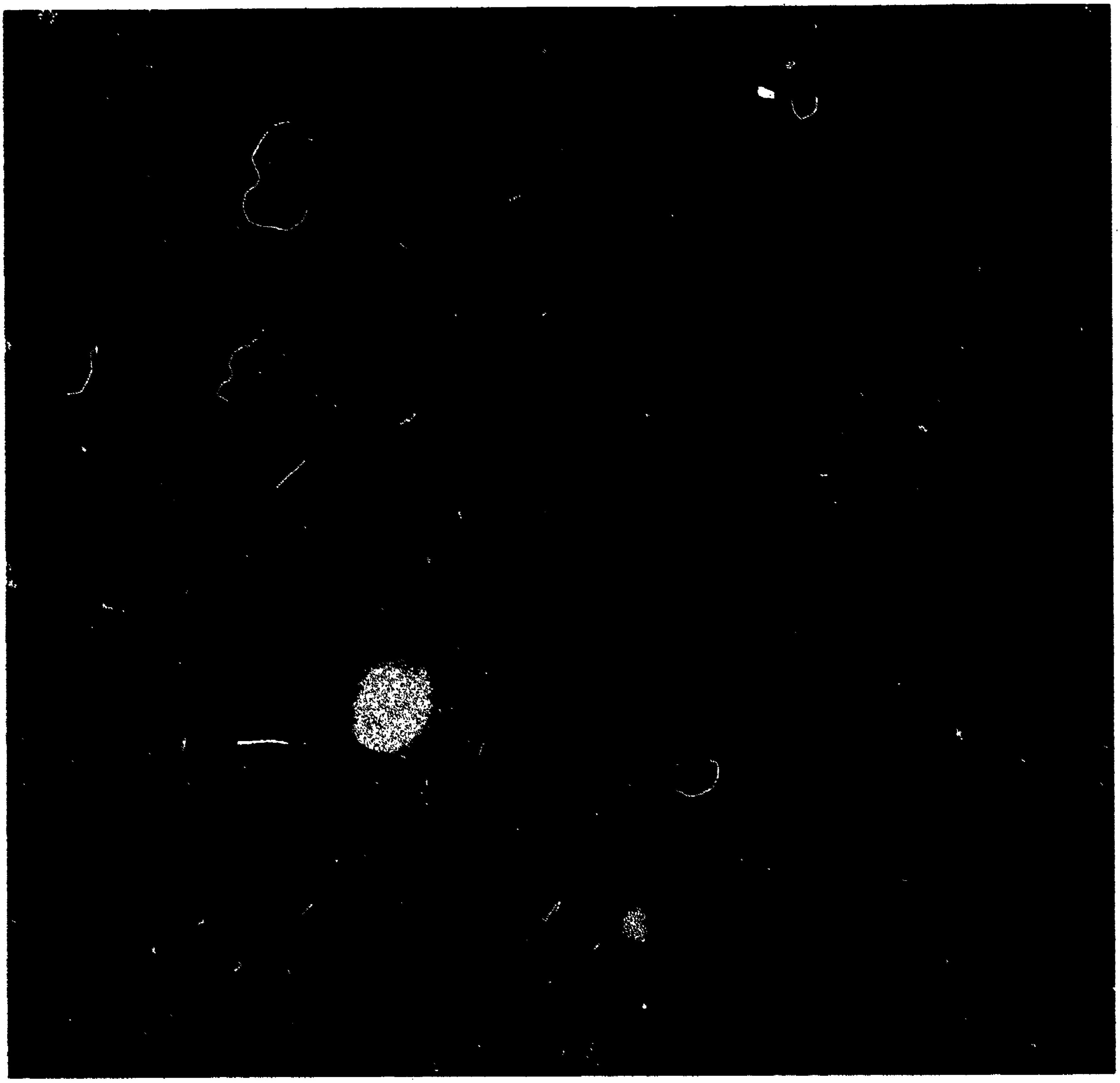
Electron micrograph of a particle collected high in the Earth's atmosphere by a U-2 aircraft. Huge numbers of such particles are believed to form the dust tail of a comet. Photo: Don Brownlee, University of Wisconsin.



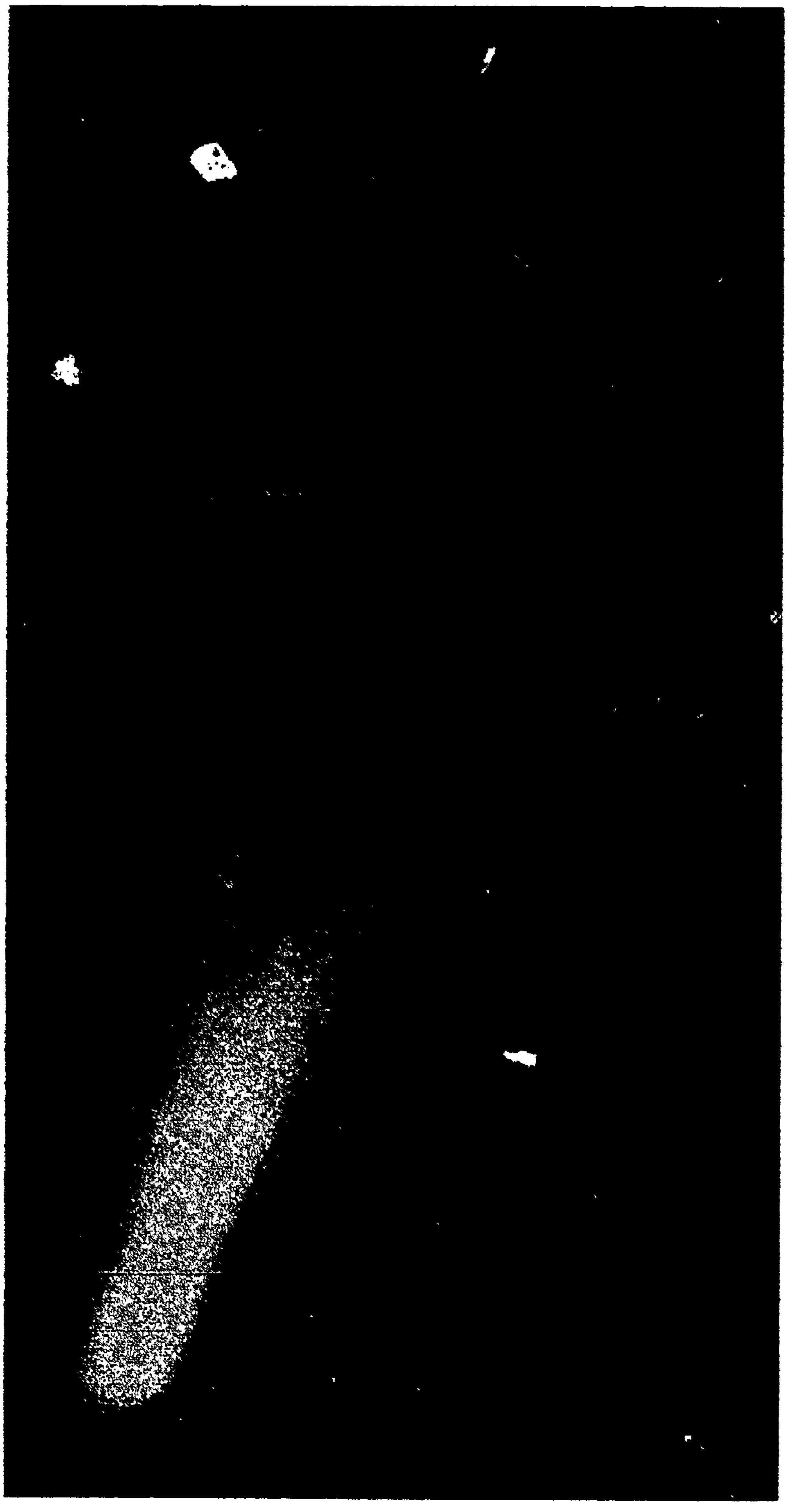
Halley's Comet as seen in 1910.

out how fast the period should change, he found excellent agreement with the changing period of comet Encke, the comet with the shortest known orbital period (3.3 years). There have been refinements and improvements to Whipple's theory, but the basic ideas have held up through the spacecraft encounters with Halley's Comet.

The coma as traditionally defined consists of gases seen in the region of the spectrum to which our eyes are sensitive, and the characteristic diameter is 50,000–100,000 kilometers. In 1969, however, a huge cloud of hydrogen, visible only in ultraviolet light, was discovered surrounding two comets and spreading across millions of kilometers. It is



Color-enhanced photo of cometary heat zones.



well understood that this "hydrogen cloud" consists of individual hydrogen atoms which have been dissociated from water molecules by ultraviolet sunlight as the water molecules flow out from the nucleus.

Comets which are large or active enough (i.e., sublimating enough gas and dust from the nucleus) will start to develop tails when the distance to the Sun is 2 AU or so. By the time such a comet has reached perihelion, which may be significantly less than 1 AU, the tail lengths may exceed 10 million kilometers. This is a truly astonishing phenomenon when one stops to consider that 10 million kilometers is nearly ten times the Sun's diameter, and that such an enormous structure derives from an object only kilometers across (the nucleus).

There are two basic types of tail and individual comets frequently manifest both types. They could hardly be more different in appearance, behavior, and origin. The first to form is the so-called "plasma tail," or "ion tail" as it is equivalently known. This tail consists of cometary ions spiraling along magnetic fields captured by the comet from the solar wind, and its location in space is approximately along the anti-Sun direction. [An ion is an atom or molecule which has been stripped of one or more electrons ("ionized"), giving it a net positive charge. Atoms and molecules are ionized either by absorption of ultraviolet rays from the Sun, or by impact with energetic solar-wind protons.] The formation of plasma tails is an extremely complex process, but the most important feature is the "capture" of magnetic fields from the solar wind. [The solar wind is an extremely hot, supersonic gas which is produced in the Sun's outer atmosphere and which flows throughout the solar system]. This capture occurs because magnetic fields cannot pass freely through an ionized gas, and this is exactly what the coma is. The fields in the solar wind become hung up or stuck in the coma and get folded around behind the comet to form a type of "magnetic windsock." Because of their net charge, ions such as CO^+ (carbon monoxide ion) spiral along the captured field lines, fluorescing in the sunlight as they do. It is primarily the fluorescence of CO^+ in the blue region of the spectrum that gives the magnetic tail its visibility.

