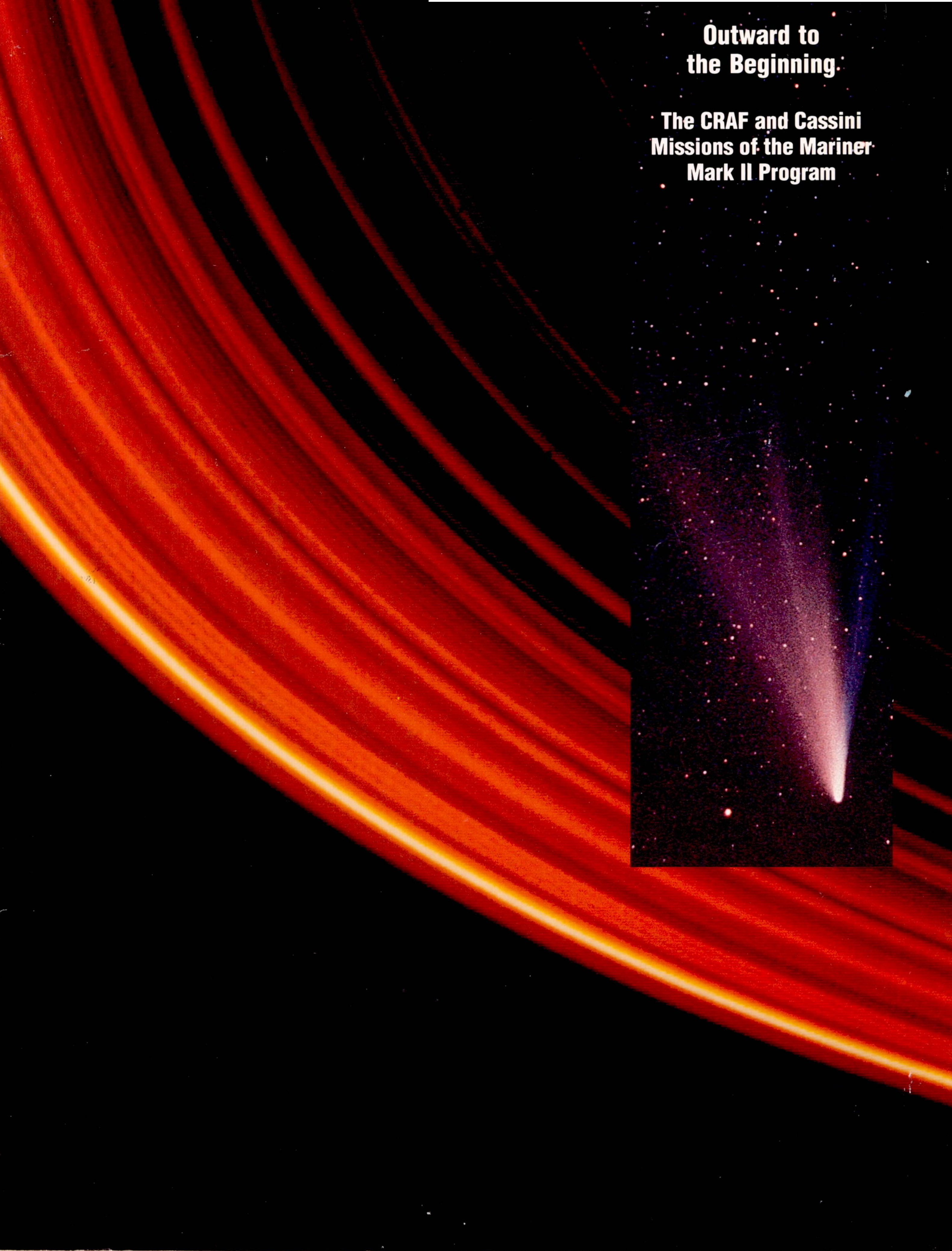
Outward to the Beginning

The CRAF and Cassini Missions of the Mariner Mark II Program

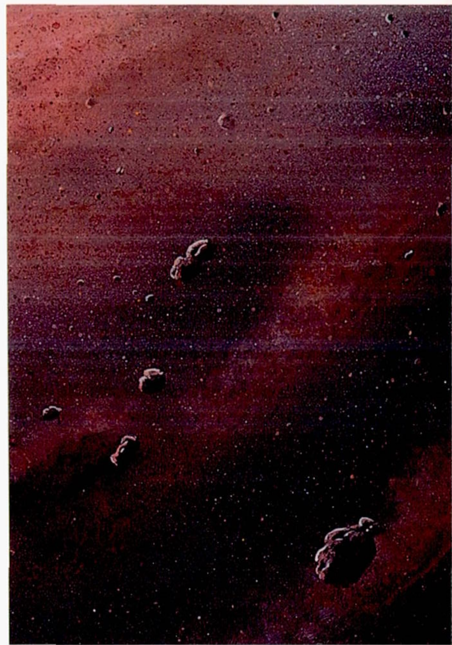


Introduction

Two successive journeys will soon offer a new perspective on the origin of the solar system – and perhaps provide new clues to the origin of life as well. Traveling on a new generation of planetary exploration spacecraft, the first of these missions will examine the most primitive bodies of the solar system, comets and asteroids. One year later, a spacecraft nearly identical in design will venture to the outer solar system to study the rich diversity of the Saturnian system, including its rings and satellites, the surface and atmosphere of its principal moon, Titan, and the nature of fields and particles in Saturn's magnetosphere. The National Aeronautics and Space Administration, in cooperation with the European Space Agency and the Federal Republic of Germany, is preparing to embark on these two journeys in 1995 and 1996.

The missions, the Comet Rendezvous Asteroid Flyby (CRAF) and Cassini (the Saturn orbiter/Titan probe), combine to form the first initiative of the Mariner Mark II program, a series of planetary missions whose common objective is to explore primitive bodies and the outer solar system, toward the ultimate goal of understanding the nature of our origin. To obtain the data needed to address that goal, the CRAF and Cassini missions carry different scientific instruments that can be flown on spacecraft of the same design.

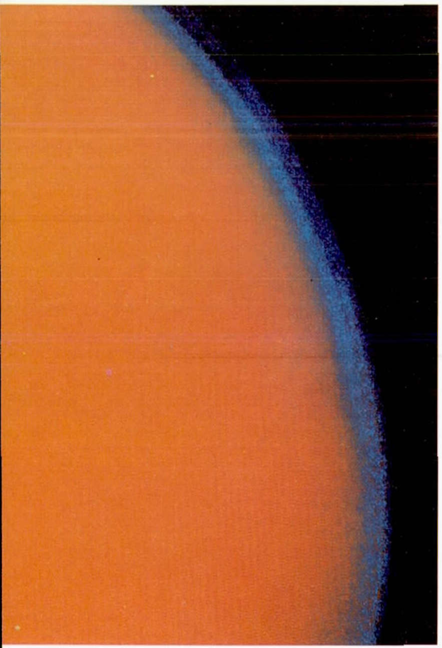
CRAF and Cassini are exciting planetary missions. The objectives that they share, the region of the solar system in which comets, asteroids, and the Saturnian system have evolved and now reside, and the spacecraft that will carry both sets of experiments to their targets in the outer solar system are described in the pages that follow.



Cover: Voyager photopolarimeter view of Saturn's F ring.
Inset: Comet West, 1976. (Photo by D. di Cicco, *Sky & Telescope*)

Above: The formation of planetesimals in the solar nebula. (Painting by William K. Hartmann)

Goals of Solar System Exploration



Above: **Limb of Saturn's moon Titan, showing its high-altitude layer of haze.**

Facing page: A region of star formation in the Orion Nebula.
Insets: The CRAF spacecraft (top) and the Cassini spacecraft (bottom).

Understanding the birth and evolution of our planetary system has been a goal of the United States civilian space program for the three decades that NASA has been in existence. In pursuit of this goal, NASA has been guided by the Committee on Planetary and Lunar Exploration (COMPLEX) of the National Academy of Sciences, whose strategy for planetary exploration calls for a three-fold progression from reconnaissance, which is accomplished by fast flybys, to exploration, which is achieved by orbiters and probes, to intensive study, which is implemented by landers and sample return missions. COMPLEX further recommends that this strategy be applied to each of the three regions of the solar system: the inner solar system (terrestrial planets), the primitive bodies (comets and asteroids), and the outer solar system (the gas giants).

The Mariner Mark II program represents NASA's application of this strategy to the primitive bodies and the outer solar system. Using a new generation of cost-effective, modular spacecraft that can easily be modified to accomplish a variety of missions to these targets, the program will focus on critical questions bearing on the origin and evolution of our planetary system.

The CRAF/Cassini initiative begins this program. CRAF will fly by at least one asteroid, orbit a comet, and drive an instrumented penetrator into the comet's nucleus. Cassini will also fly by one or two asteroids, orbit the planet Saturn, repeatedly fly near many of Saturn's moons, and send an instrumented probe into the atmosphere of Saturn's moon Titan.

