S O L A R   S Y S T E M   E X P L O R A T I O N

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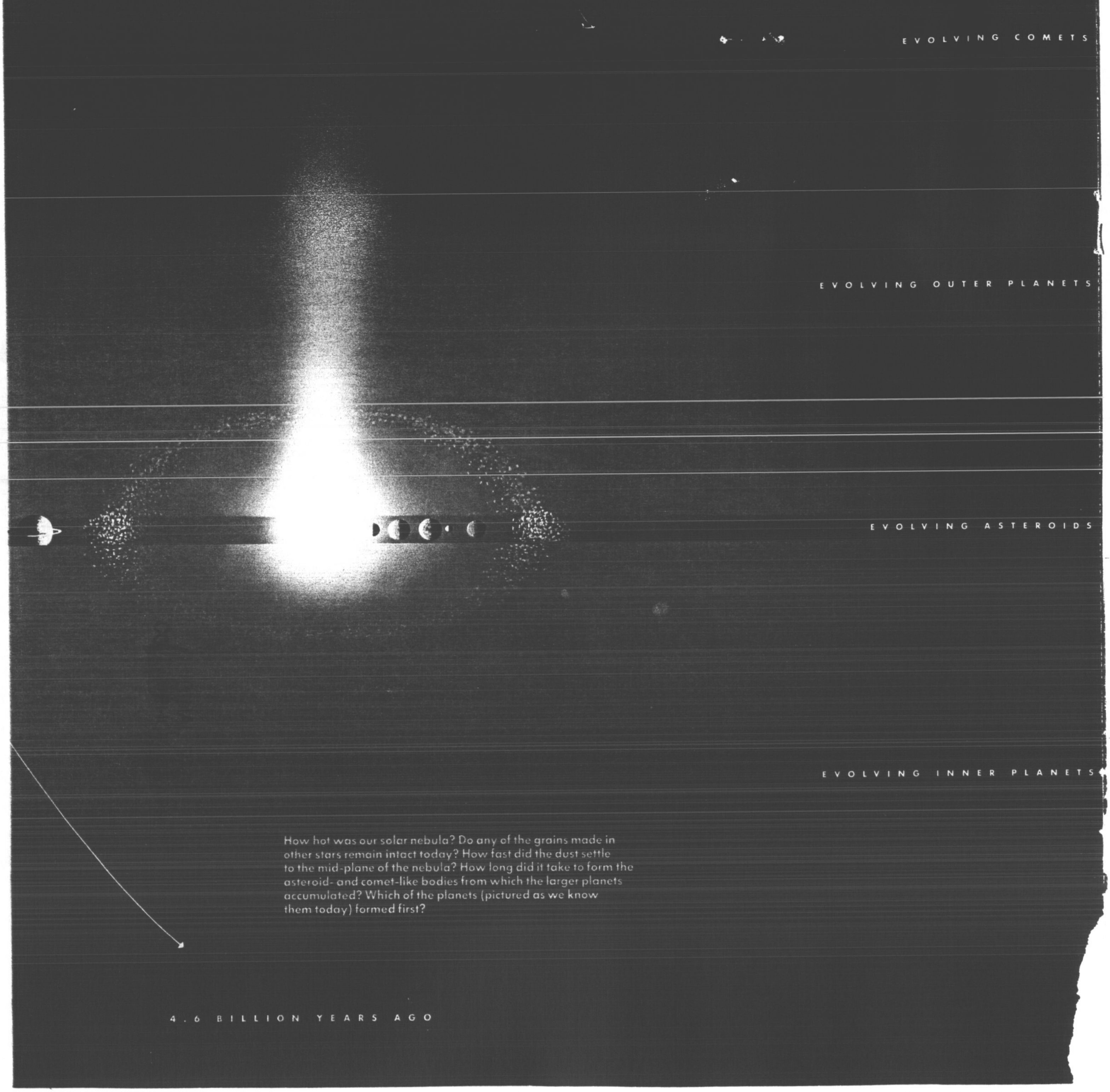


How hot was our solar nebula? Do any of the grains made in other stars remain intact today? How fast did the dust settle to the mid-plane of the nebula? How long did it take to form the asteroid- and comet-like bodies from which the larger planets accumulated? Which of the planets (pictured as we know them today) formed first?

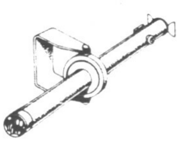
SPACECRAFT EXPLORATION OF OUR SOLAR SYSTEM

We live in an age of intense scientific curiosity about our cosmic neighborhood. Technological innovation now enables robotic instruments to examine planets close up, probe them, and even grab and return samples to Earth for detailed examination in our labs. Astronauts may again journey to explore our planetary neighbors. It is a "golden age," when the nations of Earth are reaching out for the first time, employing the full power of scientific inquiry to explore the cosmos and discover its secrets. In this booklet, we have epitomized the scientific goals established by the National Academy of Sciences as the foundation for NASA's Solar System Exploration Program: to determine the nature of the planetary system and to understand its origin and evolution, the development of life, and the principles that shape our own planet.

In order to address these goals, NASA has developed a program of seven exceptional spacecraft missions for the rest of this century. Congress has approved several missions and two are ready to go: the *Galileo* orbiter/probe mission to Jupiter and the *Magellan* Venus radar mapper. The next priority is the *Comet Rendezvous Asteroid Flyby (CRAF),* which will match orbits with a comet and study an asteroid en route. *CRAF,* the first of the Mariner Mark II spacecraft designed to explore small bodies and the outer solar system, will also fire an instrumented penetrator into the solid nucleus of the comet. The second Mariner, *Cassini,* will tour Saturn's system and send a probe to Titan's surface; it may send another probe into Saturn's atmosphere. The most ambitious mission, *Mars Rover/Sample Return,* could be underway by the end of the century, possibly in cooperation with other nations. The *Mars Observer,* already being built, will study Martian climate and geochemistry, and pave the way for returning a sample. Using a duplicate spacecraft, the *Lunar Observer* can be flown to the Moon to answer questions raised by *Apollo* about ancient cratering and volcanism on our now-dead nearest neighbor in space. Subsequent Observers may go to a nearby asteroid, Mercury, and the other terrestrial planets. New Earth-orbital telescopes will supplement probe data.

Missions planned for the first decade of the 21st Century include a comet nucleus sample return, a multiple asteroid rendezvous, and in-depth exploration of several planets. Ultimately men and women will work on the Moon and travel to Mars, and robotic probes will be sent toward the stars. In millennia to come, our civilization and Earth will fulfill their destinies in ways we can only begin to imagine. We are privileged to be alive at this moment in history when our technology permits us to begin to glimpse some answers to profound questions of our origin and destiny.

The Hubble Space Telescope.



The Earth-orbital Astrometric Telescope Facility may be deployed from the Space Station to search for planetary systems around other stars.

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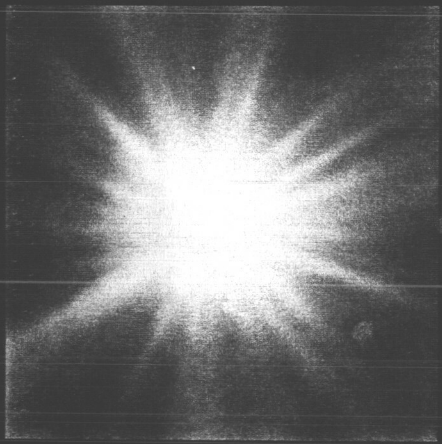
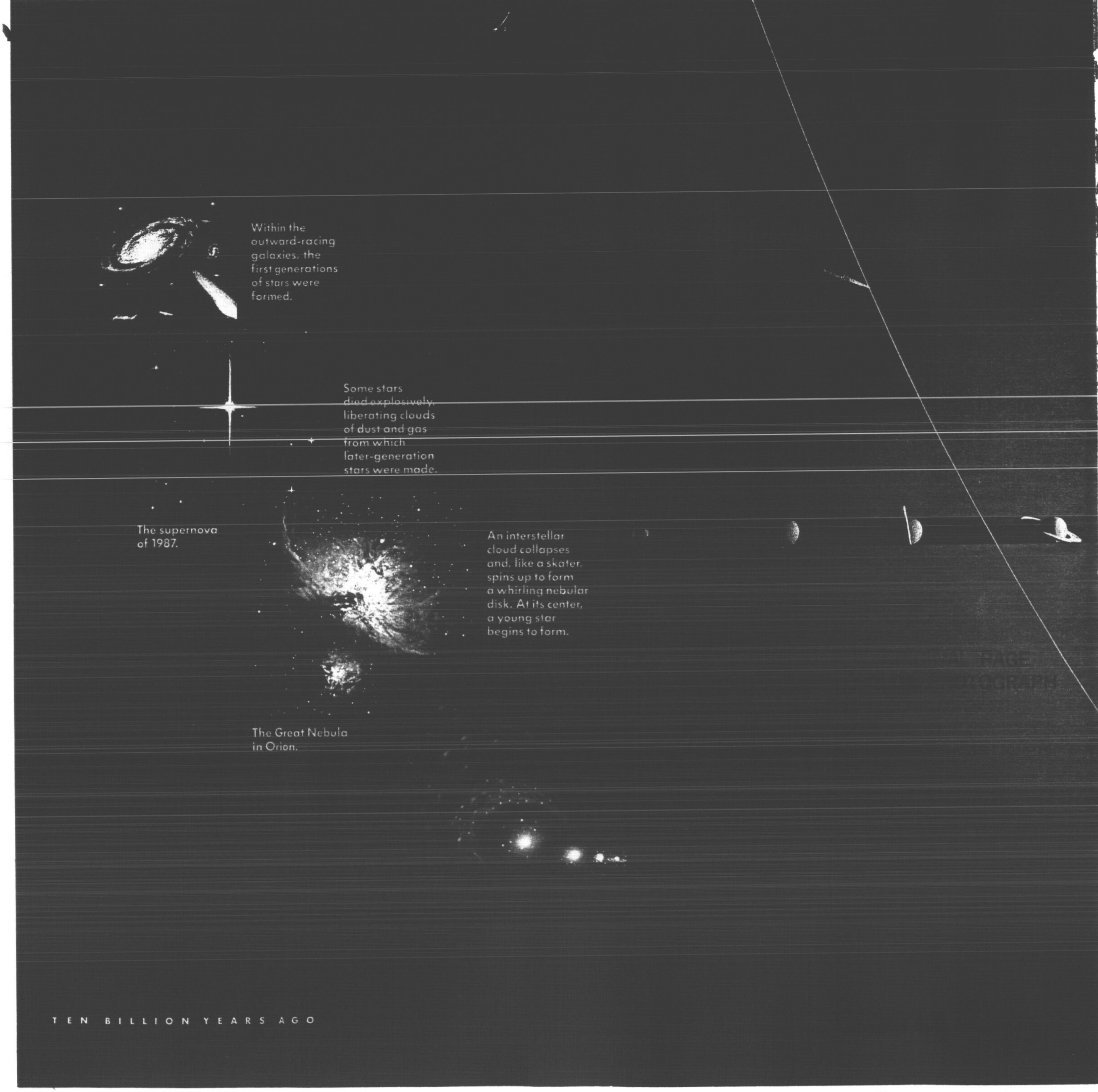
DISCOVERING OUR ORIGINS AND DESTINY