Because the solar wind is anything but steady, a plasma tail once-formed will exhibit considerable changes from night to night, and even hour to hour. Perhaps its most incredible property is the occasional total disconnection from the head, followed by the growth of a new attached tail. The disconnected tail moves rapidly away from the head and is dissipated into interplanetary space as the "new" tail grows. Such disconnection events, or "DE's", have been attributed to the interaction of comets with so-called "sector boundaries" in the solar wind, across which the direction of the magnetic field changes by 180 degrees. Halley's Comet had perhaps 20 or more DE's in 1985–1986.

The second type of tail is the dust tail, composed of small (typically micron size) dust grains originally resident in the cometary nucleus which, upon being released into the coma, are pushed by radiation pressure from sunlight behind the comet to form a broad, curving tail. The particles are literally travelling in their own independent orbits. The breadth of the dust tail depends in part on the size distribution of the dust grains, because small, light particles are accelerated by sunlight more easily than large, massive ones.

The light from dust tails is nothing but scattered sunlight, hence this type of tail is yellowish (or milky) in color, in contrast to the blue plasma tail. Although dust tails are oriented in the general direction away from the Sun, because the speeds of the dust particles relative to the nucleus are rather small, these tails do not congregate very closely to the exact antisolar direction, but are inclined significantly to it. In this respect, too, they differ markedly from plasma tails. The result when projected on the sky can be striking: the long narrow plasma tail going off almost exactly away from the Sun, and the shorter broader dust tail oriented perhaps 45 or even 90 degrees away from the plasma tail. Occasionally, under rather unusual viewing conditions, the largest particles in a cometary dust tail may project in the general direction of the Sun. This short structure is called an anti-tail.

Halley's Comet, comets Bennett, Kohoutek, and West are four of the recent comets (since 1970) which have displayed prominent dust and plasma tails, but not all comets have two tails. Some may have one kind of tail but not the other, and many of the small periodic comets have none.

As comets near the Sun, they are traveling at thousands of kilometers a minute, but they are so far away that we see them as slow-moving objects against the background of the stars that remain in view over several weeks.

Each trip an active comet makes around the Sun causes it to lose several hundred million tons of dust and vapor. The largest particles shed by cometary dust tails are the source for dazzling meteor showers when Earth passes through or near a comet's orbit. Motes left by passing comets have been found on the ocean bottoms and in the atmosphere at high altitudes.

Even before the direct exploration of Halley's Comet by space probes in 1986, it was known that the sublimation of ices on the cometary nucleus is not a uniform process across the sunlit face of the nucleus. Telescopic views and photographs of cometary comae have shown for well over one hundred years the presence of rotating jets and expanding halos for many comets. The presumption was that there are long-lived zones of greater-than-average activity on the rotating nucleus which, when illuminated by the Sun, emit gas and dust visible as discrete structures from Earth. In a somewhat different category are the occasional random outbursts of gas and dust which probably represent the sudden exposure of fresh ices to the Sun when a portion of any insulating surface crust breaks away.

Whipple dirty snowball model of a comet nucleus states that vapor jets shoot from large patches of "ice" as they are heated by the Sun. Courtesy *Sky and Telescope* magazine.

There are several theories concerning the nature of the jets, and indeed of cometary nuclei themselves. In one, the nucleus is a frozen mass of house-sized chunks of ice or snowballs that are loosely bonded and crusted over. The jets emerge from spaces in between the snowballs, when a chunk breaks away exposing fresh ice, or sunlight hits a thinly crusted region. In another, similar concept, the nucleus is composed of boulders glued together by a dusty ice coating acquired when the comet formed. Jets come from the ice-filled gaps between the boulders.

The images of Halley's nucleus returned by the VEGA and especially Giotto spacecraft (discussed below) will perhaps help us determine which model, if either, is more accurate.

The Halley Fleet

The first spacecraft to measure a comet's environment by "going there" was the Interplanetary Cometary Explorer (ICE). Launched by NASA in 1978 as the third International Sun-Earth Explorer, or ISEE-3, the spacecraft's original purpose was to study the solar wind input to the Earth's magnetosphere from a location just "upstream" of the Earth. By 1982, the spacecraft had performed its primary mission almost flawlessly for over four years, and a great deal had been learned about the interaction of the solar wind with the magnetosphere.

NASA's International cometary Explorer Spacecraft "ICE" approaching Giacobini-Zinner.

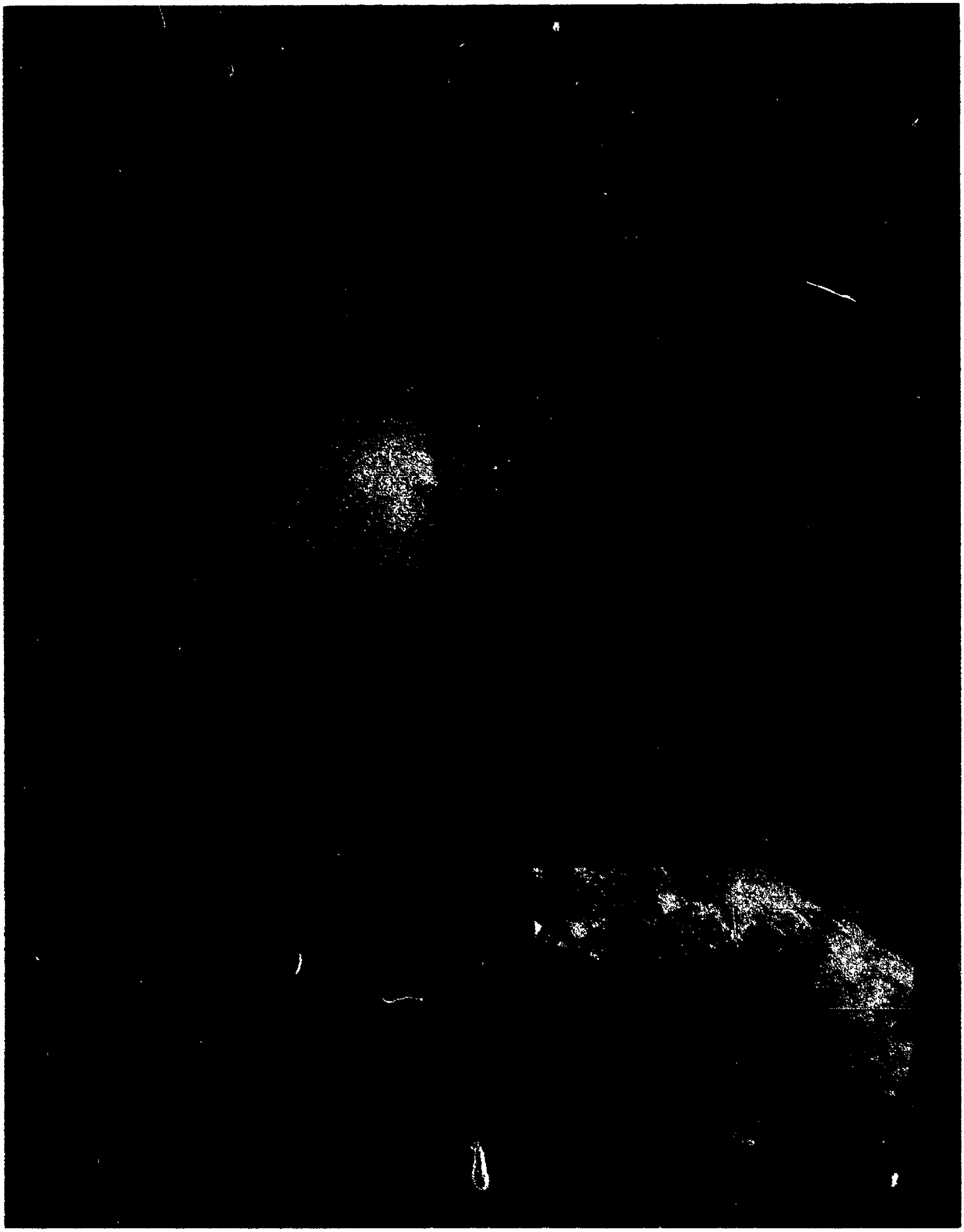
Its initial objectives essentially achieved, a team led by Robert Farquhar studied the feasibility of using the spacecraft to carry out other missions, including a flyby of comet Giacobini-Zinner (G-Z). G-Z would be passing perihelion in early-September of 1985 at a point in space very near the Earth's orbital plane and slightly less than 0.5 AU from Earth, and there was a chance that by sending ISEE-3 through the complex combined gravity field of the Earth and Moon, the spacecraft could be 'sling-shotted' to an encounter with the comet. Fortunately, there was plenty of hydrazine fuel onboard to perform any needed maneuvers, but the problem of finding a proper trajectory through the Earth-Moon system which had G-Z "at the other end" was another, very much more complicated matter.

Extensive computer studies performed over many months showed that there was indeed a solution, and at this point NASA gave the go-ahead for the G-Z extension of the mission. Before it left the Earth-Moon system, ISEE-3 made two deep passes in the Earth's magnetic tail, returning a harvest of invaluable data. As the spacecraft ended its last lunar swingby maneuver in December 1983, and headed for G-Z, it received a new name, ICE, for International Cometary Explorer.