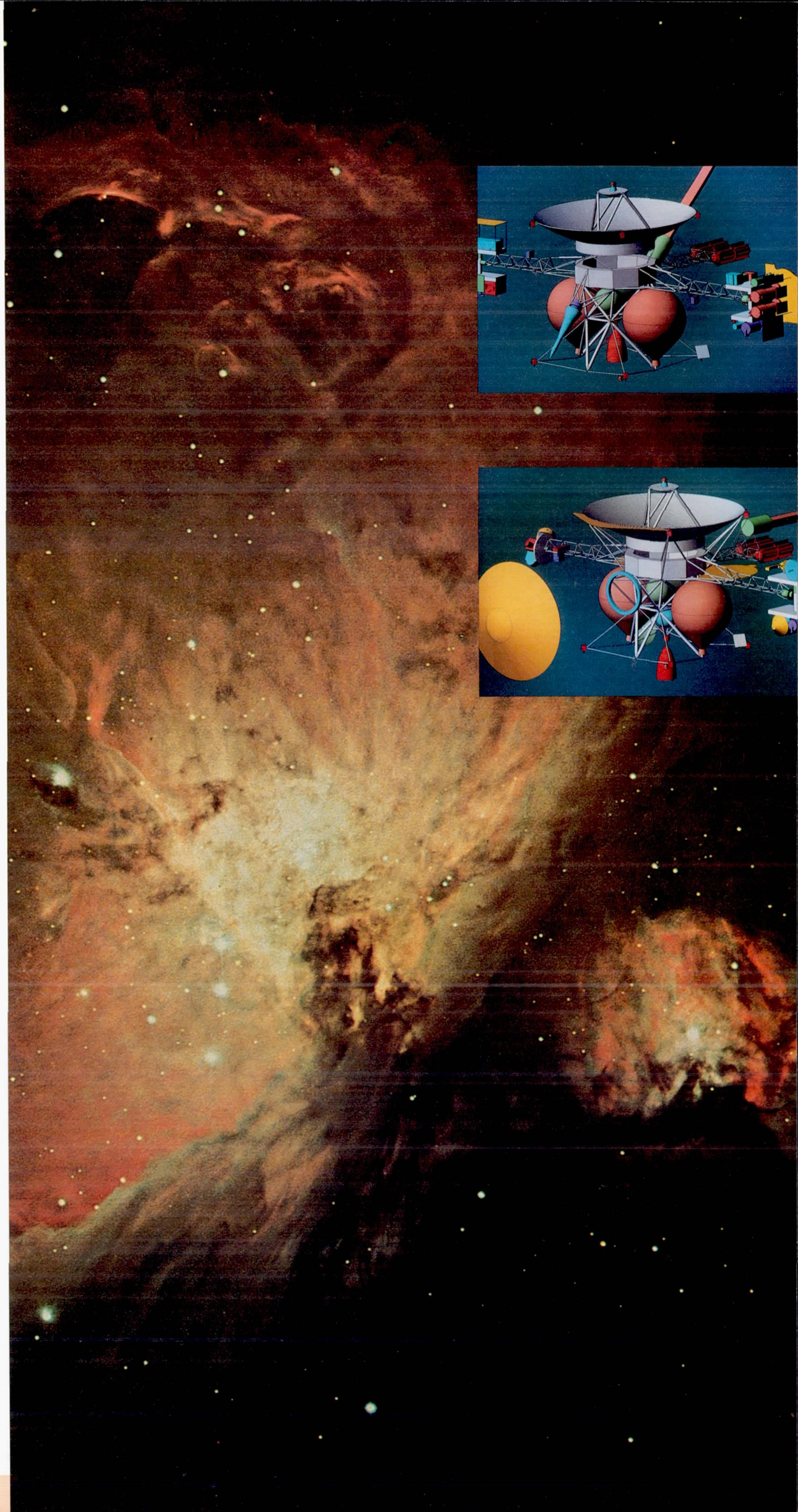
The explorations to be conducted by these two missions are complementary because their subjects – comets, Titan, and the Saturnian system – have a common origin in the outer solar system. These volatile-rich objects preserve a unique record of different key phases in the formation and evolution of the solar system. They range from the most primitive conditions in interstellar clouds, to the chaotic and complex processes of nebular collapse and planetary formation (accretion), to the final sweep-up of interplanetary debris.

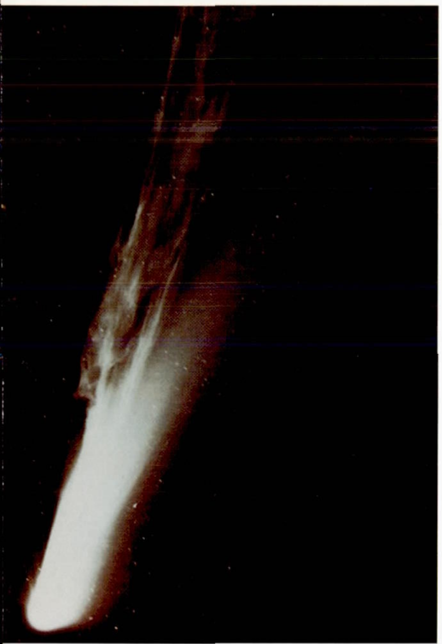
Primitive Bodies and the Outer Solar System: Clues to Origin and Evolution

Clues pertaining to the origin and evolution of the planets can be found throughout the solar system. During most of the 4.6 billion years since its origin, the solar system has been recovering from the violent, dynamic processes that created it. On Earth and on other terrestrial planets, virtually all evidence of the earliest epochs has been destroyed by continuing planetary processes. In contrast, comets, asteroids, and the planetary bodies of the outer solar system have suffered less of these modifying processes and have thus retained some record of early planetary formation.

It is commonly believed that the terrestrial planets and the cores of the outer planets grew through the accretion of countless small bodies called planetesimals, which were similar to present-day asteroids and comets. One group of these original small bodies has been preserved in the asteroid belt, a relatively stable region between the orbits of Mars and Jupiter. Disturbances by Jupiter's gravity probably prevented the asteroids from accreting into a single body of planetary size, and thus they retain many of their primitive chemical and physical characteristics. One of the most scientifically interesting features of asteroids is their apparent diversity, and understanding the origin of this diversity requires the study of a large number of asteroids. The asteroid flyby investigations carried out by CRAF and

August 1990
Magellan Arrival
at Venus





Above: Comet Mrkos, observed in 1957. (Photo courtesy of Hale Observatories)

Facing page: Voyager view of Saturn's atmosphere and inner rings.
Insets: Mosaic of Viking images of the Martian moon Phobos, which may be a captured asteroid (top). Saturn's moon Titan and its opaque atmosphere (bottom).

Cassini will build on the information that the Galileo spacecraft will provide when it encounters its two asteroid targets en route to Jupiter.

Just as asteroids and their meteoritic fragments may be samples of the building blocks of the inner solar system, so may comets be icy remnants from the accretion of the outer planets. According to this view, the newly formed outer planets gravitationally scattered the comets to the most remote part of the solar system – the distant Oort cloud, halfway to the nearest stars. There the comets remain, in the deep freeze of space, until a passing star, a giant molecular cloud, or the tidal forces of the galaxy perturb them onto new paths that bring them back into the planetary region. An alternative scenario is that comets are icy planetesimals that formed in the solar nebula beyond the orbit of Neptune. In either case, comets have most likely been preserved in a condition similar to their initial state, relatively free from the modifying processes that occurred in larger bodies and in bodies closer to the Sun.

The giant planets of the outer solar system – Jupiter and Saturn in particular – are so massive that they have retained essentially all the material from which they were originally made. Thus, these planets are expected to contain a representative sample of the original nebular material, altered in chemical form but retaining the elemental and isotopic signatures of the primordial solar nebula.

The ring systems around the outer planets permit us to study the dynamic interactions of small co-orbiting bodies, which are similar to the interactions among planetesimals that led to the accretion of planets. The satellites of the outer planets are cold, frozen worlds that record an evolution that in some ways paralleled the solar system as a whole. Ranging from the highly modified to the nearly pristine, these satellites may contain records of modifications frozen on their surfaces for our inspection.

Another important goal of the CRAF/Cassini initiative is to gather evidence concerning the process of prebiotic molecular evolution in the solar system. The issue to be addressed is how the chemical makeup of solar system material changed as it evolved from interstellar cloud to solar nebula and finally through planetary formation to assume its present form. The molecular and mineralogical compositions of cometary material will yield information about the physical and chemical conditions and the earliest processes of change in the solar nebula. The dark material on comets, on carbonaceous asteroids, and on Saturn's moon Iapetus will yield information on surface processing.

Scientists are especially intrigued by the possibility that prebiotic organic chemical evolution may have taken place in icy coatings of interstellar dust grains before these grains were incorporated into cometary nuclei; similar