In an instant, all matter and energy in the Universe emanated from the Big Bang. The unfolding cosmic processes created our habitable environment. We study other planets to fathom our origins, our existence on one planet, and our destiny. To understand the clues of these distant worlds, we must travel to them and explore...

15 BILLION YEARS AGO



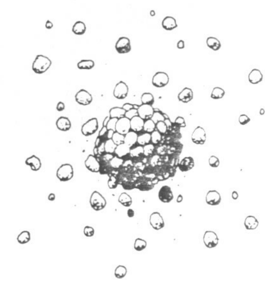
Within the outward-racing galaxies, the first generations of stars were formed.
Some stars died explosively, liberating clouds of dust and gas from which later-generation stars were made.
The supernova of 1987.
An interstellar cloud collapses and, like a skater, spins up to form a whirling nebular disk. At its center, a young star begins to form.
The Great Nebula in Orion.
TEN BILLION YEARS AGO

COSMIC EVOLUTION AND THE SOLAR NEBULA

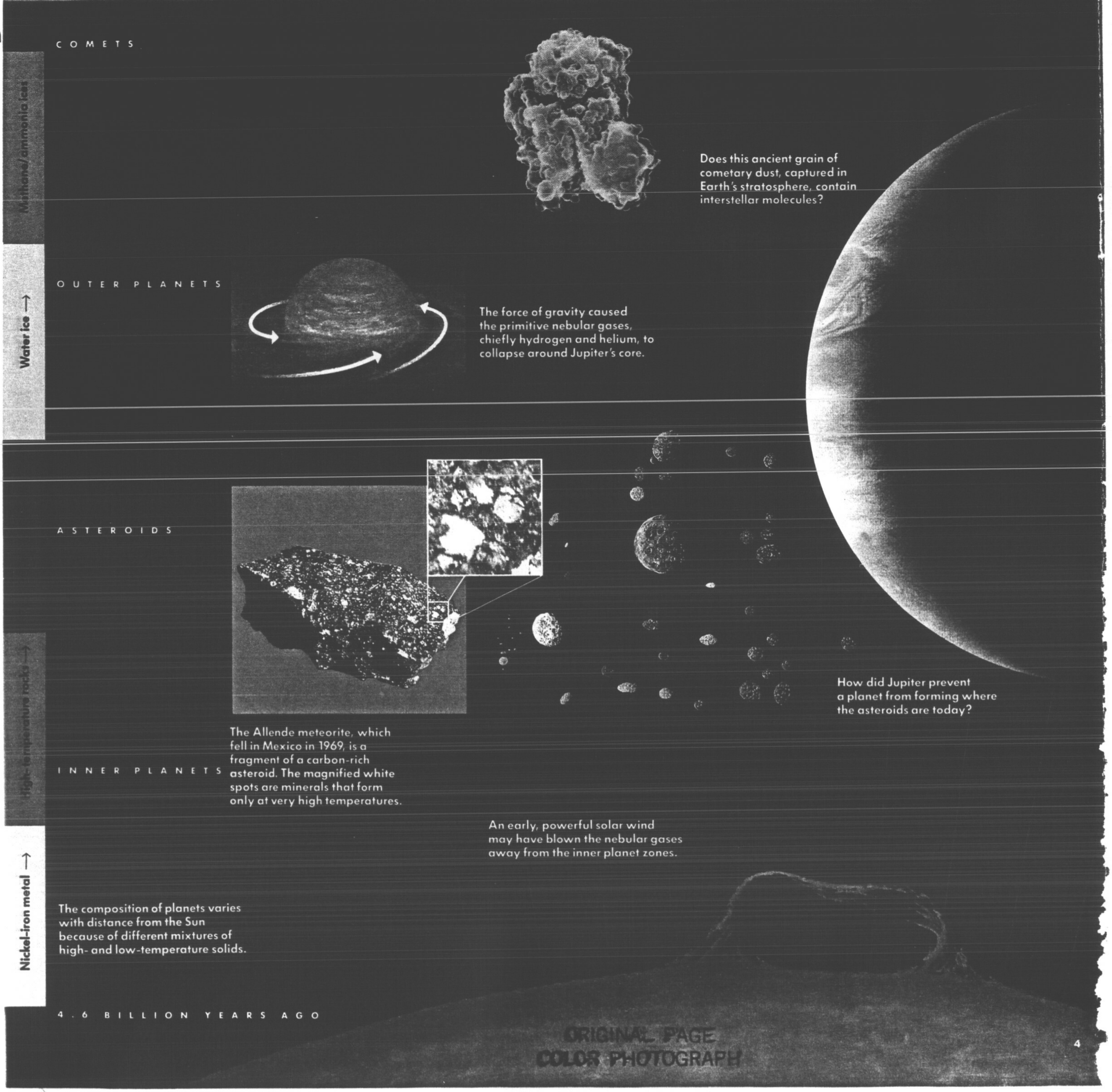
Early in the history of the expanding universe, galaxies of stars, like our own Milky Way, were formed. Nuclear furnaces within the first generation of stars began to manufacture the atomic elements, including the heavier elements that would ultimately become—at least near one star—planets and life. Many stars died spectacular supernova deaths. Remnant debris, enriched in heavier elements, accumulated into giant clouds of molecules and dust. Under the inexorable force of gravity, the clouds collapsed to form new populations of stars.

Several generations of stellar birth and cataclysmic death elapsed. Then, about 4.6 billion years ago, a particular star formed from an interstellar cloud toward the periphery of what we now call the Milky Way Galaxy. Not much larger than trillions of other stars, this star would become our Sun. Driven by laws of nature, which we are trying to understand, a spinning disk of interstellar dust and gas coalesced and our Sun began to shine. How hot and well-mixed was this "solar nebula"? It was hot enough to vaporize most material, but perhaps in comets some grains of ancient stellar debris remain intact for us to study. The minerals and ices in the nebular disk aggregated into successively larger bodies, some of which became massive enough to sweep up gas; eventually, our familiar nine planets formed. We are not certain that planet formation normally accompanies star formation. Our Sun could be more unusual than we think, and the planetary environments that have given birth and sustenance to life might be unique in our cosmic neighborhood.

The goal of planetary exploration is to understand the nature and development of the planets from their origins to the present, as illustrated here by pictures from the first two decades of spacecraft missions and by the imaginations of space artists. We strive to study planets, comets, asteroids, and moons to discover the reasons for their similarities and differences, and to find the clues they contain about the primordial processes of planet origin. By studying the planets and 4.5-billion-year-old meteorites, and by searching for possible planetary systems around nearby stars, we establish the cosmic context for the emergence of life and life-sustaining environments. We seek our origins and even our destinies, which are tied to the future of the Sun and its planets, especially Earth. To succeed, we must understand the evolutionary processes—physical, chemical, geological, and biological—that have shaped planets in the past, and continue to modify them today.



Early asteroid-like "planetesimals" formed the inner planets and the cores of the outer planets.



COMETS
Methane/ammonia ices
Does this ancient grain of cometary dust, captured in Earth's stratosphere, contain interstellar molecules?
OUTER PLANETS
Water ice →
The force of gravity caused the primitive nebular gases, chiefly hydrogen and helium, to collapse around Jupiter's core.
ASTEROIDS
How did Jupiter prevent a planet from forming where the asteroids are today?
The Allende meteorite, which fell in Mexico in 1969, is a fragment of a carbon-rich asteroid. The magnified white spots are minerals that form only at very high temperatures.
INNER PLANETS
High-temperature rocks →
An early, powerful solar wind may have blown the nebular gases away from the inner planet zones.
Nickel-iron metal →
The composition of planets varies with distance from the Sun because of different mixtures of high- and low-temperature solids.
4.6 BILLION YEARS AGO
ORIGINAL PAGE
COLOR PHOTOGRAPH

ORIGINS OF THE PLANETS

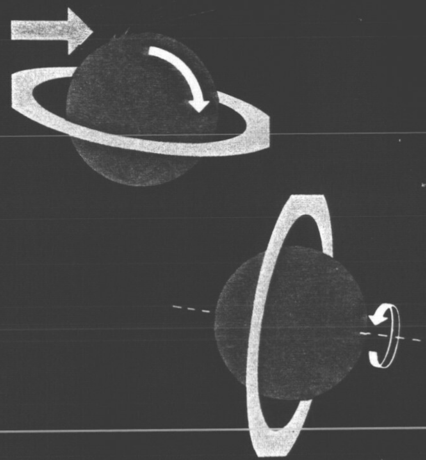
The planets were born from the solar nebula, a dusty disk of gas from which the Sun formed 4.6 billion years ago. Nebular temperatures and pressures may have imposed the trend of planetary compositions we see today: the inner planets are made mostly of rocks and metals that remain solid at high temperatures, whereas outer planets, asteroids, and comets are richer in water and ices. Or did later processes of planet growth control bulk makeup? Isotopes vary among meteorites and Moon rocks, indicating that the swirling solar nebula was poorly mixed until after solid grains began to amass into larger bodies.