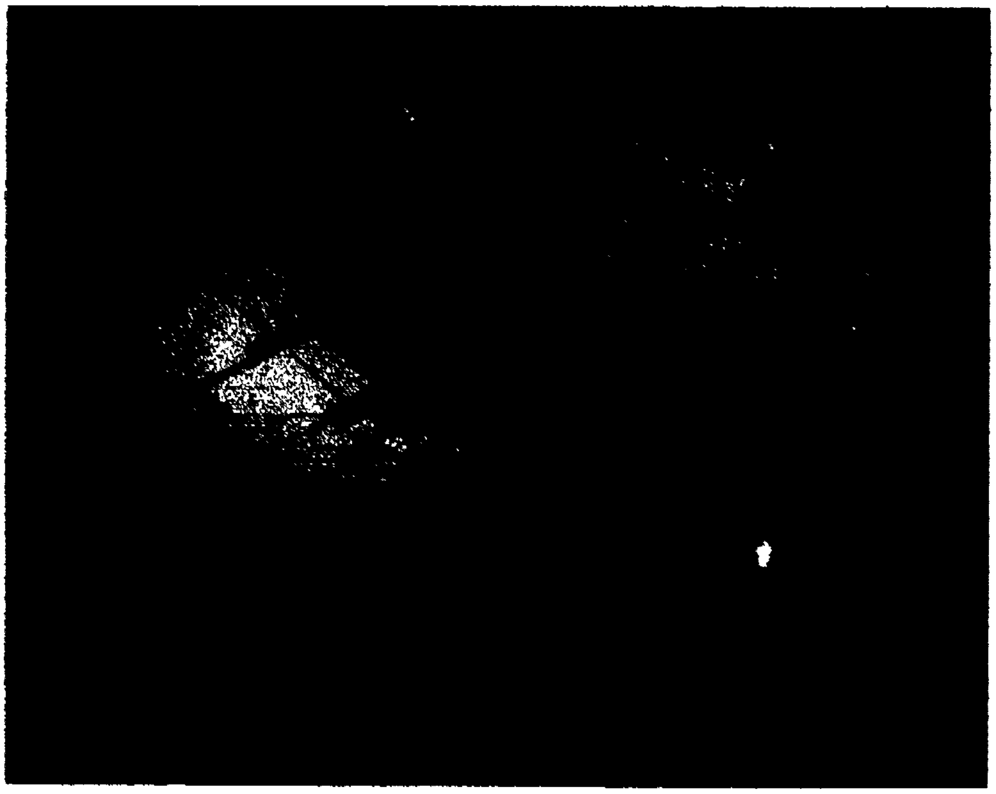
On September 11 of 1985, ICE flew by the comet and through its plasma tail at a speed of 21 kilometers per second. The data returned during the several-hour encounter were of the highest quality and fully justified the risk of the G-Z extension of the mission. The pass through the tail itself lasted only 20 minutes, but it confirmed the magnetic windsock model of cometary plasma tails and made unique measurements of the ion and electron densities there. Just as important, the hours previous to and after the tail pass provided crucial information on the interaction of G-Z's atmosphere (or coma) with the solar wind far from the comet. In particular, the expected bow wave in front of the comet was observed, although some of its characteristics were unexpected. Perhaps the best terrestrial analogy to the bow wave is the wave created by a ship moving through water. In the case of comets, the solar wind serves as the water, and the comet is the object moving through it (the ship).

Emerging from the other side of G-Z without apparent damage and with a triumphant mission under its belt, the ICE spacecraft set the stage for the world to greet the 1985-86 appearance of Halley's Comet. Many nations worked together to send a flotilla of spacecraft to greet Halley, as well as to observe the comet from the ground, Earth orbit, and interplanetary space. It was an unprecedented study of a comet. Activities were coordinated by the international space agencies from Europe, the Soviet Union, Japan, and the United States, and the degree of cooperation among them was an example of scientific planning and international goodwill at their best.

The International Halley Watch (IHW) consisted of more than 1,000 professional astronomers and 900 amateurs from 47 countries, and was administered by the National Aeronautics and Space Administration (NASA). The IHW was responsible for advocating, collecting, and archiving as much of the



Color-enhanced photo of cometary heat zones – inset of NASA *Pioneer* Venus Orbiter. This spacecraft observed Halley's Comet during its 1986 visit.



NASA Solar Maximum Mission Earth orbiter.

ground-based data taken around the world as possible. It is clear that the volume of data is enormous, and the archive, due out in 1990, should contain a treasure of data for future generations of astronomers to study.

Although the United States had no formal encounter mission to Halley, many U.S. spacecraft turned their instruments toward the comet. NASA's International Ultraviolet Explorer (IUE), an Earth-orbiting telescope, studied the composition of Halley's coma and tail, as well as the comet's total gas production rate, during much of 1985-86. It was used intensively at the time of the international space missions to the comet in March 1986. The Solar Maximum Mission (SMM), a NASA satellite launched in low-Earth orbit in 1980 to study the Sun, was temporarily turned away from the Sun and toward Halley, to provide unique images in February 1986, when the comet was nearly behind the Sun at time of perihelion.

Pioneer Venus Orbiter (or PVO, in orbit around Venus) was already situated on the far side of the Sun, which placed it in good position to study the comet near the time of perihelion, February 9, 1986. PVO measured the size and brightness of the huge hydrogen cloud surrounding Halley, data which revealed that the comet evaporated 60 tons of water per second and that over the total period of evaporation its surface sank about 20 to 30 feet. At that rate, the comet should be active for another 1,000 apparitions or so. At 20 million kilometers in radius, the hydrogen cloud of Halley was fifteen times larger than the Sun, making the comet the largest object in the solar system, if only temporarily.

The week of March 6-14, 1986 was as eagerly anticipated a week in space as scientists are likely to experience in a long time. Not one, but five spacecraft launched by the Soviet Union, European, and Japanese space agencies were scheduled to pass through various regions of Halley's Comet during that extraordinary interval. And it was here that international cooperation was most needed in order to promote the success of the last of these individual, yet interconnected space missions (which were often collectively referred to as "the Halley Armada"). The *Giotto* spacecraft of the European Space Agency (ESA) was being targeted to make a very close approach to the Sun side of Halley's nucleus on March 14 in order to obtain detailed images of its surface. A minimum distance of 500 kilometers was desired, but here there was a problem: ground-based imaging of the very innermost coma could not establish the probable position of the invisible nucleus to an accuracy any better than the desired "miss distance," i.e., 500 kilometers. There was every chance, therefore, that unless additional data could be obtained, *Giotto* might pass on the night side where the nucleus would be too dark to photograph and the camera would be looking directly into the Sun! Thus was born the concept, and actual project, called "Pathfinder."

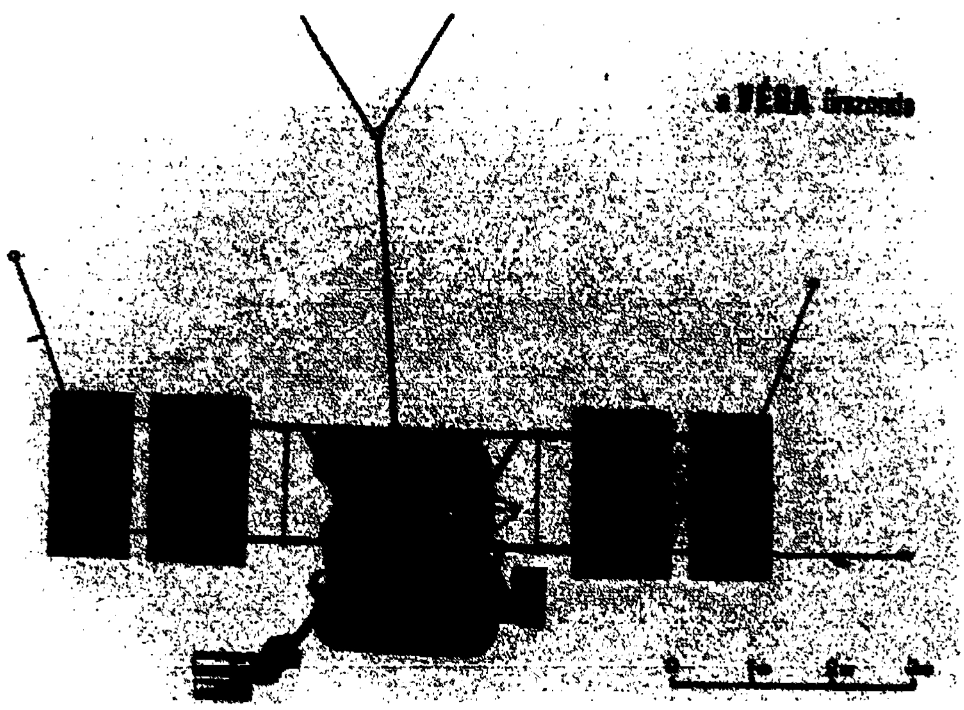
The idea was to make full use of the images obtained by the Soviet VEGA-I and VEGA-2 spacecraft, which would be making their encounters on March 6 and March 9, respectively, to pinpoint the location of the nucleus at least ten times more accurately than was possible from ground-based photographs. With the Halley nucleus twice-observed eight and five days before *Giotto*'s close pass, it would be possible to alter *Giotto*'s course extremely late in the mission to ensure the proper trajectory on the Sun side. Fortunately the cameras on the VEGA spacecraft worked as hoped, and the result for *Giotto* project was an historic mission to the heart of Halley's coma, the near-nuclear region itself. In short, Project Pathfinder was a brilliant success.

The VEGA spacecraft were heavily instrumented with experiments to observe Halley, but first dropped off balloons in the atmosphere of Venus before continuing on to the comet with a gravitational assist from Venus. Because of Halley's retrograde orbit and the necessarily prograde orbits of all the Armada spacecraft, the encounter speeds were very high. In the case of the VEGAs, the relative velocity

Artist's concept of dust and gas cloud released from a comet's nucleus as it approaches the Sun.

between comet and spacecraft was about 80 kilometers per second (or about 250 times the speed of sound on Earth). Such a large encounter velocity meant that the impact of even medium size dust particles on the scientific instruments could seriously impair, or even knock them out of operation, and so the VEGA spacecraft were equipped with "bumper shields" for protection.

The VEGAs were both targeted for a minimum encounter distance between 8000 and 9000 kilometers on the sunward side, and the images they returned showed not only the existence of a solid nucleus (proving Whipple's 36-year old theory), but also its location, size, and brightness. Somewhat surprisingly, the nucleus was a blacker-than-coal object shaped like a potato. It was larger than had been believed, about the size of Manhattan Island, 16 kilometers long by 8 kilometers wide, with a mass of about 150 billion tons. The nucleus surface was heated to well above freezing, and jet vapors were breaking through the outer crust from the underlying ices. Spectroscopic data showed that water accounted for close to 80 percent of the gas coming off the comet, with the remainder being mostly carbon dioxide and carbon monoxide. In the case of Halley's, about 16 tons of water, enough to fill a small swimming pool, was sublimated off the nucleus every second during the VEGA-I flyby, and twice as much during that of VEGA-2 three days later.