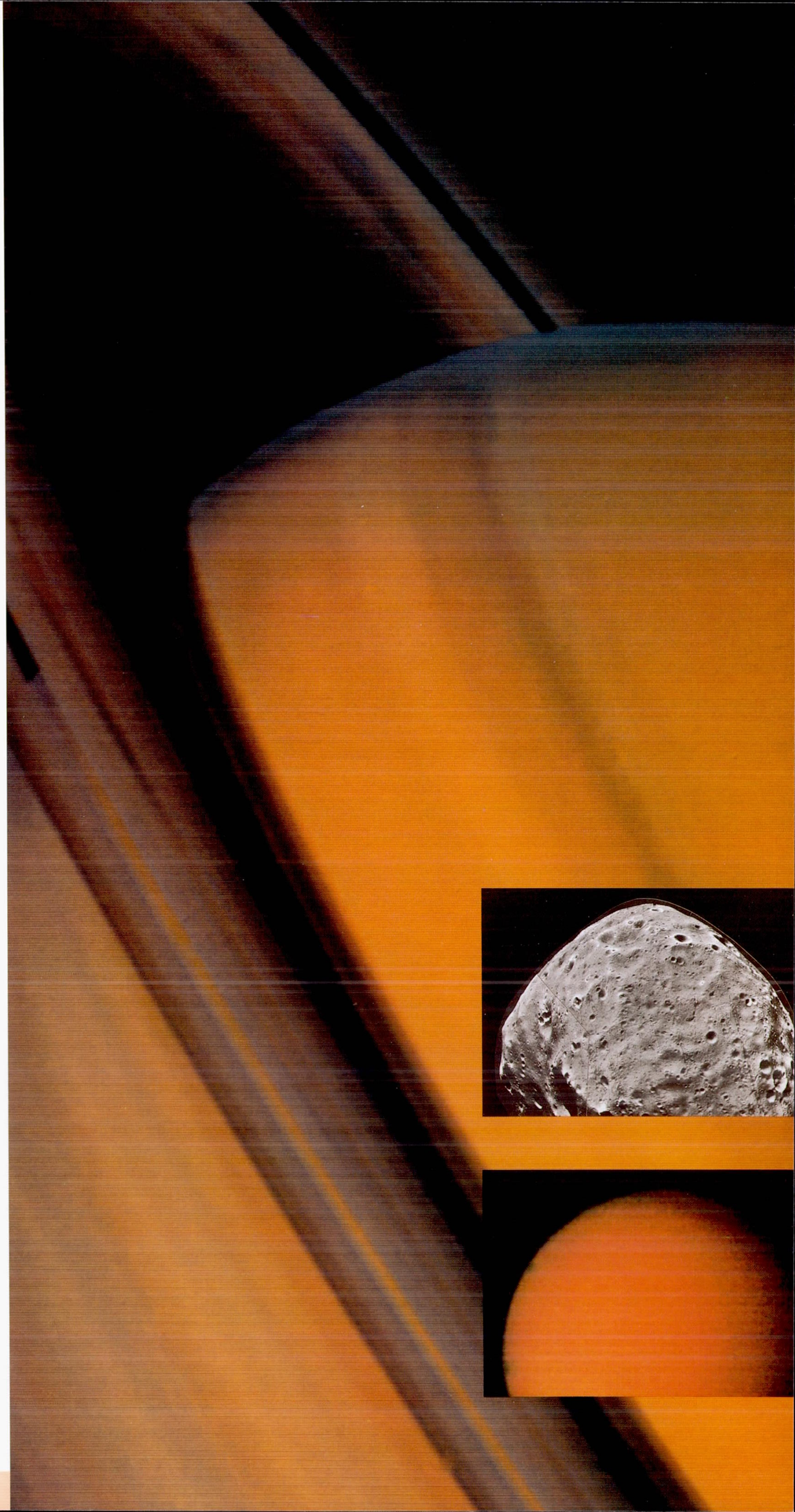
October 1990
Ulysses Launch

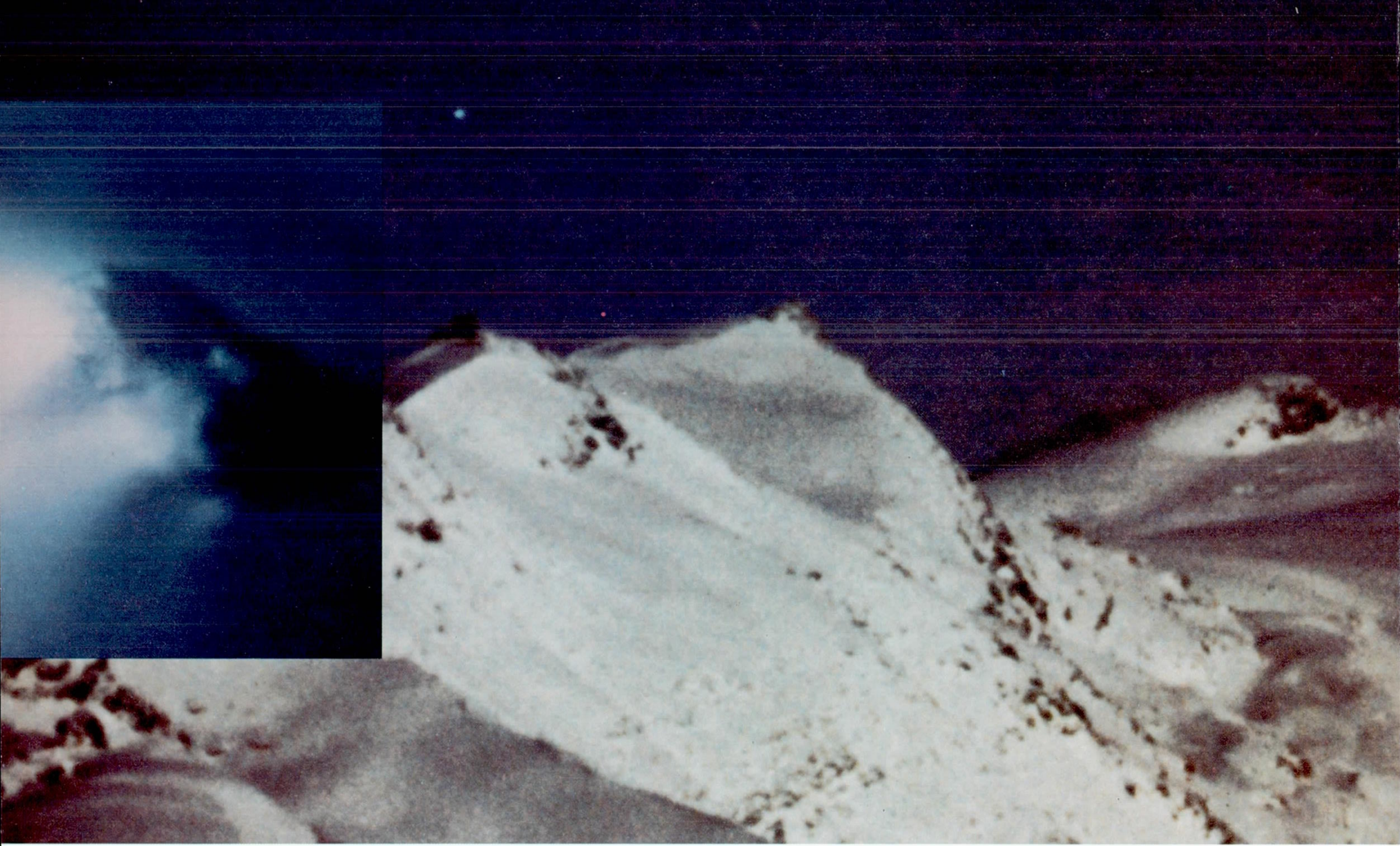
April 1991
Magellan End of Mission

October 1991
Galileo Gaspra Flyby

chemical evolution may still be occurring on Titan. Both cometary ices and Titan's atmosphere contain many of the same organic molecules observed in interstellar clouds. Recent research suggests that Earth's early atmosphere may have been inhospitable to the evolution of organic material and that the necessary complex, prebiotic molecules may have been delivered to Earth from the outer solar system by comets and asteroids. An alternative theory is that the primitive terrestrial atmosphere may have been similar to Titan's present atmosphere. Thus, clues to understanding the origin of life on Earth may lie in the investigation of both the organic material frozen in comets and the contemporary organic synthesis in Titan's atmosphere.

The CRAF/Cassini initiative also seeks to enhance our understanding of a wide range of astrophysical processes by studying examples of those processes that can be found within the solar system. One such example is the use of Saturn's rings as a miniature analog of collisional and accretional processes in the solar nebula. In a similar manner, studies of the interaction of solar wind plasma with cometary gas and dust, and of Saturn's magnetospheric plasma with the moons and rings, will reveal processes that heavily influenced the chemical and physical processing of dust, gas, and planetesimals in the solar nebula. Such processes must also be important in many other astrophysical settings in which gas, dust, and plasma interact in the presence of ionizing radiation.





Above: Comet Bennett photographed over the Alps in 1970. (Photo by C. Nicollier)
Inset: The nucleus of comet Halley as seen from the European Space Agency's Giotto spacecraft. (©Max-Planck-Institut für Aeronomie, 1986. Courtesy Dr. H. U. Keller)

Spacecraft studies of the outer solar system will also yield information about solar system evolution and comparative planetology. The icy satellites extend the range of conditions and material properties of solid bodies for comparative studies of geological processes. The magnetospheres and atmospheres of the giant planets such as Jupiter and Saturn, and the atmospheres and perhaps oceans on moons such as Saturn's Titan and Neptune's Triton, provide points of comparison with the terrestrial planets. The unifying theme for exploring primitive bodies and outer planets is the study of our origin and evolution, including the analysis of possible prebiotic organic chemistry in this frozen, volatile-rich part of the solar system.