Scientists have ideas about how planets grew. First, dust settled into a flattened layer within the more distended nebula; that dense, unstable disk may have split into innumerable eddies, each of which contracted by gravity into a "planetesimal," several kilometers in size. Within a million years, such asteroid-like building blocks bumped into each other, aggregating into ever-larger bodies of rock and—in the outer zones—ices. Nebular gas rich in hydrogen and helium was swept up by proto-Jupiter and proto-Saturn; most of Jupiter's mass remains today as a compressed sample of the original nebula. Jupiter may have had its own nebular disk, which mimicked the planetary system: rocky moons formed near the radiantly hot planet, while outer Ganymede and Callisto remained ice-rich.

Apparently, little gas collapsed onto the inner planets; perhaps it was blown away by a powerful "wind" from the young Sun. The effects of Jupiter's gravity evidently interrupted the growth of even a small, solid planet between itself and Mars; only asteroids remain. Many icy comets that failed to accumulate into late-forming outer planets were ejected into distant orbits and stored where the Sun's light and gravity are feeble. Other remnant planetesimals, maybe even grown planets, careened around the young solar system. The largest ones crashed into the planets, perhaps stopping Venus's spin, tipping Uranus on its side, fragmenting Mercury to its core, and creating the Moon from the infant Earth.

The planets were warmed by accretionary impacts, by solar wind electric currents, or by intense radioactivity of now-decayed aluminum-26. Heavy metal sank to form cores; lighter rocks and ices formed mantles and crusts. Molten magma flowed onto the surfaces of the Moon and other bodies. Even some small, rocky asteroids became hot, forming metallic cores; melting ices soaked others with liquid water. Perhaps in some oxygen-poor asteroidal environment, such moist warmth fostered the synthesis of organic compounds, precursors to life.

C O M E T S

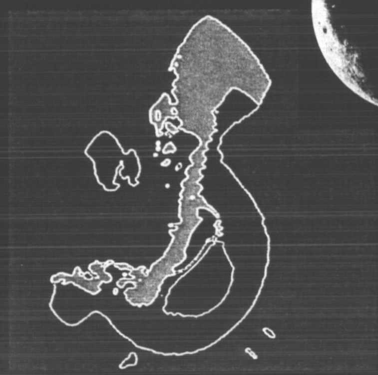


O U T E R   P L A N E T S

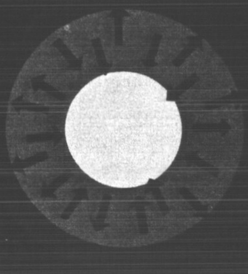
Glowing Jupiter and its Galilean satellites (Io, Europa, Ganymede, Callisto) formed much like a miniature solar system.

Perhaps a giant impact tipped Uranus's poles by more than 90 degrees.

A S T E R O I D S



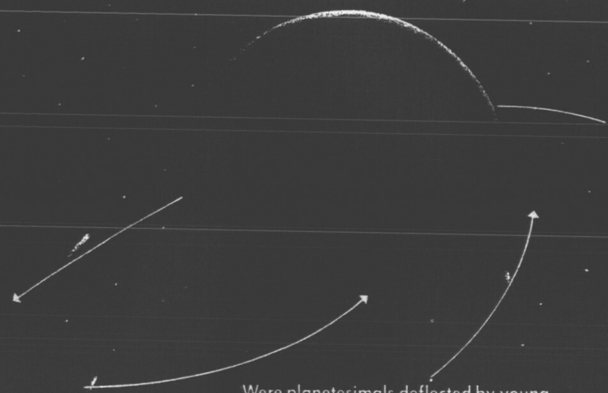
I N N E R   P L A N E T S



Materials within the warm, young planets began to segregate into cores, mantles, and crusts.

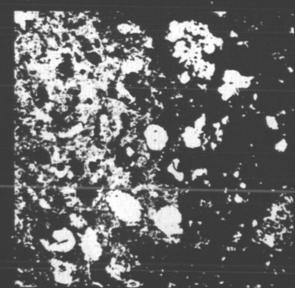
One stage of a computer model of Earth being disrupted by the impact of a Mars-sized body. This is how the Moon may have originated.

4 . 5   B I L L I O N   Y E A R S   A G O

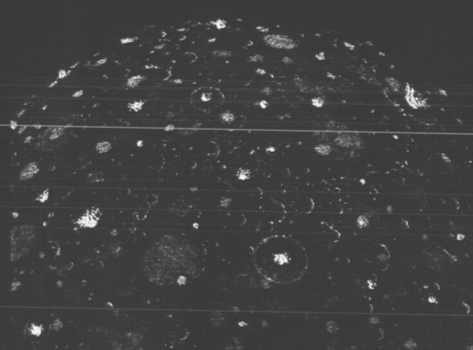


Were planetesimals deflected by young Neptune to populate the immense spherical cloud of comets that fills the Sun's neighborhood of interstellar space? Or are comets from an outer fragment of the solar nebula, always far beyond Neptune and Pluto?

Saturn's moon Rhea is covered with craters, a legacy of remnant planetesimals and perhaps also of debris orbiting the ringed planet.

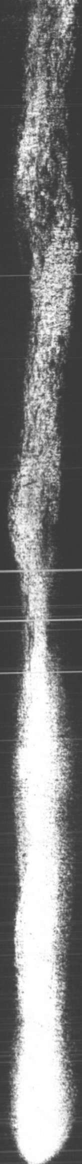


This photomicrograph of a carbon-rich meteorite shows minerals that were chemically altered when a water-rich asteroid was heated long ago.

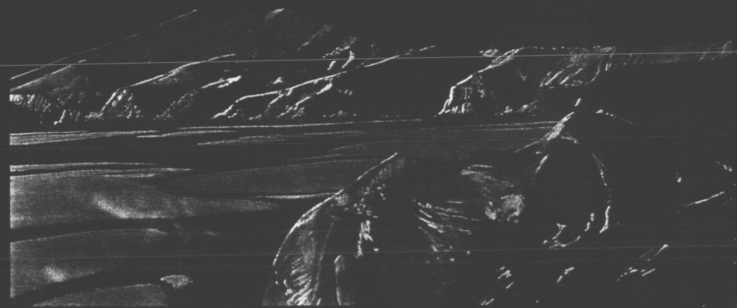


Molten rock separated from the Moon's interior and rose to form its ancient crust, according to analysis of rocks returned to Earth by *Apollo* astronauts.

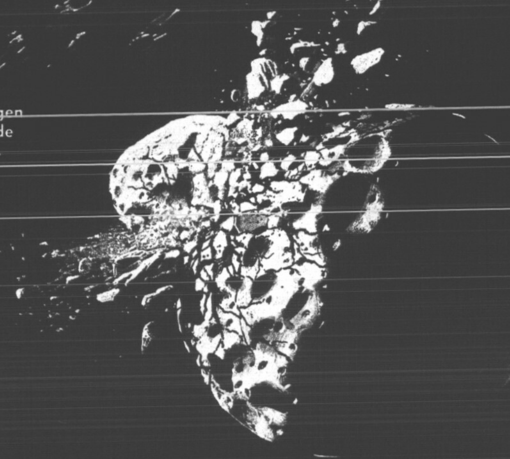
C O M E T S



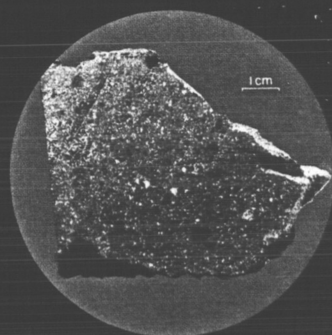
O U T E R   P L A N E T S



Until the Cassini mission flies, artistic imagination may be our best guide to the scenery beneath Titan's hazy skies. The nitrogen and methane atmosphere of Saturn's largest moon may provide a natural laboratory for studying pre-biotic organic processes.



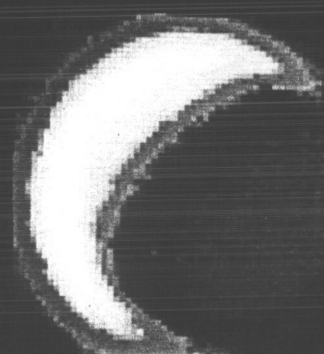
A S T E R O I D S



Ices in the last cometary planetesimals to impact Venus and other inner planets may have contributed to their atmospheres and oceans.

Great collisions shattered asteroidal rocks, resulting in meteorites that look broken up and re-compacted.

I N N E R   P L A N E T S



When were our planet's prevalent oceans first formed? Were they a primordial "soup" from which organic compounds and life ultimately arose?

Ultraviolet image of Venus's thick atmosphere. Were gases originally trapped within the planetesimals that formed Venus, and later outgassed from the planet's interior?

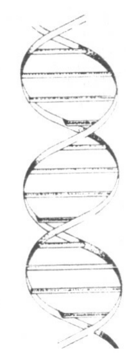
F O U R   A N D   A   Q U A R T E R   B I L L I O N   Y E A R S   A G O

Shrouded in the mists of time are the earliest histories of the newly formed planets. There were stupendous impacts, heat, and tumult. Steamy atmospheres swirled across molten streams and lakes of lava. Crusts formed and foundered into the infernos within the young worlds. After several hundred million years, many planets and moons gradually assumed forms recognizable today. But potential clues about how young planets "work" were destroyed or obscured by the very processes we seek to study. Not until rocky or icy crusts had cooled and solidified could they record lasting crater scars of impacting asteroids and comets for us to read 4 billion years later. In modern laboratories, we dissect rocks for chemical and isotopic evidence about their formation ages, temperatures, pressures, and magnetic and chemical environments. But few rocks formed on the larger, evolving planets during primeval epochs have survived.