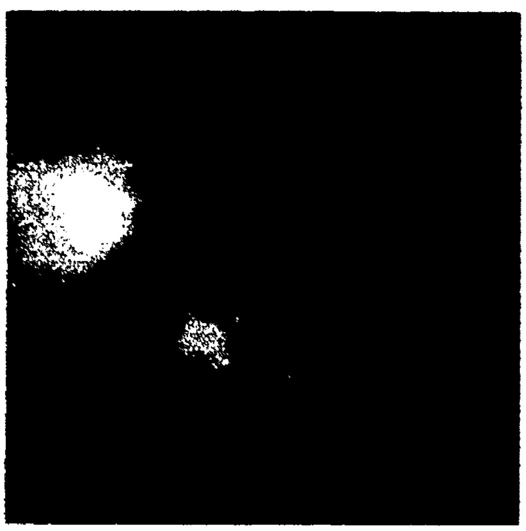


USSR's *Vega* spacecraft.

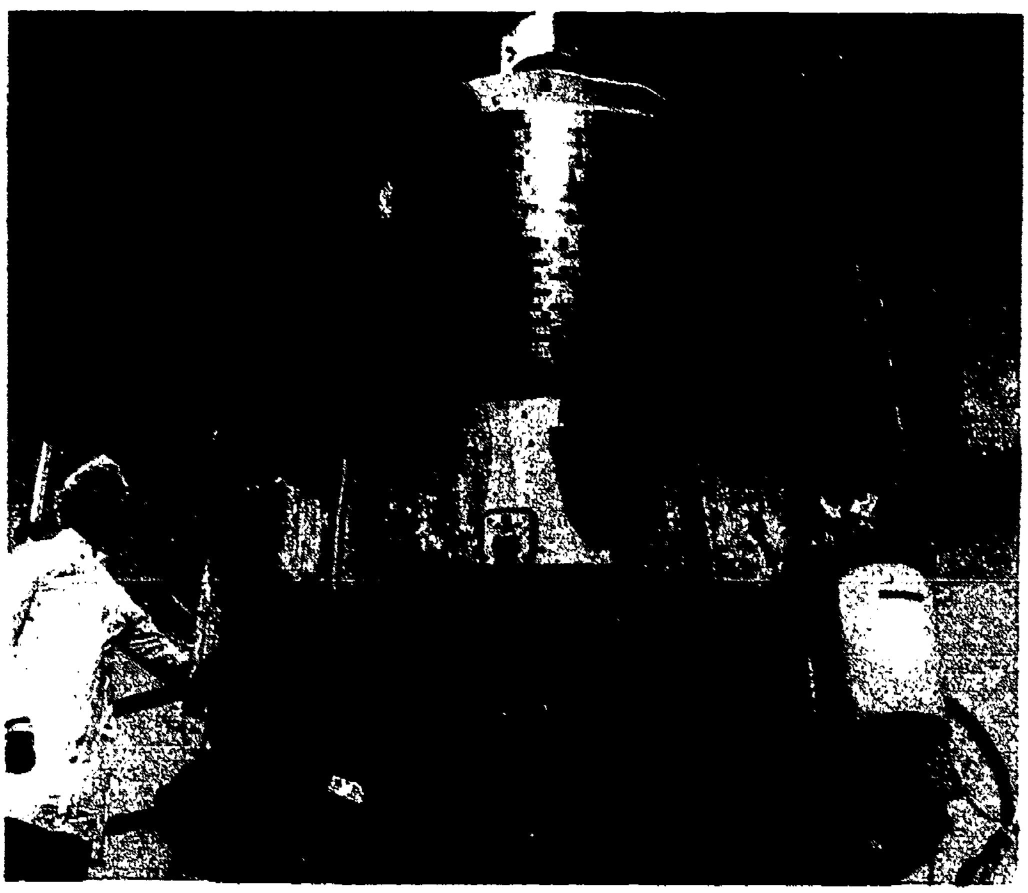
Japan's *Sakigake* spacecraft.

Japan's first interplanetary spacecraft, named *Suisei* and *Sakigake*, were sent to Halley's Comet to study the interaction of comets with the solar wind and interplanetary magnetic field, as well as the vast hydrogen cloud surrounding Halley. Because the spacecraft were to study the comet from relatively safe distances, 150,000 kilometers for *Suisei* on March 8 and 7,000,000 kilometers for *Sakigake* on March 11, they carried no dust shields. Still, even at these large minimum distances, a few dust hits were recorded by onboard instrumentation. The variable hydrogen production rates observed by *Suisei's* ultraviolet camera provided the important fact that Halley's nucleus rotates in about 52 hours, and *Sakigake* was able to monitor the solar wind input to the comet not only near the time of the *Suisei* encounter, but those of the VEGA and *Giotto* encounters as well.

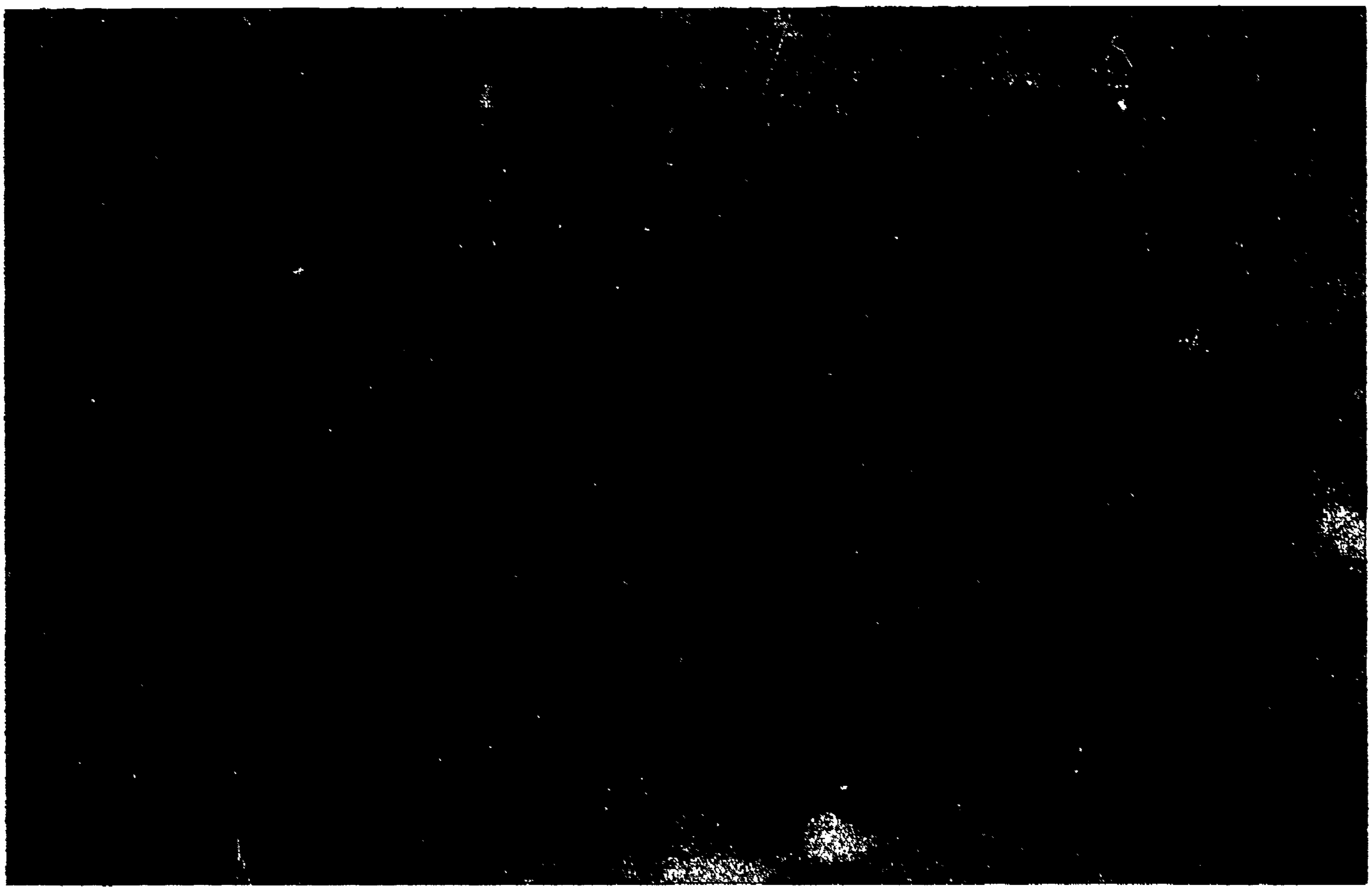
Europe's contribution to the Halley fleet was the *Giotto* spacecraft (named after the Florentine painter), and its mission was to penetrate as close as possible to the comet's nucleus on March 14. The danger due to dust impacts was especially heavy for this armada spacecraft, and it was fitted with a double bumper shield to protect the instruments and spacecraft subsystems. Many scientists considered *Giotto* to be on a suicide mission with little chance for surviving the closest approach. Indeed, despite the protection offered by the double shield, *Giotto*



The nucleus of Comet Halley, as seen in a composite of 60 images from *Giotto* that have been combined to maximize the detail visible in all the bright and dark areas. The Sun is toward the left. The nucleus measures 14.9 by 8.2 km.
Courtesy *Sky and Telescope* magazine.



Giotto spacecraft (European Space Agency)



NASA Kuiper Airborne Observatory, the "flying telescope."

was hit by one or several large dust particles at about 1,200 kilometers from the nucleus, which resulted in the telemetry antenna being knocked off the direction to Earth. Miraculously, however, the antenna realigned itself 34 minutes later and resumed transmitting data on the outbound trajectory. *Giotto* is now being considered for use in studying another comet.

Because *Giotto* came the closest of any of the probes, it sent back the most detailed images of Halley, which included such features as mesa-like plateaus, a 1.4-kilometer-diameter crater, and a 430- to 530-meter-high mountain. *Giotto*'s images have led to the speculation that the comet's dark crust consists of the dust and complex molecules left over as the comet's ices evaporate. Because vapor vents make up only 10 percent of the surface and are active only when facing the Sun, most of the comet's surface remains insulated by layers of dusty debris that encase the underlying ices.

Back on Earth, studies were made from the ground and aboard the Kuiper Airborne Observatory (KAO), NASA's "Flying Telescope." For two months, KAO flew in the stratosphere over New Zealand measuring the dust, gas, and water that Comet Halley produced. The KAO is a cargo plane outfitted with an infrared telescope, and flies at 12.7 kilometers altitude. This distance is above most of the interference and infrared absorbing atmosphere, allowing scientists on board observations impossible to make from the ground. The KAO measurements of Halley in the Fall of 1985 provided the first detection of neutral water vapor in any comet. Visible light cameras onboard the KAO filmed an ion tail disconnection.