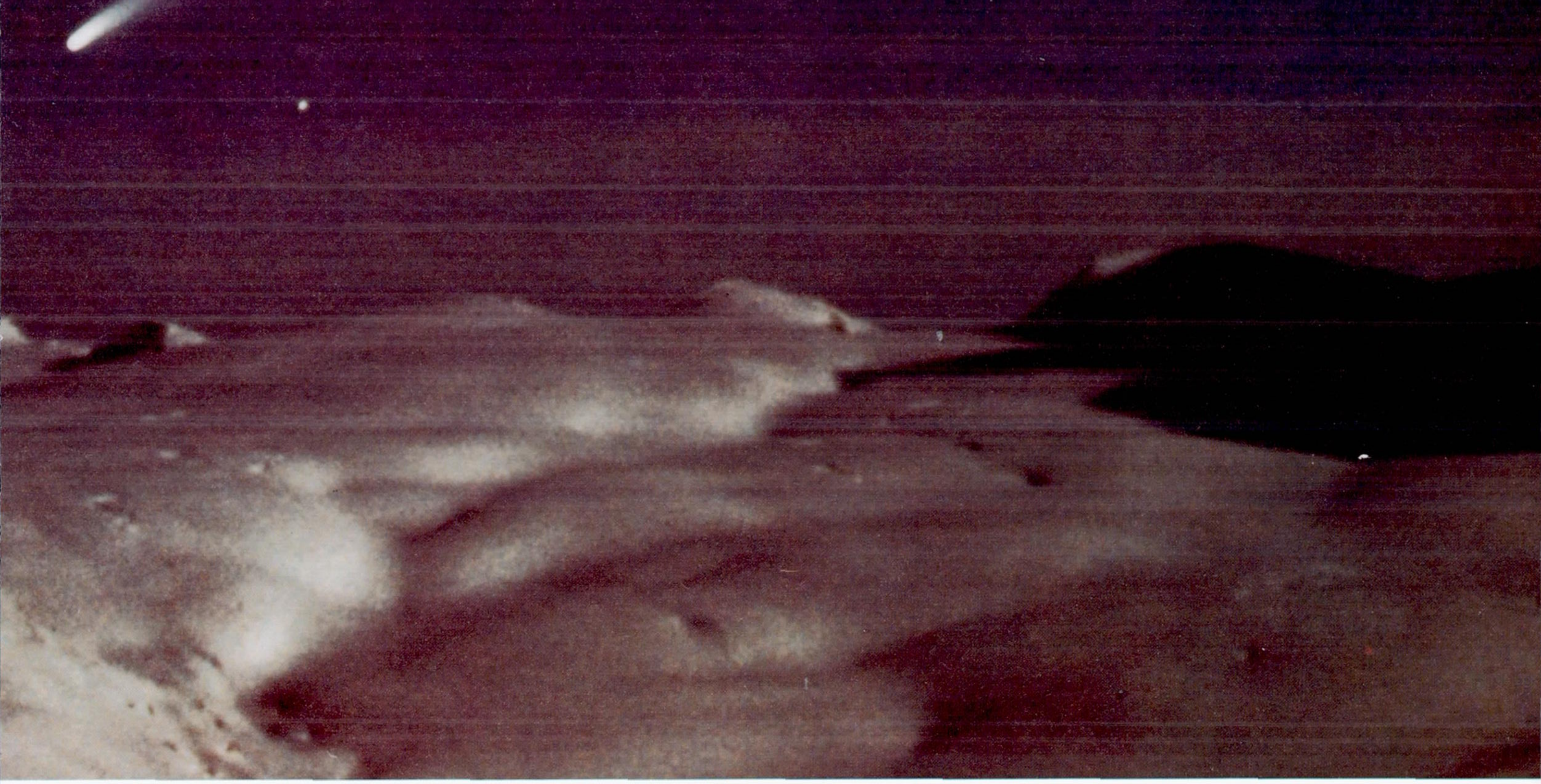
Comet Rendezvous Asteroid Flyby

During its 10-year journey, CRAF will explore a comet and at least one asteroid. To see how a comet was formed and how it comes apart under the influence of sunlight, CRAF will fly along with a typical short-period comet as it moves around the Sun from its farthest to its closest point. CRAF will determine the elemental, isotopic, molecular, and mineralogical composition of cometary material as well as investigate the comet's microscopic to large-scale physical structure. Further, CRAF will study the physics and chemistry of the comet's atmosphere and its interaction with sunlight and the solar wind. Finally, CRAF will survey the physical properties of one or two asteroids, including their sizes, shapes, rotation periods and poles, and surface morphologies, and it

September 1992
Mars Observer Launch

August 1993
Mars Observer
Arrival at Mars

August 1993
Galileo Ida Flyby



will gather preliminary information about their chemical compositions, in addition to measuring the asteroids' bulk densities.

The Halley missions gave us a first quick glimpse of a comet nucleus and the first in situ measurements of cometary gas and dust. In many respects, however, the Halley flybys raised more questions than they answered. We learned, for example, that comets contain a large amount of organic material, but we were unable to determine precisely which organic molecules were present. We learned, too, *that the nucleus of a comet is a* dark, irregularly shaped body, but we could not determine its density or the physical cause(s) of its irregular shape.

The rendezvous mission designed for CRAF represents a substantial advance beyond the ultrafast Halley flybys. In a rendezvous mission, a spacecraft follows an orbit around the Sun that precisely matches the comet's orbit. Hence, after a rendezvous maneuver, the spacecraft and the comet travel together indefinitely. Among the many significant advantages of a rendezvous mission over a flyby are its ability to produce more detailed mapping, its longer observation times and lower relative speeds, its use of a penetrator, and its capacity for adaptive exploration.

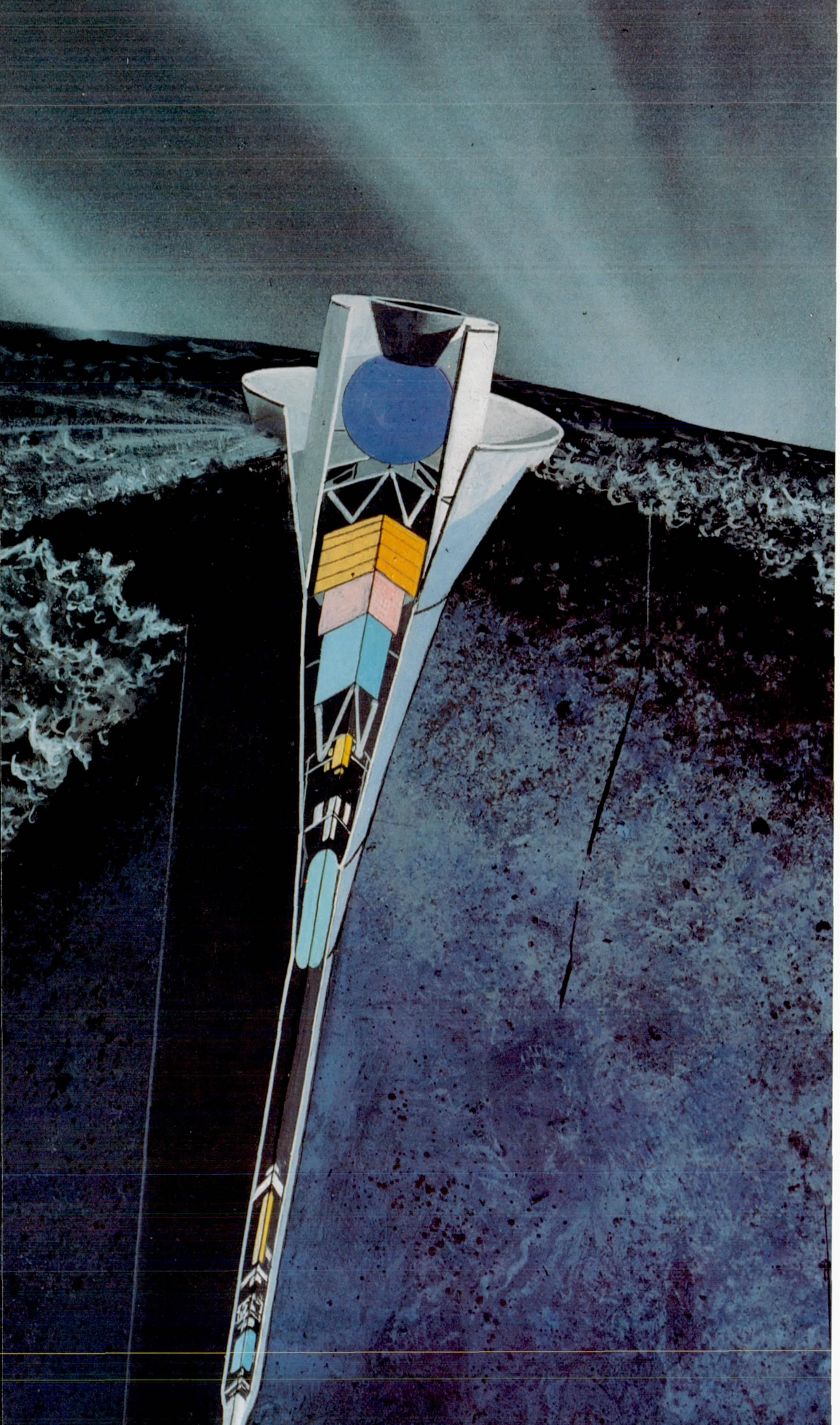
The target for CRAF's rendezvous is the short-period comet Wild 2, which was perturbed into its present orbit from farther out in the solar system by a close encounter with Jupiter in 1974. Wild 2 is a desirable target because its interior probably has not yet reached thermal equilibrium with its new surroundings, and so it has lower internal temperatures than other short-period comets in similar orbits.

To reach Wild 2, the spacecraft will be launched on an orbit that brings it back to Earth after two years for a gravity assist that will then fling it out toward the orbit of Jupiter. Along the journey the spacecraft will encounter one of the larger main belt asteroids, Eunomia, which has a diameter of 270 kilometers. *After this asteroid encounter, and* perhaps one other depending on available fuel, the spacecraft will arrive at Wild 2 near aphelion where the comet is relatively inactive.