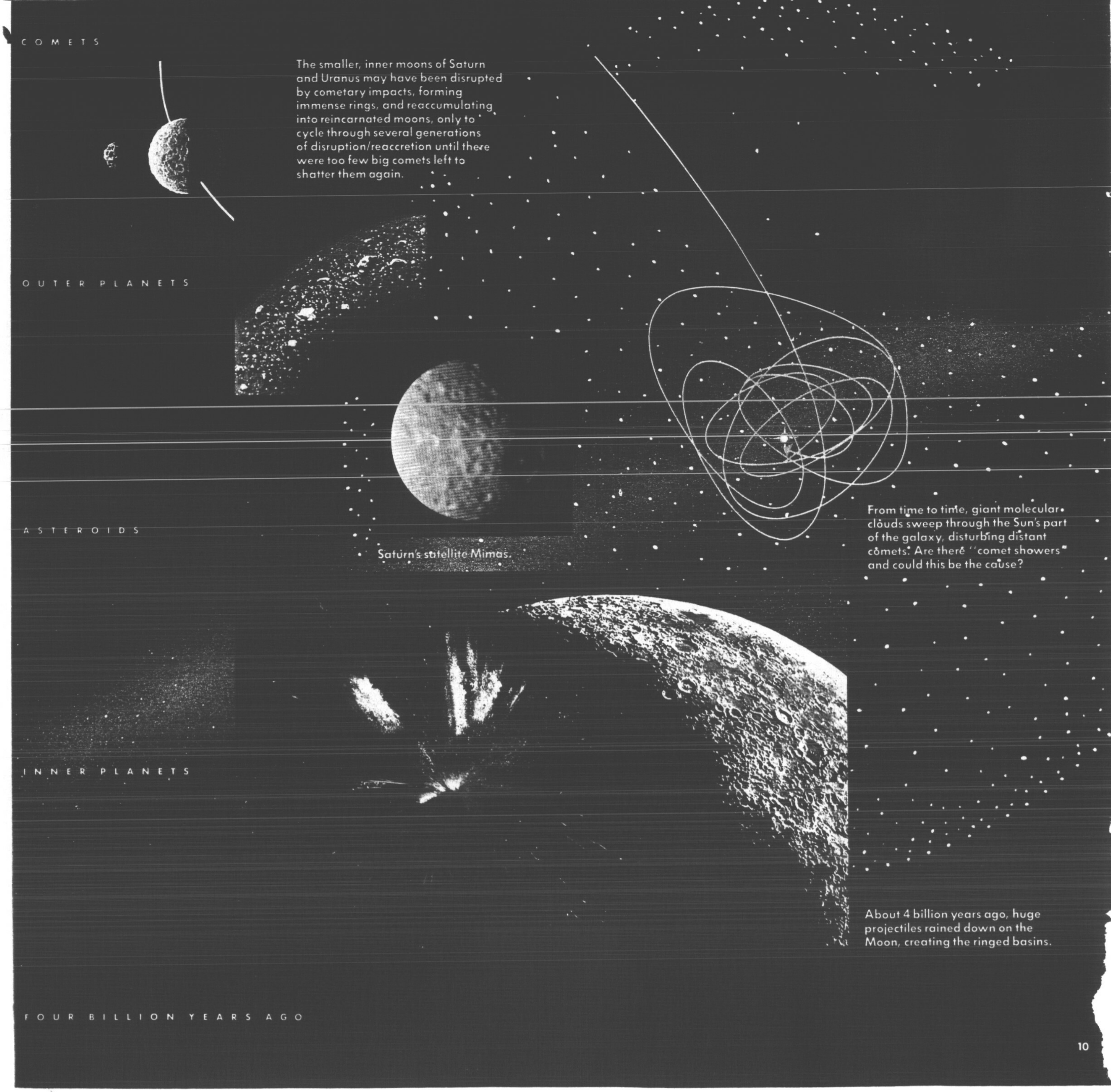
Asteroids cooled and solidified much more quickly than planets; many never melted at all. To read the inner solar system's earliest history as recorded in meteorites (which are asteroid fragments), we need only disentangle the secondary effects of subsequent asteroid collisions. And comets, we believe, were preserved 4.5 billion years in cold storage at the edge of the solar system. Access to their clues about primordial epochs requires random passing stars or massive molecular clouds in the Milky Way's arms to nudge a few into the inner solar system.

Today's dislodged comets carry clues to solar system origin. But many others entered the inner solar system in primeval times, bringing their water- and volatile-rich ices to the warm, rocky inner planets. Perhaps ancient cometary impacts contributed much of the moisture that life seems to require. Our oceans and rains, the rivers that once flowed on Mars, the gases in terrestrial planet atmospheres, and even the organic precursors to life itself conceivably resulted from a primeval deluge of young comets.

Until space missions first investigated the Moon and inner planets twenty years ago, we didn't realize that incessant volcanism and asteroidal bombardment had so badly obscured the first half-billion years of planetary history. Perhaps, by exploring the outer planets, we may at last peer into this fascinating "missing age": some primitive environments may have been retained more nearly intact in the comparative tranquillity of the cold outer solar system. We want to learn about such intriguing worlds as Saturn's Titan—perhaps a natural laboratory for studying the origin of life—and Neptune's large, frozen moon Triton.



When did life begin to evolve on Earth?


COMETS
The smaller, inner moons of Saturn and Uranus may have been disrupted by cometary impacts, forming immense rings, and reaccumulating into reincarnated moons, only to cycle through several generations of disruption/reaccretion until there were too few big comets left to shatter them again.
OUTER PLANETS
ASTEROIDS
Saturn's satellite Mimas.
From time to time, giant molecular clouds sweep through the Sun's part of the galaxy, disturbing distant comets. Are there "comet showers" and could this be the cause?
INNER PLANETS
About 4 billion years ago, huge projectiles rained down on the Moon, creating the ringed basins.
FOUR BILLION YEARS AGO

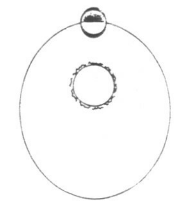
We once thought our Moon's pock-marked surface dated from the earliest times. But we discovered that most Moon rocks returned by *Apollo* astronauts had their formation ages brutally reset a half-billion years after the Moon's birth, during a violent epoch called the "late heavy bombardment." Then, spacecraft took pictures of other planets and satellites: many of them are crater-scarred as well. Evidently, Mercury and Mars were struck by huge projectiles just like those that formed the immense lunar basins, which were soon filled with lava. (These dark "seas" of early astronomers form the familiar man in the Moon.) We now realize that cometary and asteroidal debris left over from planetary accretion must have hit all planets, including Earth, for aeons. Rare impacts by numerous, smaller bodies continue today. But the precise source of the projectile blizzard that battered the inner planets 4 billion years ago remains unknown.

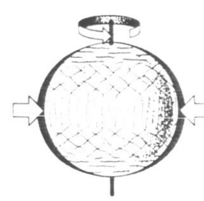
Many outer planet satellites imaged by *Voyager* also show cratered landscapes. However, the relative numbers of large and small craters differ from those on the Moon, so comets and planet-orbiting debris, not asteroids, were responsible. Some giant comets blasted apart whole moons, creating rings and debris that rained down on neighboring satellites. To learn just when craters in the outer solar system formed, we must date the relevant rocks (or ices).

Some worlds remained in turmoil with faulting, upheavals, and earthquakes. Steamy oceans and atmospheres oozed from their insides, creating environments, like today's hot springs, where single-celled life might have evolved. Meanwhile, mantles and crusts of planets like Mercury were cooling, shrinking, and thickening. As vents to deep magma sources were pinched off, volcanism ceased. The history of water, so critical to life, began to diverge on Venus, Earth, and Mars. Hot sunlight filtered through Venus's clouds to boil its oceans; hydrogen from water molecules ripped apart by solar ultraviolet rays evaporated into space, leaving our sister planet's air a torrid, smothering blanket of carbon dioxide.

Outer solar system worlds changed more slowly. The Sun's weaker gravity diminished cratering rates and orbital changes. Ices rich in ammonia and methane melt at very low temperatures, so many of the colder moons remained actively "molten" long after a rocky or watery world would have frozen solid. Ices mimicked Earth's rocks, and water and other liquids mimicked lava in shaping landforms, but the different properties of ice and rock resulted in some strange surface features on Ganymede, Europa, and other moons.

Solar tides, varying in strength as Mercury revolved in its elliptical orbit, gradually despun the planet into its "captured" 59-day spin.

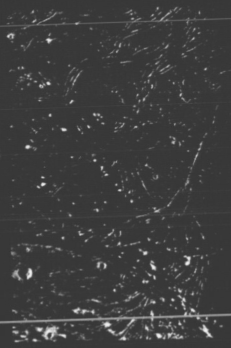




Does Mercury's global fracture pattern hold clues about its early geophysical evolution?

C O M E T S

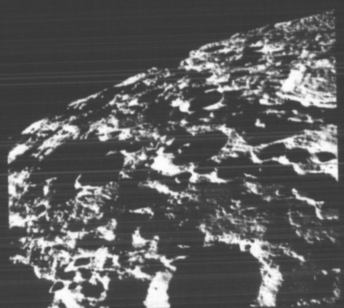
O U T E R   P L A N E T S



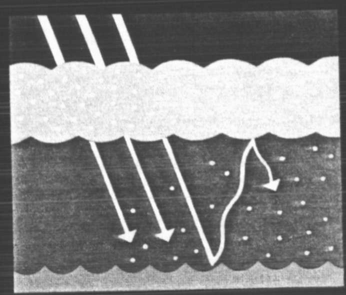
The two outer Galilean moons, Ganymede and Callisto, originally had dark, cratered surfaces. Why did Ganymede's split apart, and what formed these weird grooved tracts between patches of the old terrain?