Because Halley's volume was found to be ten times greater than expected, and its mass was not much different from expectations, its inferred density is significantly smaller. This has led scientists to conclude the nucleus must be quite porous, more like newly fallen snow rather than compressed ice.

The nucleus of Halley's Comet wobbles and tumbles like a badly thrown football, flipping end over end as it spins and flutters. Apparently the rotational motion is extremely complicated, and different rotation periods of 2.2 and 7.4 days have been determined using different types of data. Probably a combination of both periods is needed to adequately describe the very complicated motion of Halley's nucleus.

Through the Halls of Time

History is filled with tales about how comets have affected the behavior of humans. But what about Earth itself? Have comets ever changed or altered our planet? Comets, for example, may have played a role in "seeding" the early Earth's atmosphere with the ingredients for life. A number of years ago, two British astronomers proposed that comets carry amino acids. Perhaps Earth's primordial soup, from which life is thought to have sprung, contained some of the complex molecules and amino acids evaporated off cometary nuclei. Carbonaceous material in comets may even help explain how the Earth received some of its carbon and what form it took. It is estimated that about 100,000 comets the size of Halley's could supply all the carbon now in Earth's crust.

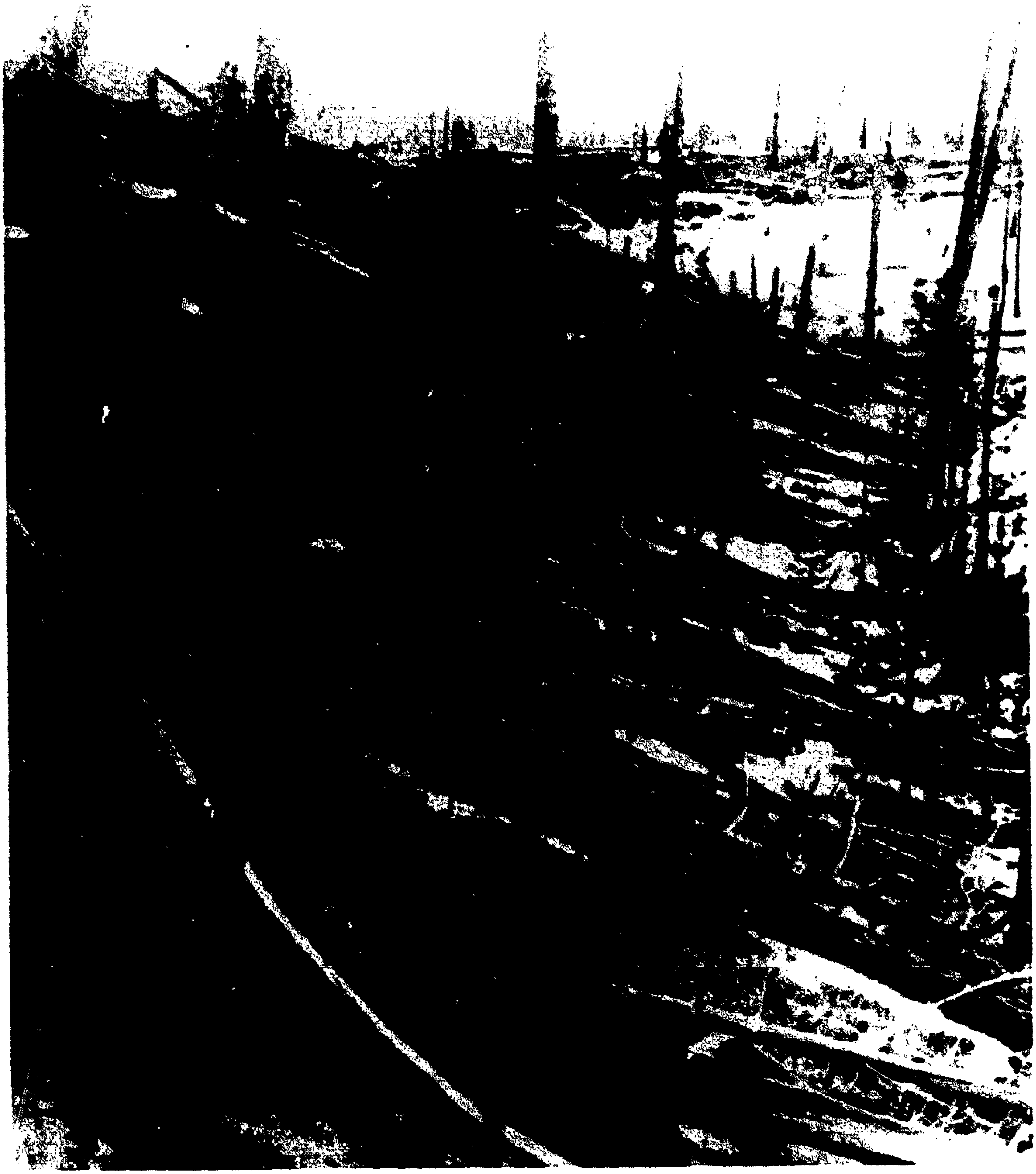
A theory prominent today suggests that a comet may have played a role in the disappearance of the dinosaurs. Strong evidence supports a notion that something struck Earth about 65 million years ago, wiping out about three-fourths of the known species, including the dinosaurs. With these huge land animals gone, an evolutionary advantage was given to a relative newcomer, the mammal, which arose to fill the ecological niche.

Although Halley's will never collide with Earth because the two orbits do not cross, other comets may, and evidence that one or more objects impacted Earth comes from dozens of sites where the ancient boundary layers between Cretaceous and Tertiary rocks show a thin deposit of iridium-enriched clay. Iridium is a rare element on Earth, but is common in extraterrestrial objects. The deposits also contain grains of quartz that have been deformed by intense shock waves, possibly caused by a high-impact collision. Carbon in the deposit suggests a fire storm may have swept the planet.

Exactly what collided with Earth or how the dinosaurs died is still a controversy, but some suggest the culprit was a comet. An apparent connection in the disappearance of life-forms and the impact of our planet fits with an even broader theory that something disturbs the Oort Cloud every 26 million years. This disturbance looses hordes of comets, and sets them on lengthy elliptical orbits. Ideas about what causes this disruption include an invisible tenth planet called Planet X, or a companion star to the Sun, called Nemesis. Such arguments are causing some scientists to rethink their interpretations of the universe and solar system.

Very close to our own time, it seems plausible that a comet may have struck Earth. In 1908, a massive explosion occurred in the air over Siberia, causing a fireball that felled trees over 50 square kilometers and knocked down people as far away as 64 kilometers. No tangible evidence of a physical projectile was ever discovered, leading scientists to postulate that an icy comet had entered Earth's atmosphere, detonated, and vaporized.

Depiction of comet theory of dinosaur extinction. Painting by Ron Waid, Langley Research Center Graphics Department.



A small piece of a comet or an asteroid is believed to have caused this devastation in Tunguska, Siberia, in 1908. The shock waves of the impact were felt throughout the world. Photo: E.L. Kirinov

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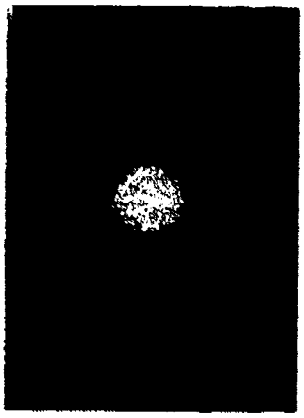
Other Heavenly Wayfarers



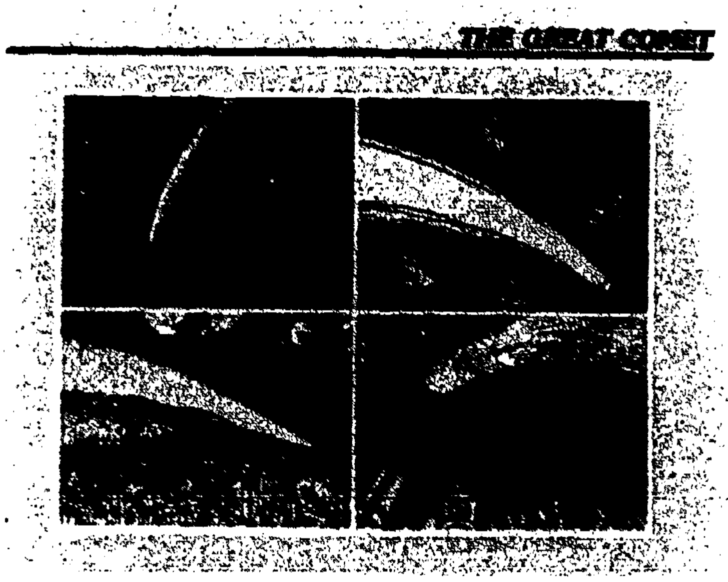
Photograph of periodic Comet Encke taken in 1961. Short period comets and bright comets far from the Sun are much less impressive and are often seen only with telescopes. Courtesy of U.S. Naval

Although Halley's is the most famous comet, others have been spectacular and influential. Barely two years before Halley's 1986 visit, Comet Giacobini-Zinner became the first comet to be visited by a spacecraft (see "The Halley fleet"). The comet was discovered in 1900 and its 1985 visit was its ninth recorded passage.

Some comets have exhibited unusual behavior. Comet Biela, with a period of 6.75 years, had normal passages during the 18th and early 19th centuries. In 1846, it split into two distinct and complete comets, each alternating in comparative brightness. In 1852, both comets appeared to be about 2,400,000 kilometers apart, and then were never seen again.

Encke's Comet has the shortest orbit, 3.3 years, almost no tail, and a very small coma. It has evidently lost most of its icy mixture and is turning into a dark, sponge-like asteroid, a process that may take several thousands of years.

Two comets appeared in 1811, and one remained visible for 17 months. The Great Comet of 1843 had a tail 320 million kilometers long and was even visible during daylight. Donati's Comet, discovered in 1858, developed multiple tails, and the coma was characterized by the presence of several outward-moving concentric shells or halos, which suggested that whatever process was creating the material in the coma was time-dependent. In 1861, perhaps the brightest comet in recorded history appeared. Because its coma was huge, and its perpendicular orbit took it extremely close to the Sun, it was so bright its light cast shadows on Earth.