October 1993
Mars Observer
Mapping Orbit

August 1994
Ulysses Over
Sun's South Pole

April 1995
CRAF Launch



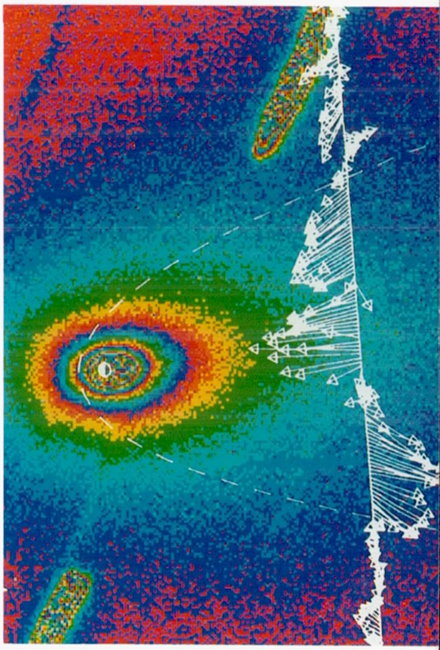
From a distance of 50 kilometers, the spacecraft will use remote-sensing instruments to study the comet. Imaging at a resolution of better than one meter will provide details about the size, shape, and surface morphology of the comet nucleus. By analyzing the spectrum of reflected sunlight, we will be able to identify ices and minerals on the comet's surface. Temperatures will be mapped to determine thermal properties and energy balance as well as to aid in the identification of surface materials. Accurate radio-tracking data will be used to determine the mass of the comet nucleus. Combined with the size, as estimated from the imaging data, this information will allow the calculation of the comet's bulk density. Taken together, these measurements will enable scientists to establish whether the interior of a comet nucleus more closely resembles a hard-packed snowball or a newly fallen, fluffy bank of snow. This will then tell us how the comet nucleus accreted and what processing it might have undergone since its formation.

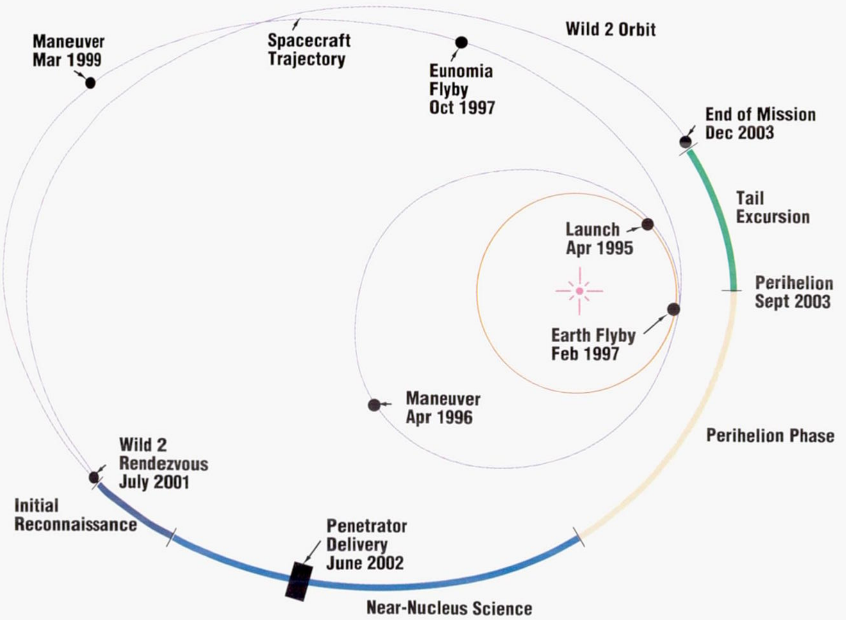
About a year after the spacecraft's arrival at the comet, a penetrator carrying a set of instruments will be fired directly into the surface of the comet nucleus to measure the elemental composition of the nucleus and to determine its temperature profile and surface strength, as well as the nature and composition of the icy organic mix. The penetrator will transmit data back to the CRAF orbiter for about one week.

When the comet nears the Sun and becomes active, the spacecraft will move in and out through the atmosphere, collecting dust for onboard analysis of the elemental, chemical, and micro-scopic properties of the dust. Emitted gases will be analyzed for their composition and temperatures and for the velocity at which they flow out. The cometary atmosphere and nucleus will be studied as Wild 2 moves along the eccentric orbit, reaching maximum activity at perihelion.

A complete set of plasma instruments will study the interactions of cometary gas and dust with sunlight and with the solar wind in efforts to clarify the formation and constantly changing shapes of comet tails, the acceleration of energetic particles, and other plasma processes. Following perihelion, a 50,000-kilometer excursion down the comet's tail will explore the comet–solar wind interaction in further detail.

Following the tail excursion, the CRAF spacecraft will return to the vicinity of the nucleus as its activity wanes. As the comet once again begins to journey outward from the Sun, CRAF will conclude the mission by studying the changes that the nucleus has undergone during perihelion.





Facing Page: Cross section of the instrumented penetrator for the CRAF mission, implanted in the nucleus of comet Wild 2.

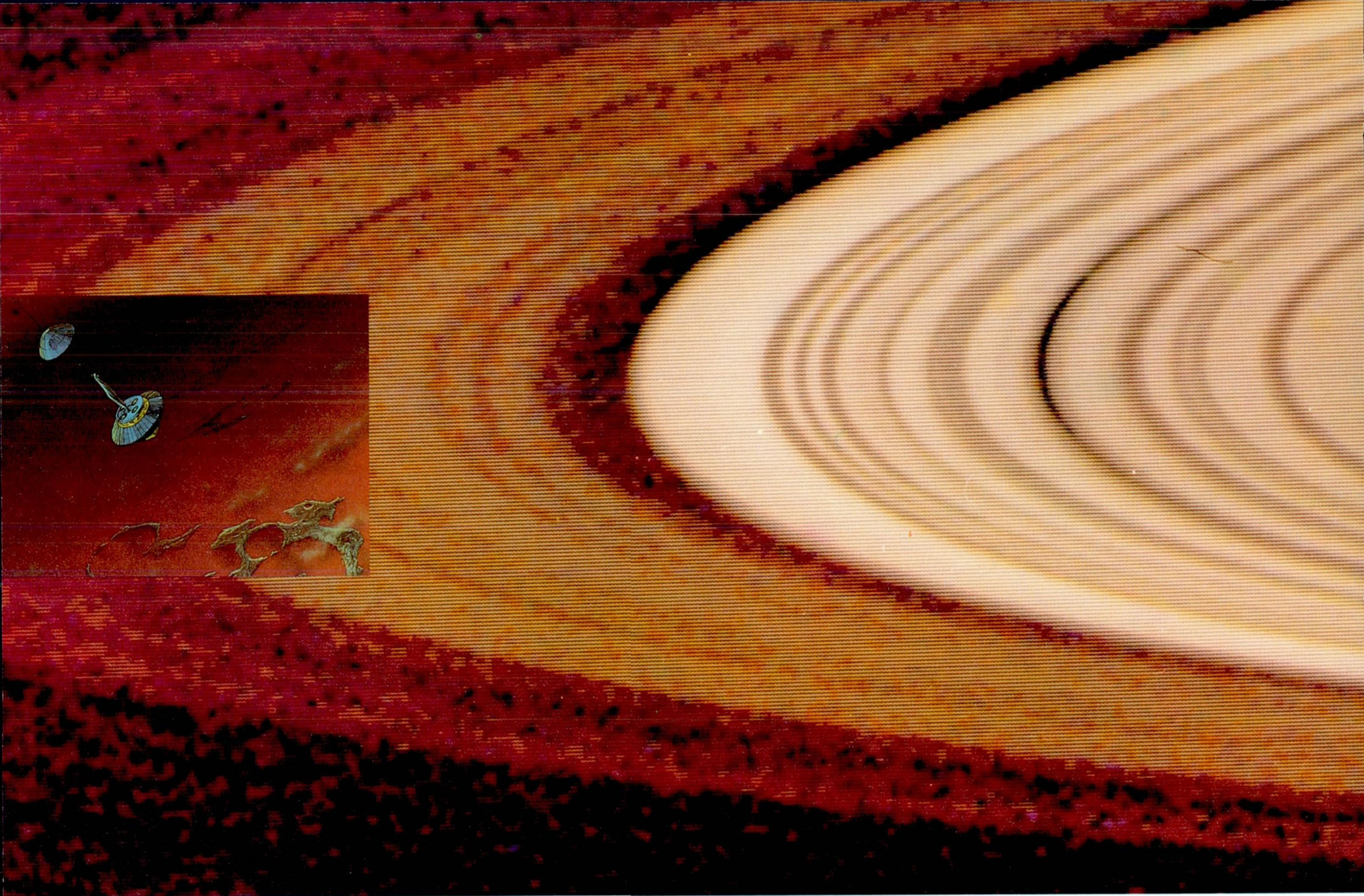
Above: Magnetic field vectors, measured by the ICE spacecraft in the tail of comet Giacobini-Zinner, superimposed on an image obtained at the Canada–France–Hawaii Telescope. (Courtesy of B. Goldberg and J. A. Slavin)

Left: The trajectory and mission phases of CRAF.

September 1995
Ulysses End of Mission

September 1995
Mars Observer
End of Mission

December 1995
Galileo Arrival at Jupiter



Above: Saturn's rings. Inset: Artist's concept of the Cassini probe entering the atmosphere of Titan. (Painting by M. Carroll)

Facing page: The interplanetary trajectory of the Cassini spacecraft.

Cassini

Cassini will explore the Saturnian system, which contains a host of volatile-rich bodies with a record of the processes that have modified these bodies. The mission will be composed of a Saturn orbiter spacecraft built by NASA and a detachable Titan entry probe supplied by the European Space Agency. The Saturn orbiter will deliver the probe to Titan and will make close flybys of Titan on every orbit to allow intensive study of this most unusual moon of Saturn.