A S T E R O I D S

I N N E R   P L A N E T S

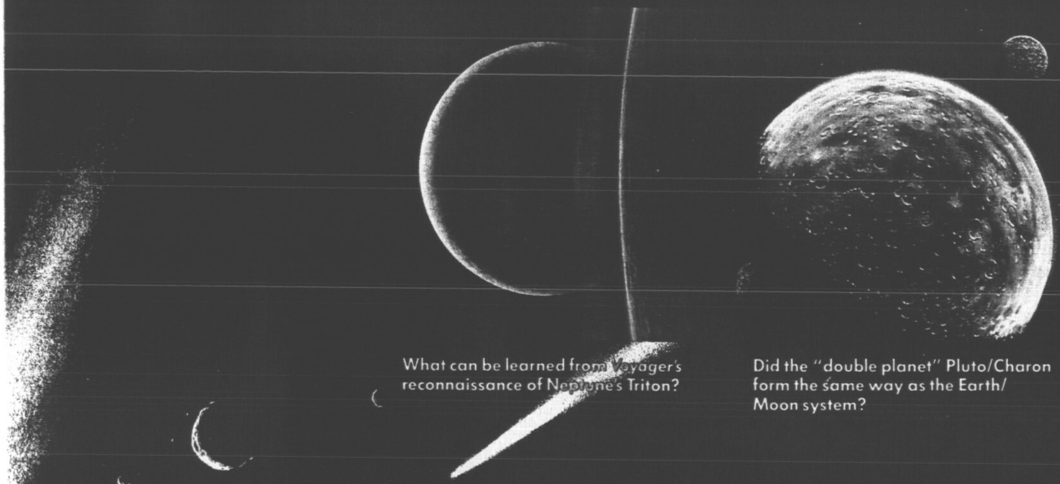


Gradually, the late heavy bombardment waned, leaving crater-scarred surfaces on moons and planets throughout the solar system.



After a billion years of outgassing, Venus may have had an Earth-like ocean and climate. Then a runaway "greenhouse effect" trapped the heat and boiled away the water. Could human activity trigger such a catastrophe on Earth?

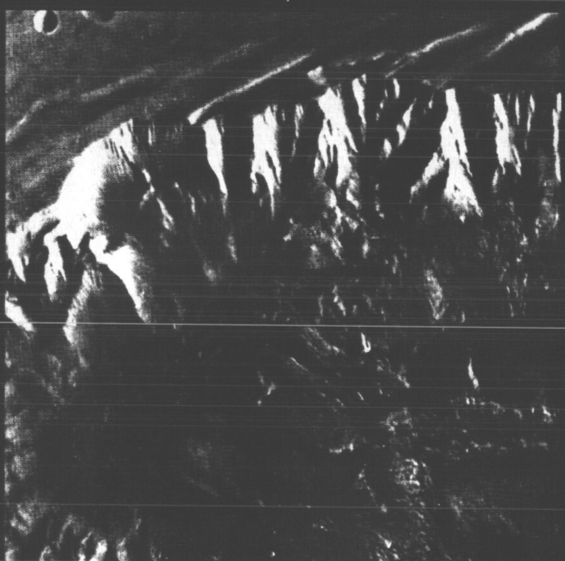
F O U R   B I L L I O N   Y E A R S   A G O

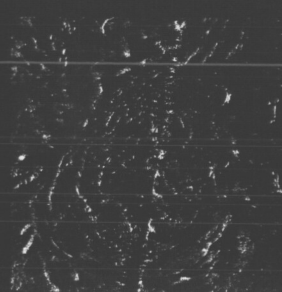


What can be learned from Voyager's reconnaissance of Neptune's Triton?

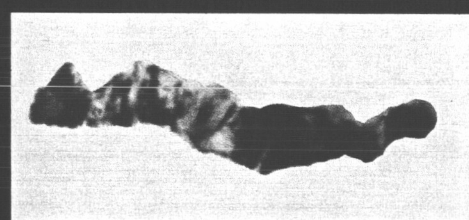
Did the "double planet" Pluto/Charon form the same way as the Earth/Moon system?

As the Tharsis plateau began to thrust upward, the Martian crust cracked, opening up canyons whose smaller tributaries equal Earth's Grand Canyon.



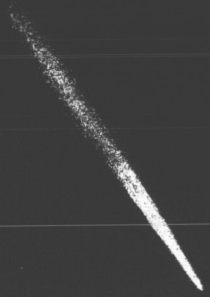


Soviet *Venera* radar map of Nightingale Corona on Venus. Are coronas unique to that planet, or are there terrestrial analogs?



Fossilized remains of Earth's earliest microscopic life-forms date from early post-bombardment epochs.

C O M E T S

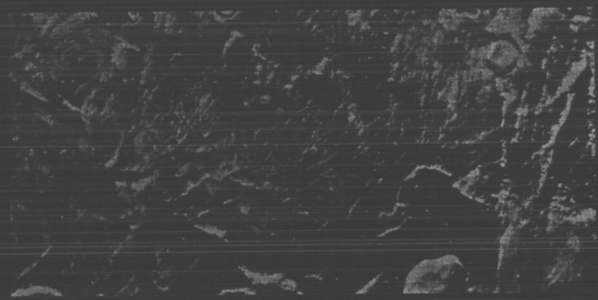


Two hundred kilometers above Titan's surface, ultraviolet sunlight decomposes methane, enshrouding Saturn's largest moon in a smoggy haze. The smog particles gradually settle, accumulating into possibly the richest deposits of hydrocarbons in the solar system.

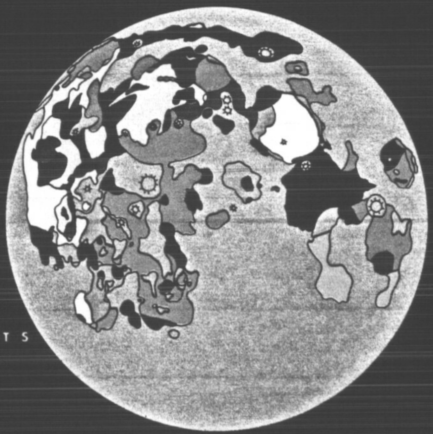
O U T E R   P L A N E T S

A S T E R O I D S

A network of old river channels on Mars. Are they proof that it once rained on Mars, or could they have been created by sapping in subsurface aquifers?



Lunar lava flows of different composition (titanium-rich basalts are shown blue on this multispectral map) tell us about rock-forming processes deep in the lunar crust as it thickened and cooled.



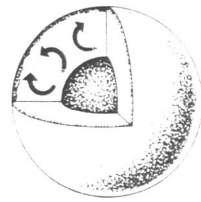
I N N E R   P L A N E T S

Are the mysterious grooves on Phobos the combined result of a large cratering impact and powerful Martian tides?

Great wrinkled scarps, like this one photographed by *Mariner 10*, testify to a period of global shrinkage of Mercury as the planet's interior cooled.

T H R E E   A N D   A   H A L F   B I L L I O N   Y E A R S   A G O

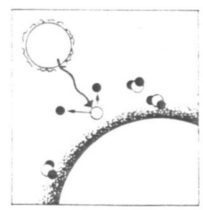
The bombardment trailed off nearly 4 billion years ago. Just half a billion years ago, in the Cambrian geological period, advanced life-forms began to "take over" Earth. The intervening 3 billion years were the middle ages of planetary history. Asteroids occasionally collided, scattering fragments around the inner solar system, and a rare comet wandered in from great distances. But most planetary history was being wrought within the bodies themselves as their radioactively driven internal heat engines gradually wound down. The ancient internal churnings are still manifest in surface geology. Less tangible processes (atmospheric chemistry, planetary magnetism) may have left traces in the chemistry and mineralogy of planetary rocks, which we can decipher when such rocks are returned to terrestrial laboratories.



Theoretical modeling of processes (like convection) that occur deep in planetary interiors has changed our ideas about thermal histories.

Once the last lunar lavas were laid down, the Moon's vents shut off forever. There is still an occasional tidal moonquake or impact. Otherwise, when not shielded by Earth's magnetosphere, the naked Moon remains passively immersed in the solar wind, its surface a valuable record of earlier epochs. As Mercury cooled and shrank, its surface wrinkled up with compressional scarps. Much earlier, small satellites and asteroids had lost their atmospheres to space; they had also rapidly radiated away their heat, so they have been inert from the middle aeons to the present.

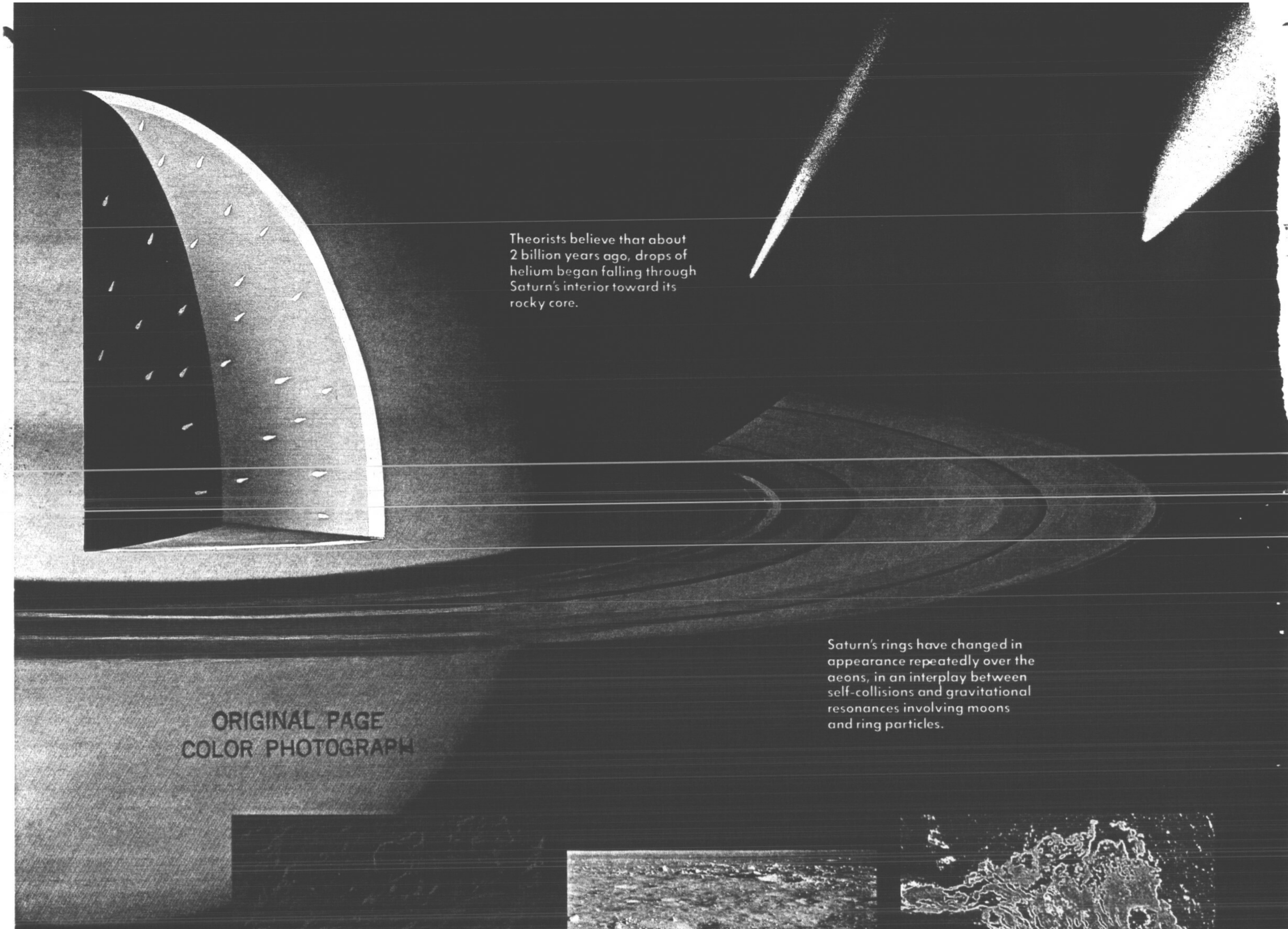
The geology was evolving on some outer-planet moons. Io is still tortured by vying tides between Jupiter and the other Galilean moons; its sulfurous volcanism has erased all record of even its most recent history. Perhaps the easily meltable ices of Saturn's Enceladus and Uranus's Miranda were also warmed by tides.