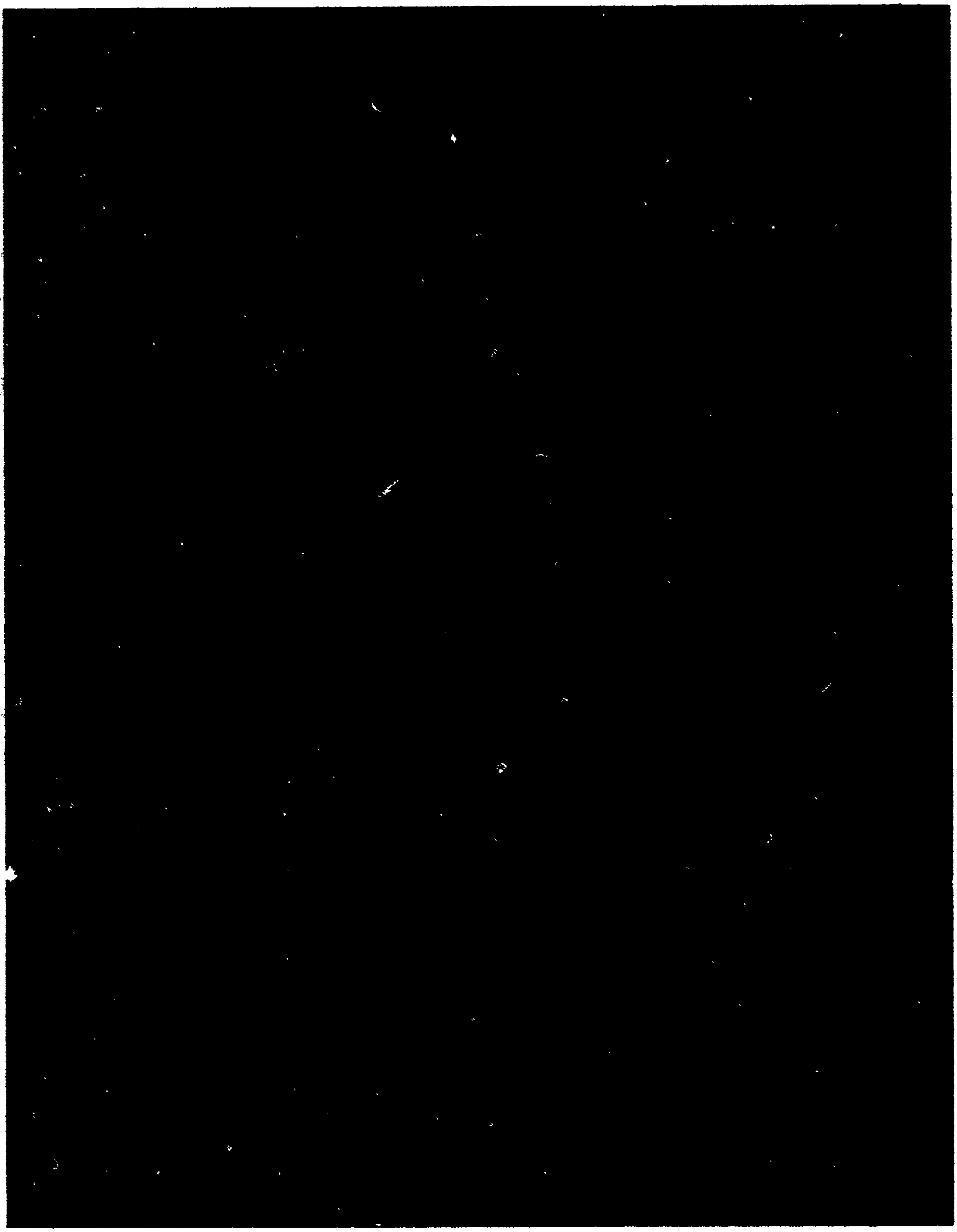


Presentations of comets from the past (clockwise from upper-left): Donatis Comet over Paris; German engraving, "Great Comet of 1577," from Prague; London Punch, 1906, "Discovery of a comet at Greenwich Observatory"; German engraving "Great Comet of 1577."

A relative handful of comets have perihelion distances so small that they almost literally graze the upper atmosphere of the Sun, and have been given the name "Sun gazers." Their extremely close pass to the Sun results in the vaporization of huge quantities of ice, and several of these comets have been visible in broad daylight. Some Sun gazers are torn apart by tidal forces exerted on the nucleus by the Sun near the time of perihelion. Comet Ensor, discovered in 1906, and Comet Westphal, discovered in 1913, had been predicted to be spectacular when they passed perihelion, but as they approached the Sun they became increasingly faint and fuzzy until they completely disappeared.

Comets that retreat back into the depths of the solar system are not completely gone; they leave pieces of themselves behind. Every November, around the 14th, we can see dazzling meteor showers as Earth passes through the region of Comet Beila's orbit. Remnants of Halley's provide the source for meteor showers called the Eta Aquarids, which appear in May, and the Orionids, which appear in October. Other meteor showers occur in August (the Perseids), December (the Geminids), and in November (the Taurids). The showers are named after the constellations in which they seem to appear rather than after the comet that left the particles behind.

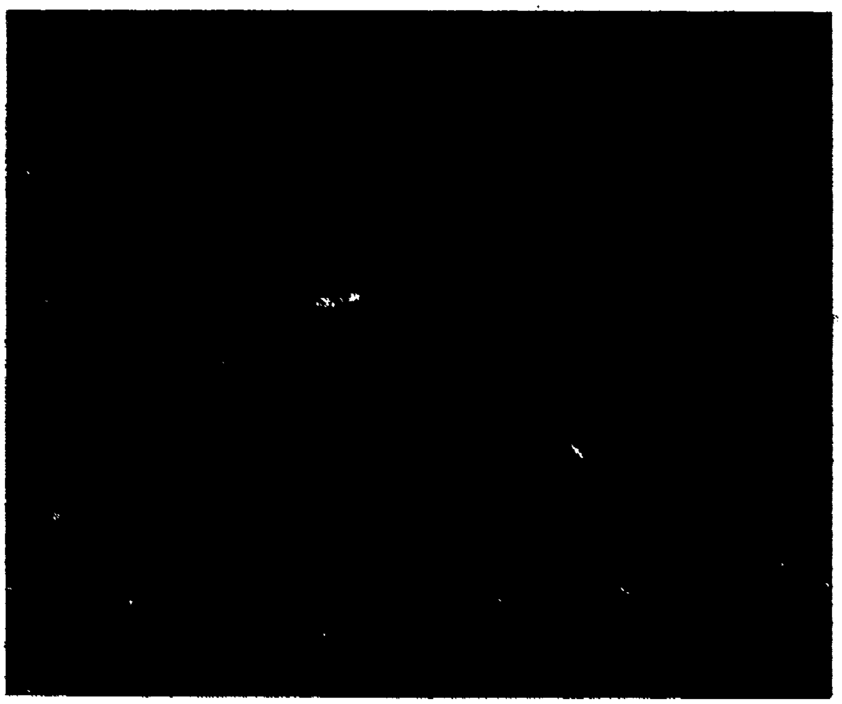
The overwhelming majority of comets are yet to be discovered as a result of their vast distance from us in the Oort cloud. Comet Wilson, the newest at this writing, was discovered by a student. Professionals and amateurs alike discover comets; all it takes is a knowledge of where to look, a little luck, and a lot of patience.



Comet Giacobini-Zinner. Courtesy of U.S. Naval Observatory.

Touching the Future

NASA's Comet Rendezvous-Asteroid Flyby mission, or CRAF, is currently planned for launch sometime in the 1990s. Unlike the Halley flyby missions, the goal of the CRAF mission is to "rendezvous" with a comet, staying with it for hundreds of days in its orbit. Such a mission would provide significantly more than the data "snapshots" returned by the Halley probes. A successful CRAF mission would be able to map the entire nucleus with high resolution imagery, provide a detailed history of the gas production rate of the comet as it approached the Sun, study the developing interaction with the solar wind, and measure in a detailed way the composition of the atmosphere. One possible experiment would involve implanting a four-foot-long golf-tee shaped device in the nucleus to relay information back to Earth.



Artist's depiction of the CRAF spacecraft in orbit around a comet nucleus (Comet Rendezvous/Asteroid Flyby Mission).