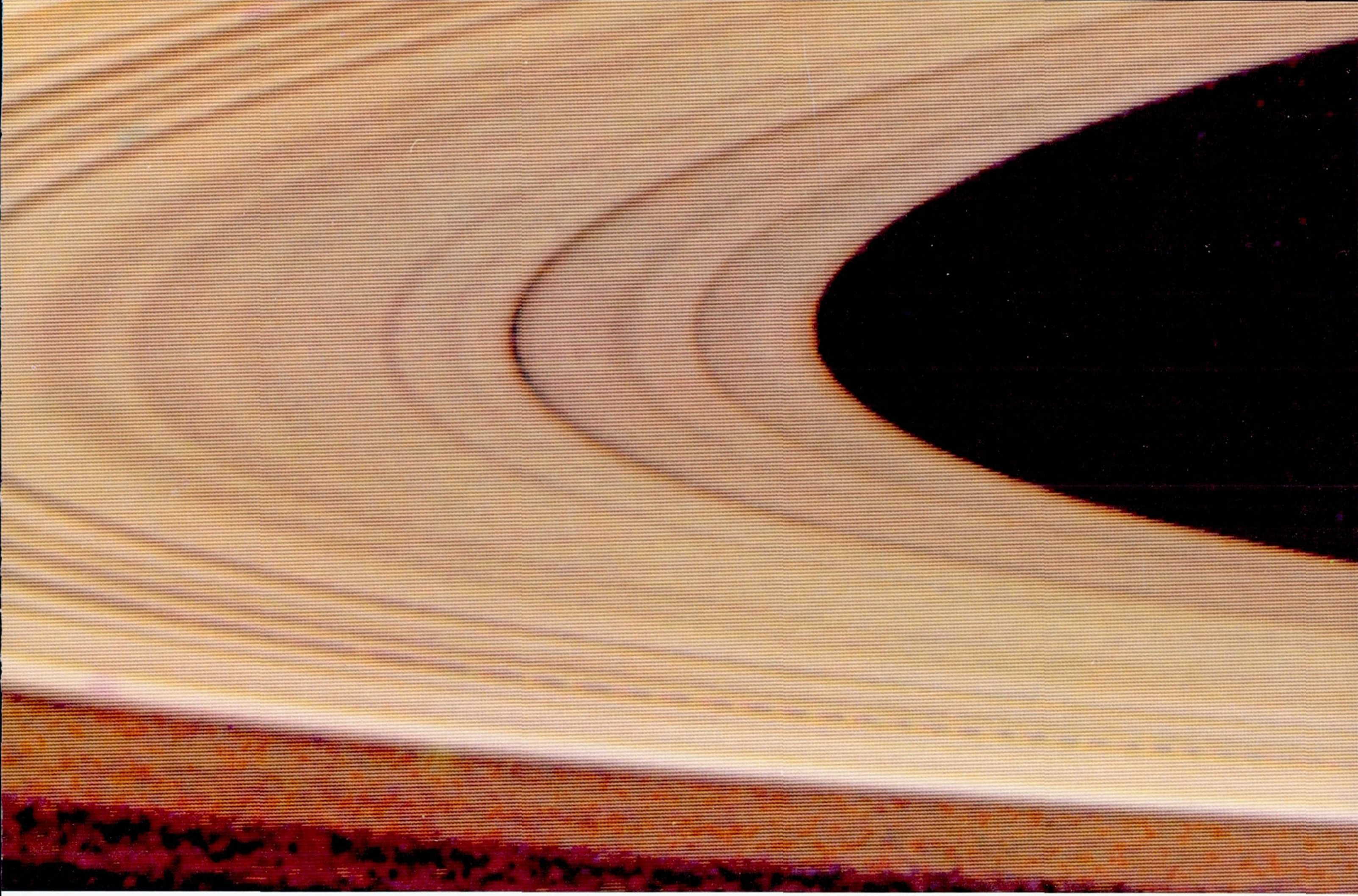
One of the most intriguing aspects of Titan is the possibility that its surface may be covered with oceans or lakes of liquid hydrocarbons that result from photochemical processes in Titan's upper atmosphere. These hydrocarbons condense to form a global smog layer and eventually rain down to the surface. Cassini will use onboard radar to peer through Titan's clouds and determine if there is liquid on the surface. Experiments on both the orbiter and the entry probe will investigate the chemical processes that produce this unique atmosphere.

As the probe descends to Titan's surface by parachute, it will begin measurements just above the cloud tops. The probe will carry a well-equipped robotic laboratory with which to make chemical analyses of Titan's atmosphere and clouds. Other instruments on the probe will measure the temperature, pressure, density, and energy balance in the atmosphere all the way to the surface. Properties of the surface will be measured remotely, and a camera will take pictures of the Titan panorama as the probe breaks through the cloud

April 1996
Cassini Launch

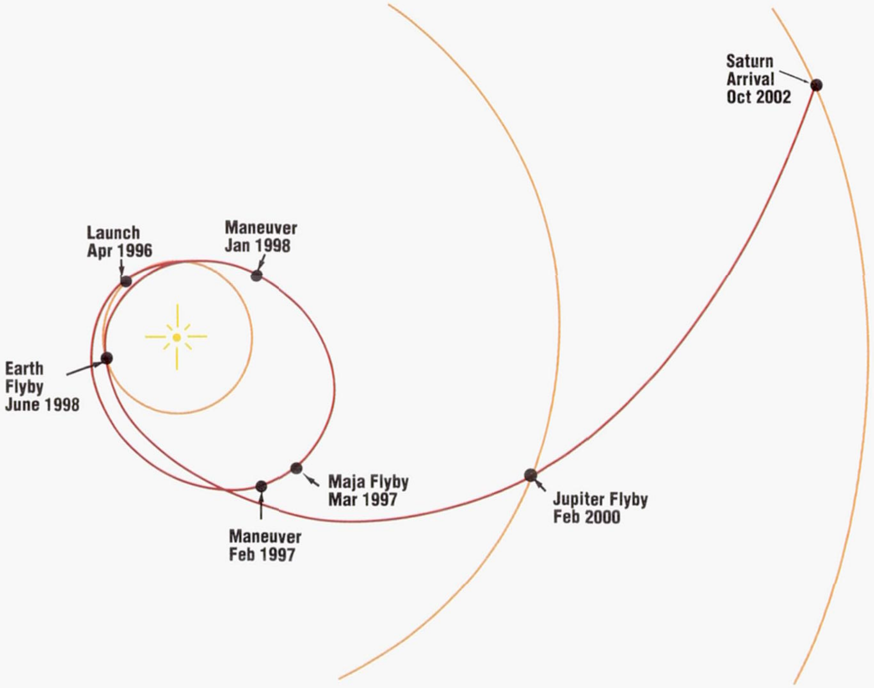
June 1996
Galileo Ganymede Flyby

February 1997
CRAF Earth Flyby



deck. The probe may survive the landing, in which case it will relay measurements from the surface before the orbiter flies beyond the horizon.

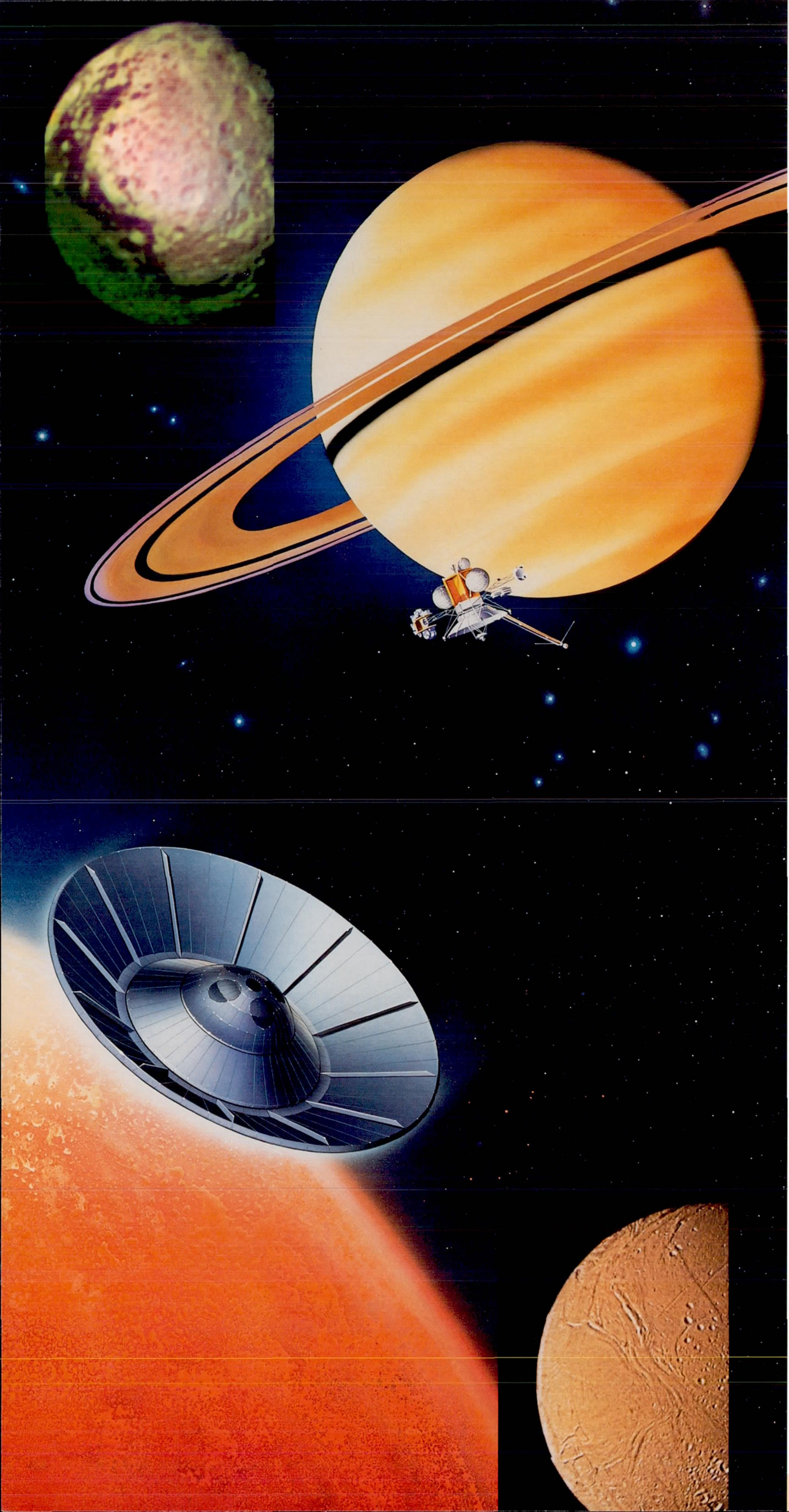
Through the clouds, the orbiter's radar will take pictures of Titan's surface, mapping the majority of it to a resolution of several kilometers and portions of it at 200-meter resolution. The orbiter will also carry remote-sensing instruments to measure the composition and structure of Titan's atmosphere on a global scale. The orbiter will come so close to Titan on many passes that it will actually fly through the upper atmosphere. At those times, several aeronomy instruments will make in situ measurements of atmospheric composition.