Conditions of temperature, composition, and solar radiation can influence the rate of loss of a planet's atmosphere into space.

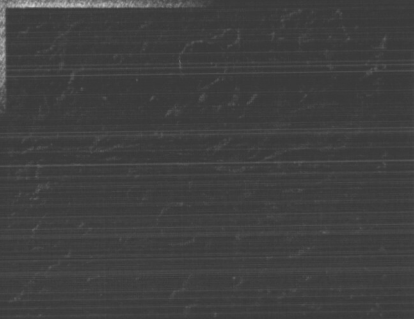
Chemical reactions redressed imbalances between new atmospheres, oceans, and landforms. Microbial photosynthesis enhanced oxygen in our air. On Earth (Venus, too?) crustal plates shifted about, subducted, and melted; mountains thrust up, only to erode and wash into the seas and onto spreading seafloors again. Possibly it rained on Mars during a past, warmer climate; certainly rivers ran. Then its air thinned and surface waters froze, while icy subterranean rivers still undermined the land. Rare, ferocious floods dug channels in the ochre Martian deserts.

The atmospheres of the gas-giant planets have always been turbulent, driven by solar and internal heat contrasts. Sunlight impinging on Titan's upper atmosphere began the photochemical processes that may have accumulated an ethane ocean on Saturn's largest moon. Meanwhile, planetary rings formed, spread, became captives of tiny moons, and formed again.



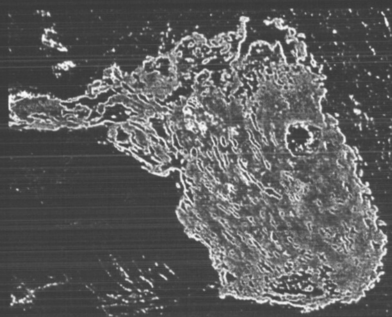
Theorists believe that about 2 billion years ago, drops of helium began falling through Saturn's interior toward its rocky core.

Saturn's rings have changed in appearance repeatedly over the aeons, in an interplay between self-collisions and gravitational resonances involving moons and ring particles.



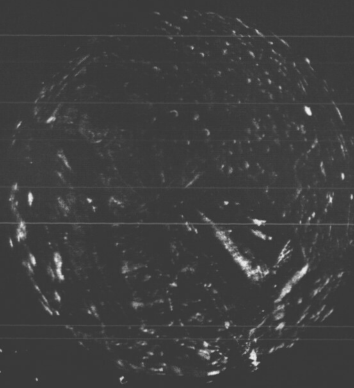
Are the younger channels on Mars due to episodes of catastrophic flooding?

Asteroids and comets continued to crater the Moon and planets.

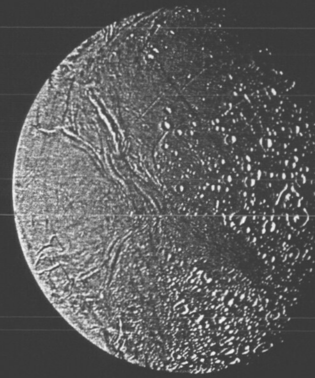


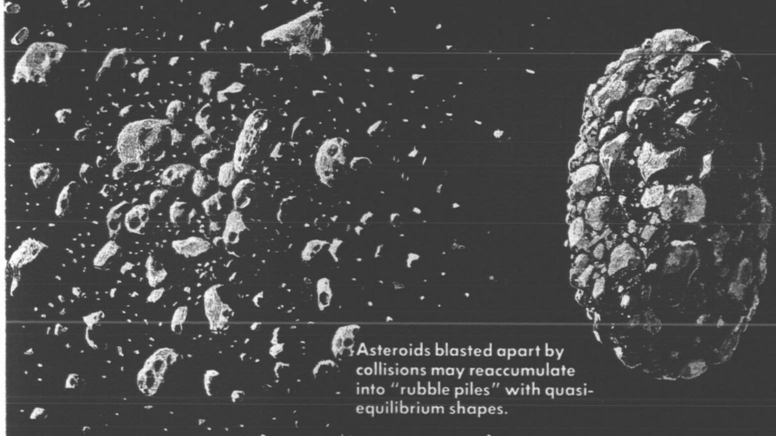
Are the mountains on Venus related to Earth-style plate tectonics? This map by the Arecibo radar telescope shows the Maxwell Montes, which cap the Ishtar continent.

Tiny, frigid Miranda—the innermost satellite of Uranus—exhibits the most exotic geology in the solar system.



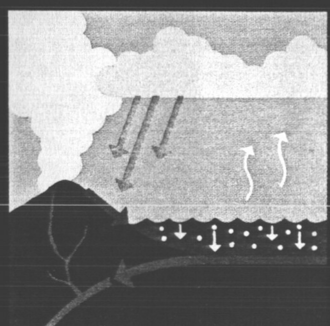
Somehow, Saturn's icy moon Enceladus was geologically active for billions of years, as indicated by the regional erasure of craters in this *Voyager* photo.



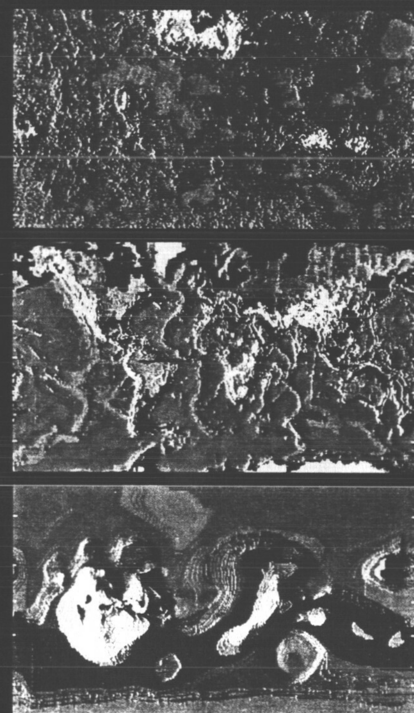


Asteroids blasted apart by collisions may reaccumulate into "rubble piles" with quasi-equilibrium shapes.

Cross-polarized photomicrograph of a Moon rock. There was no more volcanism during the last half of the Moon's history.

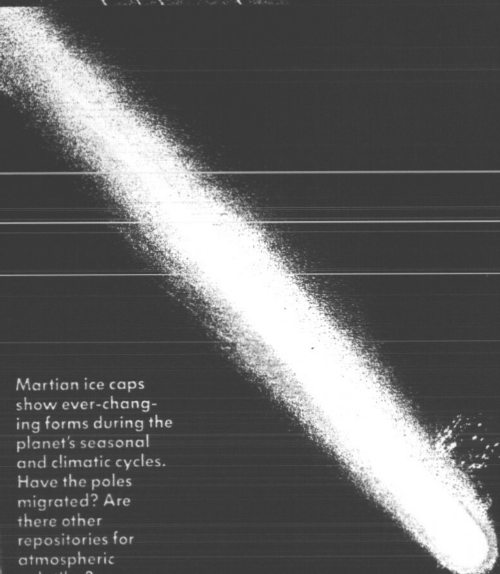


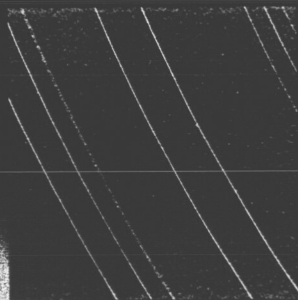
On Earth, rains, weathering, erosion, and sedimentation wash minerals into the seas, where carbonates are precipitated. Then plate motions cycle seafloors through volcanic renewal processes and Earth's geochemical cycle continues. What cycles control the near-surface and atmospheric environments of other planets?

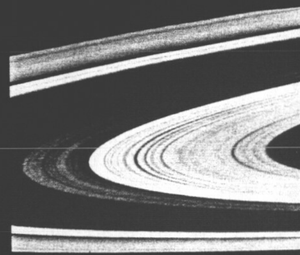


What geophysical processes have shaped the different distributions of highlands and lowlands on Venus, Earth, and Mars?