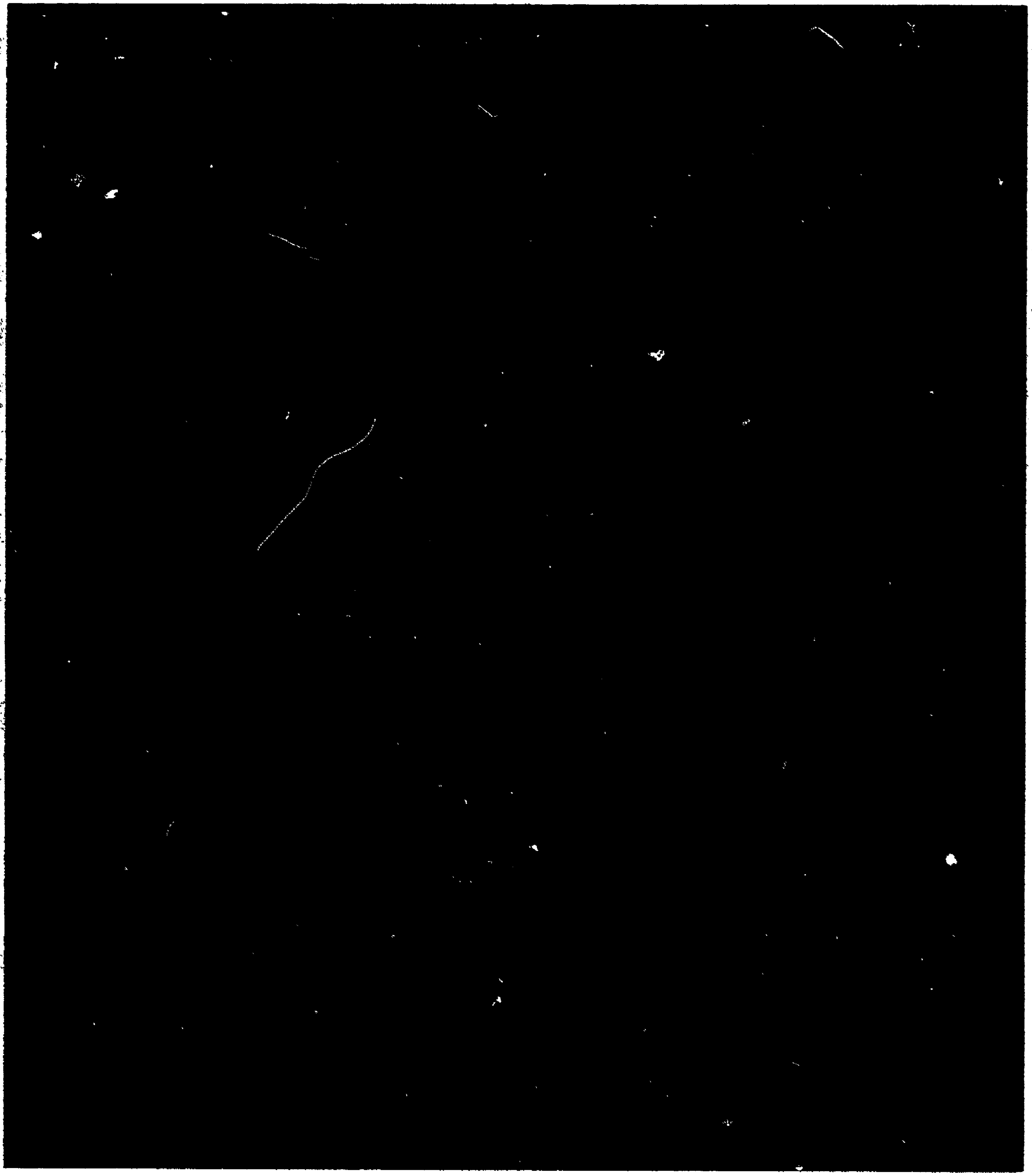
Although the specific comet with which CRAF would rendezvous has not yet been selected, most mission scenarios include a safe flyby of a large asteroid before the cometary rendezvous.

A second comet flyby is possible for *Giotto*, the European space probe that passed within 300 miles of Comet Halley. *Giotto* survived its encounter with Halley and may now be retargeted to within several hundred kilometers of the nucleus of Comet Grigg-Skjellerup in 1992 to get color images.

The ultimate and most daring mission is for an international nucleus sample-return mission that will actually bring back to Earth a piece of a comet nucleus for study. Such a mission will be exceedingly expensive, will probably require new technology, and hence is not likely to occur until the twenty-first century. However, a sample return mission to a comet may spawn as yet undreamed of spin-offs and scientific applications.

Many questions about comets remain unanswered, even as new ones have been raised with the recent passage of Halley's. With the continued accumulation of new data, we may be able to answer such questions as: Why do the gas and dust jets emerge from some regions on the nucleus and not others? Is the nucleus more like an ice-ball or fluffy snow? What is the composition of the surface material? and How does the comet interact with the solar wind? We also hope to get a better understanding about such fundamental issues as how the solar system was formed, and the effect comets might have had on the evolution of life.

Perhaps the most far-reaching implications from all the comet studies will result from the multinational effort initiated by the study of Halley. Cooperative space exploration means that participating countries will share both costs and benefits. International science will be enhanced because of the greater complexity and greater number of missions made possible by this continuing cooperation.



This image, taken by the Halley Multicolor Camera on March 13, 1986, at a distance of 20,000 kilometers from the nucleus of Comet Halley, shows different colors corresponding to different light levels. The nucleus is in the upper left corner and even the darkest part of it is clearly visible. The bright area is a dust jet originating at the sunlit area on the nucleus. This dust jet is illuminated by sunlight. Photo: Max Planck Institute fur Aeronomie.

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Image of Comet Halley's coma sent to Earth from the *Pioneer Venus* spacecraft. The coma, or cloud of gases surrounding the nucleus, is 20 million kilometers in diameter. Concentric areas show decreasing brightness from the comet's center outward.

Classroom Activities

These activities are presented to supplement section 1. Activities may be used as curriculum ideas or as stand-alone exercises. They are not labeled by discipline, grade, or ability level, and the teacher's individual creativity and ingenuity can make use of them in any area of study. The study of comets offers teachers an opportunity for an interdisciplinary approach in their classrooms. As new comets are discovered and previous ones return for subsequent visits, comets will continue to fascinate students of all ages.

The Ultimate Time Travelers

Concept: By studying comets, we may learn more about the origin and evolution of the solar system and the ties between comets and other objects in the cosmos.

Vocabulary:

atoms	cosmos	primordial
clues	eons	vapors
cometary	Halley	
composition	interplanetary	

•

Comets are named after their discoverers, many of whom are amateur astronomers. Encourage students to become sky-watchers. The sky must be scanned on a routine basis with a good telescope or binoculars, in a location that is not affected by light pollution. By consulting a sky chart, the student can see if there is a new point of light that moves, relative to the stars, over a period of several nights. This may be a comet.

•

Create a learning center with a telescope. Illustrate how the lenses of the telescope work. Instruct students on working with a telescope, its uses, and its importance in the area of research astronomy.

•

Have students work in small groups and research the question: Why study comets? Have them select a medium other than a written report to share their findings (e.g., a slide show).

Provide prompts for narrative, descriptive and expository paragraphs. Have pupils write a paragraph on the prompt selected for study. Suggestions:

Narrative: Pretend that you have been a piece of rock in the tail of Halley's Comet since 1910. Write a letter to astronomers telling of your adventures through space since then.

Descriptive: Pretend that you are the head of a comet. Describe yourself to a newspaper reporter.

Expository: You have viewed Comet Halley through a telescope. Explain to your classmates how you set up your telescope and found the comet in the sky.

•

Until the invention of telescopes and cameras, all astronomical observations were recorded in drawings. Materials for drawing can be as simple as a pencil and notebook. Take your students out one clear night to study the sky and make drawings of what they see.

Rules to remember:

1) make your observations away from any light pollution;
2) allow your eyes 30 minutes to adapt to darkness;
3) use a small flashlight with muted red light so as not to diminish night vision;
4) give verbal descriptions to explain features;
5) indicate directions of the compass; and
6) include latitude, longitude, date, time, type of instrument used for magnification, and sky conditions.

Touching Humanity

Concept: Throughout history, Comet Halley's appearances have had an impact on human behavior.

Vocabulary:

appeasement	heralded	scimitars
catastrophe	irrational	synopsis
celestial	orientation	visitation
chronicles	prescribed	

•

The 1910 return of Comet Halley caused excitement and fear. Have students investigate local newspaper accounts of the concerns expressed in their community at that time. The month of May probably carried the most stories; why?

•

Have students research news accounts (include radio and TV) of the 1986 appearance of Comet Halley and compare them with those of 1910.

•

Have students discuss, in terms of human behavior and psychology, why they think humans acted irrationally at the appearances of comets. Then have them write and act out several scenarios that might have taken place during a Comet Halley visitation and which show mob psychology and mass hysteria.

The Bayeux Tapestry, which depicts the Battle of Hastings, includes the 1066 appearance of Comet Halley. What kind of omen was it for the Saxons? for the Normans? Have students research the tapestry.

•

Halley's Comet, a poem by T.L. Murray, appeared in the Houston Chronicle of May 17, 1910. Have students analyze it:

The tail stirs mental twitchings
Diaphanous of doubt:
It might unjoint its orbits
And knock us fellows out:
One chance within the millions,
The scientists declare--
But comets are uncanny
And doubts are everywhere.

That Halley is a-peeping
Somewhere to make a hit--
Our flesh so goes a-creeping--
We almost must admit.
What makes that comet ticklish
Is heading down so straight;
In all its pomp and glory,
And dignity of state.
He seems to be so chary
Of paths he punctuates
That he, to all appearances
Is heading for our gates.

Halley's History

Vocabulary:

fresco	omen	tapestry
gears	plague	theory

•

Establish an area of the classroom for a learning center dealing with Comet Halley. Assign a pair of students to a specific time during which the comet passed. In this activity, students become the teacher. It is the responsibility of each pair to design material, pictures, activities, etc., relating to their assigned time. Biweekly, a different student pair places material in the "Comet Center." Each group must explain the center to the class at the beginning of the two-week "expedition." Begin with 240 B.C. and end with 1987. This activity also can be used with other fields of study.

•

Use a long rope or string for a "time line." On separate 3" × 5" index cards, write the events from the "Halley's History." Give these to the students for additional research so they can either dramatize or write a story about the event. Attach the card to the "time line" at the proper place.

•

Follow the development of different facets of our society through the appearance of Halley's Comet. Have each student take a different aspect, such as religion, English history, art, or music, and talk about its stage of development at each appearance. Then project the continuing changes of that particular subject into the future for the next several appearances.

•

To help students become more familiar with geography, enlarge a world map to bulletin board size. Get stick pins of varying colors. Make paper strips of the events found in "Halley's History." Next have students select a strip and read it aloud. As a class, discuss the event and its location; then, with the stick pin, attach the event strip at the correct place on the world map. Discuss the importance of the geographical location of each event.

•

Alfred Lord Tennyson's play, *Harold*, which was published in 1876, is about the Saxon king who died in the Battle of Hastings. Have students read and discuss this 19th century view of history.

•

Mark Twain was born in 1835 and died in 1910, two years of consecutive Comet Halley appearances.

•

Have students read *A Connecticut Yankee in King Arthur's Court*.

•

Students will find Comet Halley in Giotto's fresco The Adoration of the Magi, in the Arena Chapel, Padua. Painted in 1303–06, it refers to the 1301 appearance of the comet. Have students study the painting and compare it to pictures of Comet Halley's later appearances created in different media.

•

The airplane, television, and radio are three modern inventions not available in 1910. Discuss with students the changes in transportation and communication since then.

Where Do Comets Come From?

Concept: In an attempt to explain the origin of comets, many theories have been proposed.

Vocabulary:

ellipse	interstellar	short-period
elongated	omen	simulation
gravitation	planetoid	spectroscopy
inert	orbit	theory

•

Assign comet theorists to students to research; include Edmund Halley, Tycho Brahe, Aristotle, Fred Whipple, Isaac Newton, and Jan Van Oort. Have students role-play the person. In a news show scenario, each is interviewed by other students and questioned on his theory and the evidence to support it.