March 1997
Cassini Maja Flyby

October 1997
Galileo End of Mission

October 1997
CRAF Eunomia Flyby



Another of Saturn's moons, Iapetus, has one hemisphere that is six times darker than the other; many scientists suspect that this very dark material is organic in nature. How this particular moon, with its dark material and its hemispheric albedo asymmetry, comes to be among the other very bright, icy moons in the Saturnian system remains a mystery. Cassini will examine the dark material on Iapetus to determine this material's relationship both to organic material on Titan and to dark material on comets and asteroids.

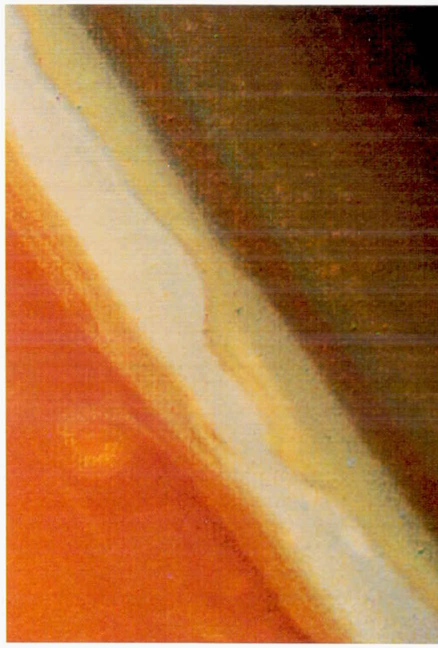
The orbiter will also pass within a few hundred kilometers of several of Saturn's other moons. The orbiter cameras will take pictures of the intensely cratered surfaces of those icy moons, the radar will map their topography, and the spectroscopic instruments will determine their compositions.

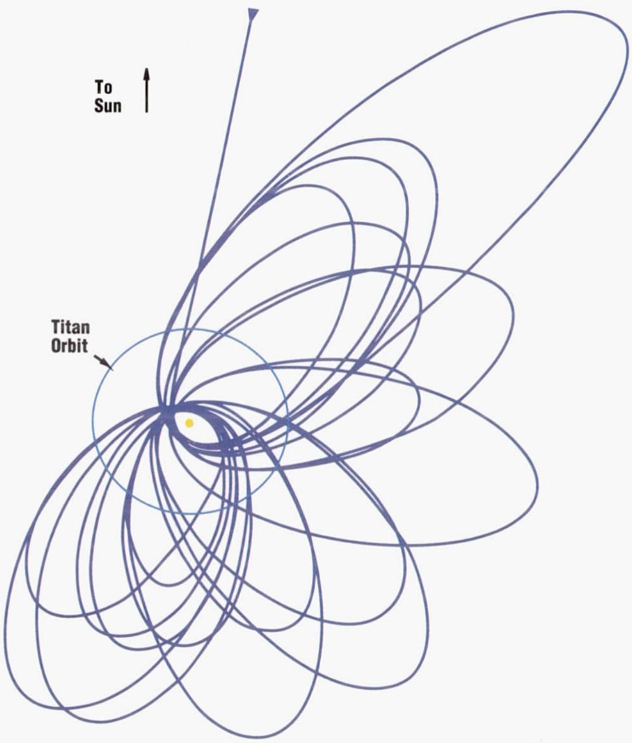
Besides the large moons, Saturn's equatorial plane contains many smaller objects and considerable dust, including the magnificent ring system close to the planet. Cassini will examine in detail the dynamic and enigmatic rings of Saturn, which were explored only briefly by earlier flybys. No other planet in the solar system contains as much orbital debris as Saturn, where several moons can occupy virtually the same orbit. Cassini will survey the small bodies orbiting Saturn and will search for moonlets within the rings. Cassini will also study the rings in fine detail to unravel the mysteries of their structure, dynamics, composition, and formation.

The structure and composition of Saturn's atmosphere will also be examined. Sensitive instruments on the Cassini orbiter will make remote chemical and physical measurements deep into the atmosphere of Saturn. The information thus derived will then be compared with the Jupiter data obtained by the Galileo mission. The resulting comparative studies of these two giant planets will contribute far more to our understanding of planetary origin and evolution than could be gained through the study of either planet alone.

The interactions of Saturn's magnetosphere with the rings and with Titan's atmosphere are the most complex examples of these phenomena in the solar system. The magnetospheric interactions with dust and moonlets in the ring plane provide information about some of the processes involving the interactions of plasma, dust, and radiation that were important at the beginning of the solar system, when the planets were formed.

Finally, one of the benefits of the Cassini trajectory from Earth to Saturn is that it takes the spacecraft through the asteroid belt. Galileo and CRAF will also visit asteroids, and a complementary type will be chosen for Cassini. Thus, in the course of these three great explorations, several asteroids, each with different surface compositions, will be studied independently.