COMETS







The rings of Uranus and Saturn are controlled by the same dynamical physics, but have superficially distinct appearances.

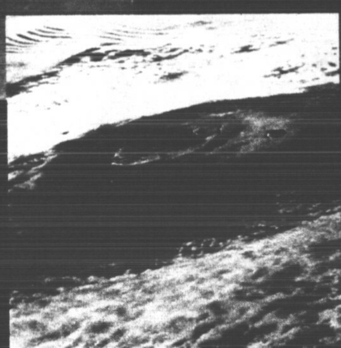
Icy Europa's mysterious crisscrossed surface may be revealed when the *Galileo* spacecraft reaches Jupiter.

OUTER PLANETS

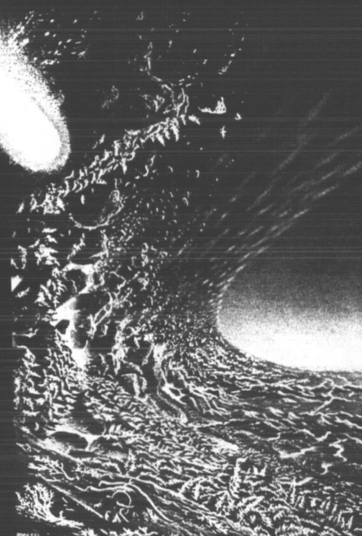
ASTEROIDS

Martian ice caps show ever-changing forms during the planet's seasonal and climatic cycles. Have the poles migrated? Are there other repositories for atmospheric volatiles?

INNER PLANETS



By far the largest known shield volcano in the solar system, Olympus Mons may be the site of the most recent volcanism on Mars. Is it still occasionally active?



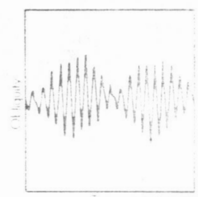
Until very recently on a cosmic time scale, dinosaurs dominated our planet. Then, some scientists believe, the inevitable impact of a modest asteroid or comet changed everything.

THE LAST HUNDRED MILLION YEARS

In the scheme of solar system history, the emergence onto land of Earth's teeming plant and animal life was recent. Planetary exploration has revealed other unexpectedly recent happenings, though not biological ones, on other planets and moons. Volcanism may still intermittently come to life on the slopes of Olympus Mons, the giant Martian volcano. Venus, too, may have active volcanism, with attendant changes in atmospheric chemistry, even weather. Certainly the bare, crisscrossed, icy surface of Jupiter's moon Europa testifies to some process ("water volcanism"?) that still erases craters to this day.

Normally, comets drift in the frigid emptiness of the Oort Cloud, a quarter of the way to the next stars. But occasionally some star or cloud in the arm of our galaxy may stir up a shower of comets that peppers the planets for a few million years. Just one such comet (or was it an asteroid?) may have wreaked such havoc on Earth 65 million years ago that many species of life, including the reigning dinosaurs, failed to survive. The rise of mammals, and eventually human beings, may be traceable to such an accidental passage of a once nearby star.

The Martian polar layers bear witness to dramatic climate cycles on the Red Planet. Its now-thin atmosphere is a way station for carbon dioxide flowing between ice caps and underground reservoirs; with more heating, water may again be temporarily more abundant on Mars. The existence of civilization on Earth is affected by ice ages, ozone variations, and other changes in atmosphere and climate. By studying the weather and climate of Mars we hope to learn more about the general principles of climatology that affect our lives.

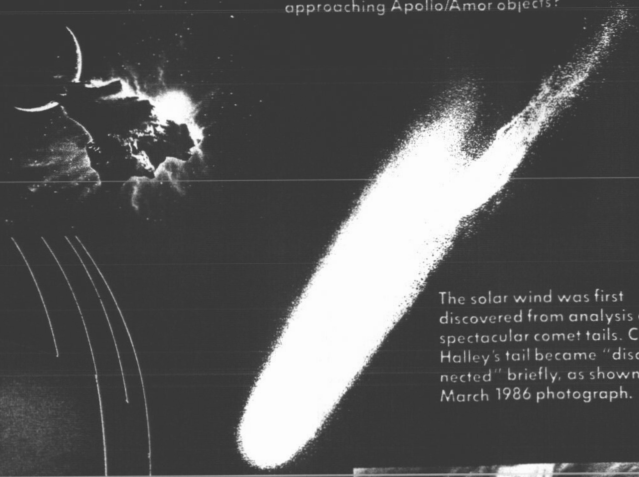


Dynamical oscillations may have induced climate cycles on the planets. The tilt of Mars's axis has oscillated by more than 15 degrees during the last 2 million years.

Our own planet's magnetic field flips direction from time to time. What about the fields of other planets: Mercury's weak Earth-like field, Jupiter's enormous one, the near absence of fields for other bodies, the off-axis field of Uranus? Are they static? Why do they differ? How is our knowledge about Jupiter's invisible interior constrained by the observable structure of its field? Unless it contains abundant sulfur, small Mercury's immense iron core should have solidified long ago, except for a thin outer molten shell; is that sufficient to permit dynamo motions needed to generate its field? Can we learn from the magnetic record in meteorites and Moon rocks, and in planetary rocks to be collected in the future, about now-vanished magnetism in the solar system? If planetary magnetism keeps the solar wind at bay, how might it have affected the development of planetary atmospheres?

COMETS

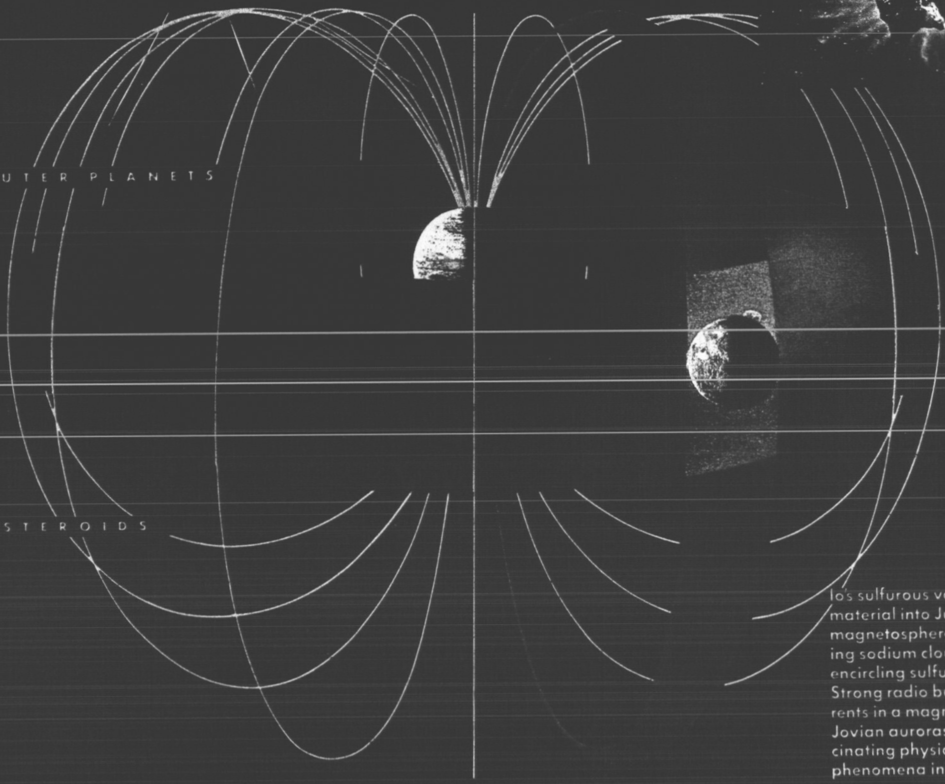
Comet dust continually encounters the planets. Every minute or so, a meteor is visible in our night sky.

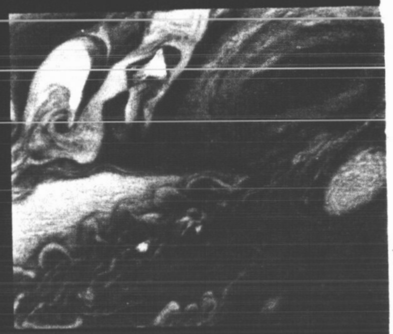


Short-period comets lose their ices after a few thousand passes near the Sun. Do they "die" and become asteroids, like the Earth-approaching Apollo/Amor objects?

The solar wind was first discovered from analysis of spectacular comet tails. Comet Halley's tail became "disconnected" briefly, as shown in this March 1986 photograph.

OUTER PLANETS



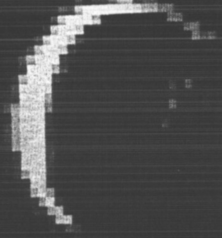


ASTEROIDS

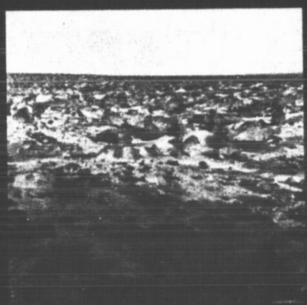
Io's sulfurous volcanoes spew material into Jupiter's immense magnetosphere, resulting in a glowing sodium cloud and the globe-encircling sulfur/oxygen torus. Strong radio bursts, energetic currents in a magnetic flux tube, and Jovian auroras are among the fascinating physical and chemical phenomena influenced by Io.

The Great Red Spot is a giant anticyclone high in Jupiter's atmosphere. Remarkably stable, it has lasted more than 300 years.

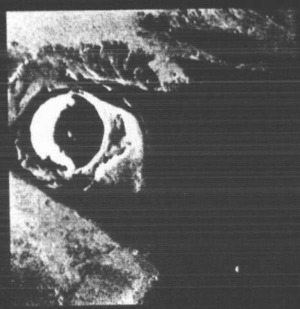
INNER PLANETS



This *Pioneer Venus* false-color image shows atomic oxygen auroral glows on the night side of Venus, within its sunlit crescent.



Early morning frost deposited amid Martian boulders.



Dark wind streaks are formed leeward of crater obstacles during annual global dust storms on Mars.