•

Tycho Brahe, a Danish astronomer, made observations in 1577 that determined the actual distance to comets. He used the principle of parallax to do this. Students can demonstrate the principle with this simple experiment:

Hold your finger a few inches in front of your eyes. Close one eye and then the other, noting where your finger appears to be compared to an object in the distance. Do the same thing with your finger held at arm's length. You will note that your finger appears to shift position by a smaller amount when it is held at a distance than when held close to your eyes. Your brain mentally compares the view from each of your eyes to "see" how much nearby objects shift compared to what is in the background. In this way you can judge the distance to objects in your environment. Challenge the students to relate this test to Brahe's observations of the comet's position. What would his observations have shown?

•

Theories are not accepted without continuous challenge and testing. Divide the class into small groups to research existing theories on comets and assign each theory to two groups. Using sound logic, one group is to argue for the theory the other against. At the end of the debates have the entire class vote on whether the theory should stand.

•

Until modern times, all cultures developed myths and legends to explain heavenly happenings. Have students research comet stories to compare and contrast. What are the differences? What were the cultural influences that made the stories vary from place to place?

•

Imagine that you and your class are visitors to Earth. The night sky is totally strange to you and to make logic out of nonsense you decide to invent constellations based on myths that you know. Divide into groups and have each group take a section of the sky and make constellations out of the star patterns, then explain what the constellation is and why.

What is a Comet?

Concept: Comets are described as "dirty snowballs" consisting of a nucleus, coma, dust tail, and ion tail.

Vocabulary:

discrete	molecules	thermal
embedded	motes	ultraviolet
fluorescence	nucleus	
micron	phenomenon	

•

To help students get a better idea of the size of a comet and how the size of its parts compare, have them build a model of a comet. Divide the class into teams and have each team work on a different part of the model. Let the students determine the materials and size to be used. A good mathematics exercise is to let them do the calculations to determine the appropriate scale to use.

•

Discuss the different types of tails on a comet: plasma—magnetic fluorescence; dust tail—scattered sunlight. Draw a diagram of a comet circling the Sun. Consider which direction these tails would go at various locations on the comet's orbit.

•

Have students draw a landscape that represents how the surface of a comet would look. After discussing "The Halley Fleet," have them draw a second picture based on information gained from the instruments of the several spacecraft. Consider the two pictures: how are they similar? different?

The Halley Fleet

Concept: Many nations of the world worked together sharing space-based technologies to provide an unprecedented study of Halley's Comet.

Vocabulary:

archive	magnetosphere	terrestrial
armada	orbital plane	trajectory
flotilla	perihelion	
infrared	retrograde	

•

Make a list of the instruments built by each country to study comets. Divide the students into groups, one for each country. Have them research why each instrument was chosen. Then have them include their own ideas on how and what they would have studied and the rationale behind each selection.

•

Based on spacecraft findings, the nucleus of Halley's Comet has been compared to a peanut or a potato in shape. Choose one of those to use as your comet, and design a model of all the parts of the entire comet in the proper scale. Make the coma, hydrogen cloud, ion tail, and dust tail, so students can get an understanding about how tiny the nucleus itself is.

•

Ask students to write a story about Comet Halley, tying fact into fiction; have them tell of their journey through space as comets, how different spacecraft looked to them, what they imagine the spacecraft to be, their purposes, the beings that sent them. Have some stories rewritten as a play, film, radio, or TV script.

•

Have students research other international space astronomy projects. Ask them to project ideas for future cooperative ventures.

Through the Halls of Time

Concept: Comets may have altered the course of history.

Vocabulary:

carbon	ecological niche	postulate
controversy	extraterrestrial	projectile
Cretaceous	ingredients	Tertiary

•

Have students brainstorm a list of extinct animals and birds. Divide them into groups and have each theorize a possibility for the mass extinctions. Have students write scenarios on how life might have evolved if the extinctions had not occurred.

•

The geneology of Halley's parallels our own ancestry. An interesting approach to our own ancestral roots is to trace family histories back to each appearance of Halley's or at different points in its last 76-year orbit. For example: where were you (your parents, your grandparents, etc.) and what were you doing when Halley's crossed the orbit of Jupiter, Saturn, Pluto, etc., on its way to Earth? Where was your family during the apparitions of 1910, 1835, 1759, and so on? Project the questions into the future.

•

The dating of Halley's appearance, past and future, can be used as a springboard for dating techniques of all kinds. What are they? How do they work? What kinds of things can we date with them? When is a particular kind of dating used? Why date things at all?

Other Heavenly Wayfarers

Concept: Many comets have appeared to humans through the ages. New comets are being discovered all the time.

Vocabulary:

concentric	influential	perpendicular
constellation	meteor showers	remnant

•

Take your students out on a night when a meteor shower is predicted to occur. Have them count the number of "falling stars" they see over a period of time and then find the average. Do this for some of the most prominent showers. Keep graphs and tables of the findings.

•

Every comet is individual. Each travels at a different speed and has a unique orbit. Once a comet is discovered, scientists can calculate these properties and tell us when to expect its return. Have students research the orbital speeds of known comets. Translate these into mach speeds (the speed of sound). Students should also be able to graph the orbits in kilometers and miles per hour.

•

Have a poster contest to represent a specific comet's appearance.

Create a class tapestry on the solar system with special emphasis on comets.

•

Have students view visual art and/or listen to musical compositions that have a celestial or planetary title and discuss the connection, if any, with the sky and its objects:

Music: Symphony No. 41 ("Jupiter") by Mozart (1756–1791) The Planets by Holst (1874–1934)

Art: Saturn Devouring His Children by Goya (1746–1828) Starry Night by Van Gogh (1853–1990)

•

Have students research the variety of artists' representations of comets through the ages: manuscript illuminations (Les Tres Riches Heures du Duc de Barry), Durer's Melencolia I, Hogarth and Rowlandson in England, Daumier in France, Native Americans, decorative arts, 20th century painters.

•

Comets are often mentioned in literature. Have students find references in Virgil, Shakespeare, Jules Verne, and H.G. Wells.

Touching the Future

Concept: Other comets will be studied more closely in the future because of the continuous advancements in science and technology.

Vocabulary:

applications	implications	multinational
enhanced	interaction	rendezvous

•

Have students research the lunar landings and the activities that were carried out on the Moon by astronauts at one-sixth of Earth's gravity. Then have them imagine how a similar spaceship would "land" on a comet nucleus that has less gravity. Have them design the equipment that would be necessary for someone to walk, drive, dig, etc., on an almost gravity-free surface.

•

Measured in "Halleys," the next appearance of the comet will be Halley 31 in 2062. Divide the class into groups and have them describe civilization as they think it will be then. Bring in such components as modes of transportation, medical advances, communications methods, forms of recreation, businesses such as grocery stores and banks, so that they all fit logically into an integrated society.

Have students brainstorm what the sociological issues might be in 2062. Have them speculate about average life span, urban development, role of the United States in world affairs, status of minorities and women in society, population characteristics, and major political, economic, and/or social issues.

•

Role play the media in the year 2062. Group students in small numbers and have each group be a particular kind of medium. Have them "cover" the return of Halley's Comet.

•

Prepare time capsules. Have the whole class discuss and justify how many items, what kind, where to store the capsules, the directions to place with them, and when to have them opened. In each individual's capsule should be a description of life in the present: a tape of a favorite song, a picture of oneself, family, home, school, car, pets, and so on. Whenever a new comet is discovered, encourage them to add new items to the box that are descriptive of their life at that time. Be sure articles about the new comet are included. Label the boxes and have the students put them away for safe-keeping to share with children and grandchildren whenever comets appear over the years.

NASA Teacher Resource Centers

Located at the nine NASA research centers, Teacher Resource Centers (TRCs) have a variety of NASA-related educational materials in several formats: videotapes, slides, audiotapes, publications, lesson plans, and activities. NASA educational materials are available to be copied at the TRCs. Contact the nearest TRC for further information.

Alabama Space and Rocket Center
NASA Teacher Resource Room
Tranquility Base
Huntsville, AL 35807
Serves Alabama, Arkansas, Iowa, Louisiana, Missouri, and Tennessee.

NASA Ames Research Center
Teacher Resource Center
Mail Stop 204-7
Moffett Field, CA 94035
Serves Alaska, Arizona, California, Hawaii, Idaho, Montana, Nevada, Oregon, Utah, Washington, and Wyoming.

NASA Goddard Space Flight Center
Teacher Resource Laboratory
Mail Stop 130.3
Greenbelt, MD 20771
Serves Connecticut, Delaware, District of Columbia, Maine, Maryland, Massachusetts, New Hampshire, New Jersey New York, Pennsylvania, Rhode Island, and Vermont.

NASA Jet Propulsion Laboratory
Teacher Resource Center
JPL Educational Outreach
Mail Stop CS-530
Pasadena, CA 91109
Serves inquiries related to space exploration and other JPL activities.

NASA Lyndon B. Johnson Space Center
Teacher Resource Center
Mail Stop AP-4
Houston, TX 77058
Serves Colorado, Kansas, Nebraska, New Mexico, North Dakota, Oklahoma, South Dakota, and Texas.

NASA John F. Kennedy Space Center
Educator Resource Library
Mail Stop ERL
Kennedy Space Center, FL 32899
Serves Florida, Georgia, Puerto Rico, and the Virgin Islands.

NASA Langley Research Center
Teacher Resource Center
Mail Stop 146
Hampton, VA 23665-5225
Serves Kentucky, North Carolina, South Carolina, Virginia, and West Virginia.

NASA Lewis Research Center
Teacher Resource Center
Mail Stop 8-1
Cleveland, OH 44135
Serves Illinois, Indiana, Michigan, Minnesota, Ohio, and Wisconsin.

NASA John C. Stennis Space Center
Teacher Resource Center
Building 1200
Stennis Space Center, MS 39529
Serves Mississippi.

Central Operation of Resources for Educators (CORE)

Designed for the national and international distribution of aerospace educational materials to enhance the NASA Teacher Resource Center Network. CORE provides educators with another source for NASA educational audiovisual materials. CORE will process teacher requests by mail for a minimal fee. On school letterhead, educators can write for a catalogue and order form and send to:

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