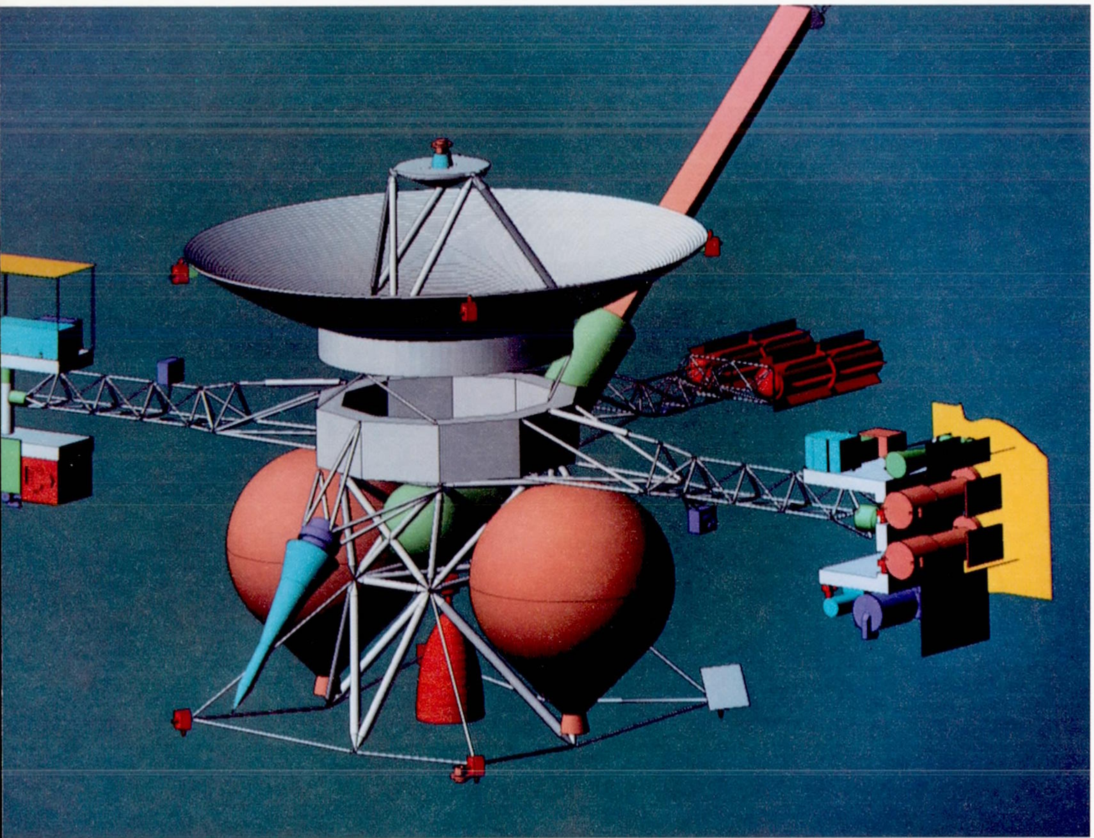


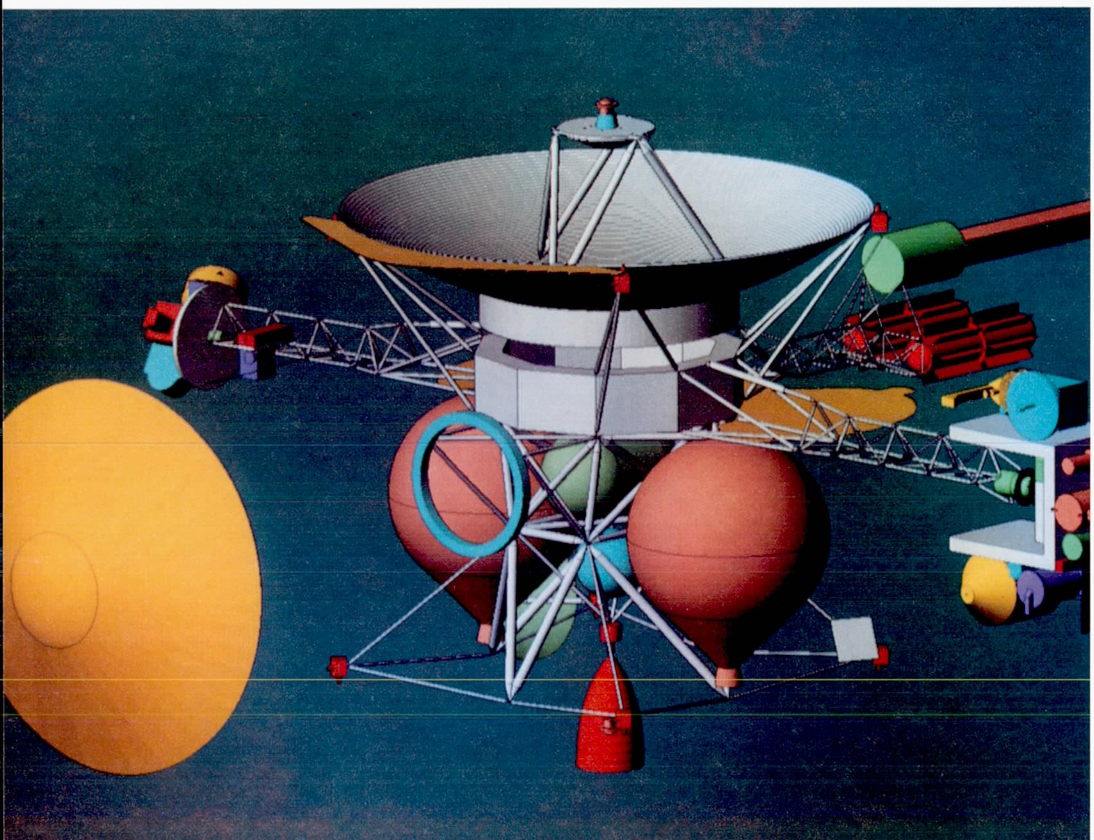
Facing page: Artist's concept of Saturn, the Cassini spacecraft (background), and the probe on its way into the atmosphere of Titan. Insets: Saturn's moon Iapetus (top), showing its light and dark hemispheres. Saturn's moon Enceladus (bottom) with its plains and heavily cratered terrain.

Above: A storm in Saturn's upper clouds.

Left: The Cassini trajectory after arrival at Saturn, passing Titan on each orbit.

Mariner Mark II Spacecraft





The Mariner Mark II spacecraft has been designed specifically to carry out deep space missions to comets, asteroids, and the outer planets. They will therefore be equipped to meet a multiplicity of demands imposed by the nature of these missions, including the need to provide electrical power at great distances from the Sun, to transmit large amounts of data to Earth over equally vast distances, and to provide highly accurate pointing for the precise aiming and/or delivery of penetrators, probes, and remote-sensing instruments, as well as for the proper orientation of high-gain antennas. Of equal significance is the need for a high degree of autonomous operation and reliability.

At the same time, the cost of the missions must be minimized without compromising quality. The Mariner Mark II program will meet this challenge by making the spacecraft for its various missions as nearly uniform in design as possible. For CRAF and Cassini, each spacecraft will be designed to carry either set of instruments as well as to power these instruments, point them, and store and transmit their data with the fewest possible changes in spacecraft design. Where detailed requirements differ, the final design will be driven by the requirements of the more demanding mission. The size of

June 2002
CRAF Penetrator Delivery

the propellant tanks, for example, will be determined by CRAF's requirements; Cassini will use the same tanks, but they will not be completely filled with fuel. As another example, the size of the antenna will be defined by the distance between Saturn and Earth; a smaller antenna would be sufficient for the CRAF mission. The cost of over-designing for the mission with the less stringent requirements will be more than compensated by savings derived from the design, construction, testing, and operation of identical subsystems on both missions.

Computer-generated drawings of the two spacecraft, complete with their scientific instruments, are shown at left. The principal common features are the central ten-sided spacecraft bus that holds most of the electronics, the large propulsion subsystem (fuel tanks, rocket engine, and structure) below the bus, the high-gain antenna and radio feeds above the bus, the two nuclear-powered radioisotope thermoelectric generators on a boom behind the bus, and the booms on which experiments are mounted. *In the foreground, the figures* show CRAF's penetrator and Cassini's Titan probe at the same location on each of these versatile multimission spacecraft.

The spacecraft will fly with their high-gain antennas pointed toward Earth. On CRAF, two instrument-laden platforms will keep the telescopes and other sensors trained on the target under study. Cassini will use one of the CRAF platforms, but the other will be replaced by a turntable that will continuously map the dust, plasma, and energetic particles arriving from all parts of the sky.

The spacecraft are being designed and built by NASA, the Titan probe by the European Space Agency, and the CRAF propulsion subsystem by the Federal Republic of Germany. Scientific instruments will be supplied by all of the international partners. Both the CRAF and Cassini missions will be launched on the expendable Titan IV/Centaur G': CRAF in 1995 and Cassini in 1996.

Facing page: The CRAF spacecraft (top) with the penetrator in the foreground. The Cassini spacecraft (bottom) immediately after release of the probe.

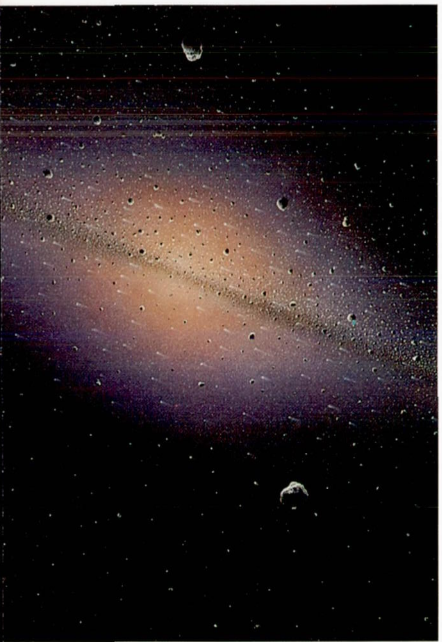
Above: Comet Halley as photographed from the *UK Schmidt Telescope in* Australia. (© Royal Observatory, Edinburgh)

October 2002
Cassini Arrival at Saturn

January 2003
Cassini Titan Probe Delivery

September 2003
Comet Wild 2 at Perihelion

Summary



Artist's view of the solar nebula before the planets formed. (Painting by Don Davis. © 1985 Time-Life Books Inc. All rights reserved. Reprinted by permission from Time-Life Books Inc.)

What we will learn from the CRAF/Cassini initiative will greatly enhance what we have already discovered about the outer solar system through ground-based observations and through our previous missions – Pioneer 10 and 11 and the Voyager encounters of Jupiter, Saturn, Uranus, and, soon, Neptune. CRAF will help us explain the intriguing glimpses into the mysteries of a comet nucleus first offered by the international flotilla of spacecraft that flew by Halley's comet. Cassini will provide a thorough investigation of the Saturnian system that complements the Galileo investigation of Jupiter. Our strategy for an orderly progression of exploration through the solar system leads us to these next logical targets: the primitive bodies and Saturn.

With the implementation of the CRAF and Cassini missions, NASA will fulfill a substantial part of our nation's commitment to the exploration of the solar system. We will have orbiters at Venus (Magellan), Mars (Mars Observer), Jupiter (Galileo), Saturn (Cassini), and a comet (CRAF), and probes will have been delivered into the nucleus of a comet (CRAF), Jupiter's atmosphere (Galileo), and Titan's atmosphere (Cassini). At the same time, Galileo, CRAF, and Cassini will have begun the reconnaissance of asteroids, with multiple flybys of asteroids of different compositional types.

To accomplish these missions, an exceptional spacecraft has been designed that can accommodate a wide variety of targets and scientific instruments with only minor modifications in the spacecraft design from one mission to the next. Future Mariner Mark II missions may return a sample from a comet nucleus for laboratory analysis on Earth; a spacecraft may be sent to Uranus or Neptune to learn more about those distant targets than Voyager was able to tell us; and a spacecraft may rendezvous with one of the larger main belt asteroids, study it in detail for several months, and then move on to examine a second asteroid of a different composition. Endless possibilities exist to satisfy our need for knowledge and understanding and to unravel the clues, hidden for billions of years, that the outer solar system holds to the mysteries of our origin and our evolution.

December 2003
CRAF End of Mission

February 2006
Cassini High
Inclination Orbits

September 2006
Cassini End of Mission