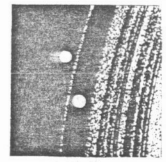
THE PRESENT

The present is a window on the past. For example, the physics of Saturn's ring particles today might teach us how planetesimals behaved long ago; or, if we understood asteroidal collisions, we could strip away their confusing effects to read the ancient meteorite record. But we also wonder how things work *today*: what fundamental laws of nature govern the universe? Our solar system is an extraterrestrial laboratory where we can study unearthly physics, geology, and meteorology. For example, why and just how do spectacular ionized tails stream away from comets?

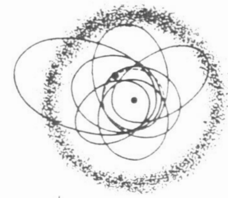
Some planetary processes take long compared with our lives, but are ephemeral on cosmic time scales. Comets, captured by Jupiter into short-period orbits near the Sun, dissipate their ices in a few thousand years, becoming dead comet cores indistinguishable from other Apollo/Amor asteroids. *Voyager's* movies show Jupiter to be a cauldron of dynamic motions that somehow balance between solar heat deposited near its equatorial jet stream and the planet's own global warmth; how can the Red Spot anticyclone have lasted centuries amid such turbulence? Venus's clouds rotate faster than the solid planet: why? *Voyager* found unexpected transient "spokes" in Saturn's rings. Ring particles could be agglomerations that change from week to week. How rapidly do the rings of Jupiter and Uranus change? Are rings of recent origin, or could they somehow date from aeons ago? Scientists model the dynamical and collisional behavior on computers and in laboratories, but we still don't grasp most of the physical principles behind the visual beauty of planetary rings.

Spacecraft data yield surprises, motivate hypotheses, and test and refine our understanding of ongoing processes. A theoretical prediction of Ionian volcanism just before *Voyager's* first Jupiter encounter was but a harbinger of the wonderland of remarkable phenomena to be fathomed as Io, immersed in its cloud of glowing sodium, plunges through Jupiter's magnetosphere: its sulfurous geology, which changes before our eyes; the donut-shaped torus of ions encasing its orbit; the tube of concentrated magnetic field, which carries tremendous electric currents between Io and Jupiter's poles; and Io's effects on Jupiter's radio beacon.

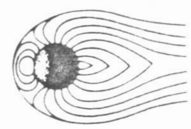
Violent lightning bolts strike Jupiter, and possibly Venus. Dust storms envelop Mars nearly every Martian year. Saturn's satellite Hyperion spins in a chaotic lopsided way that bears theoretical connection to the mechanisms that bring asteroid fragments to Earth. Spacecraft observe transient frosts, atmospheric auroras, and unexpected glows that demand new nomenclature. Planetary processes pique our curiosity, and help us grasp the mysteries of our own existence on Earth.



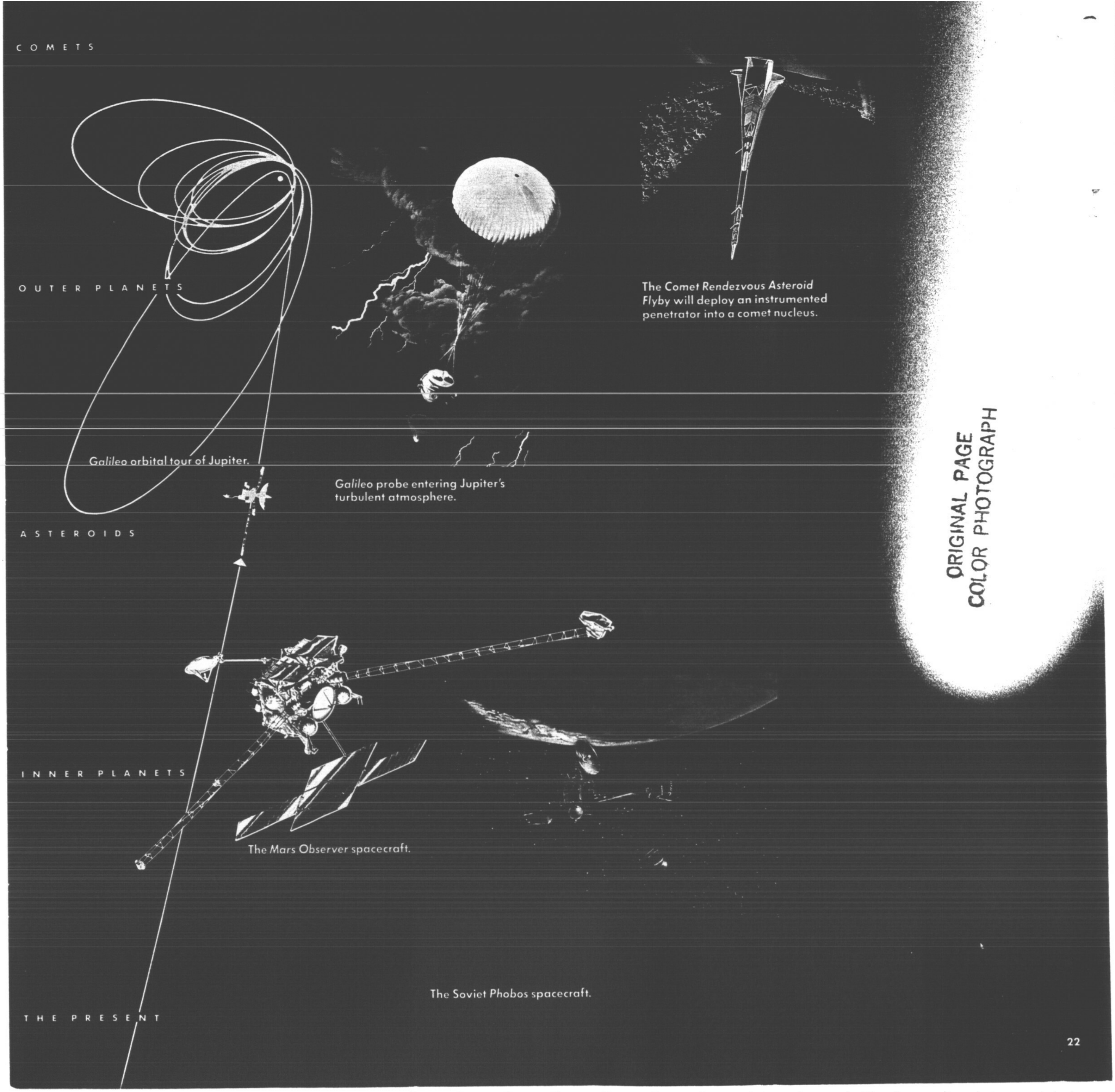
Shepherding satellites confine some of the narrow rings of Saturn and Uranus.



The mathematics of chaos explains the tumbling spin of Saturn's Hyperion, and how meteorites are delivered to Earth from the asteroid belt.



Interaction of the solar wind with planetary bodies yields a range of plasma-physical processes, which not only shed light on planetary environments, but also help us understand analogous astrophysical phenomena.



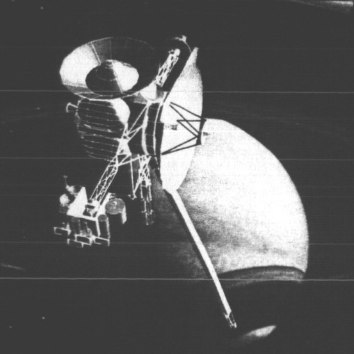
The *Comet Rendezvous Asteroid Flyby* will deploy an instrumented penetrator into a comet nucleus.

Galileo orbital tour of Jupiter.

Galileo probe entering Jupiter's turbulent atmosphere.

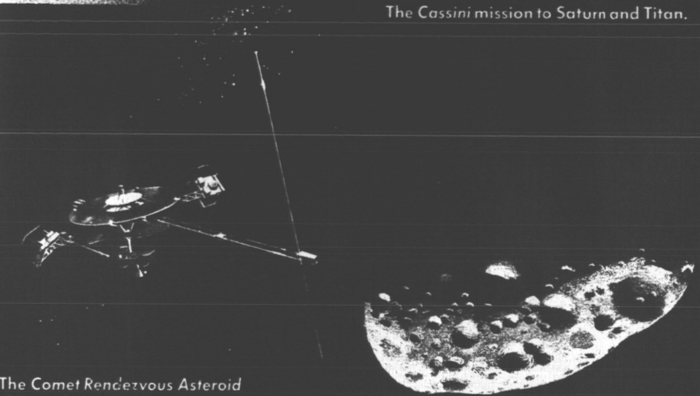
The *Mars Observer* spacecraft.

The Soviet *Phobos* spacecraft.

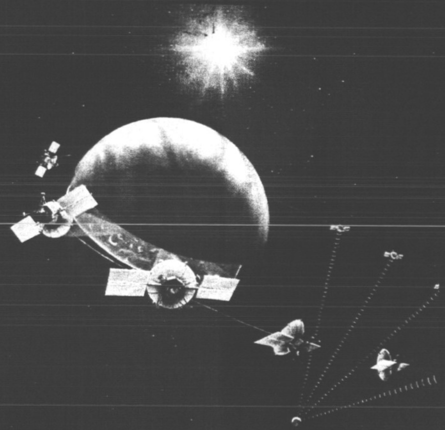


The *Cassini* mission to Saturn and Titan.

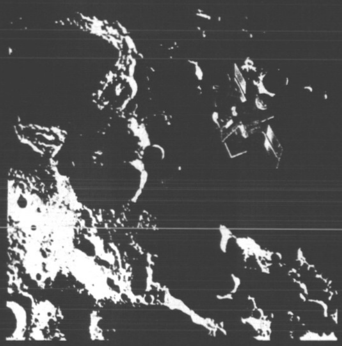
The *Comet Nucleus Sample Return* mission will fly after the turn of the century.



The *Comet Rendezvous Asteroid Flyby* will pass by an asteroid and then will fly in formation with a comet for 1,000 days.



The *Magellan* radar-mapper mission to Venus.



The *Lunar Observer* will study the Moon's geochemical and geophysical properties.

The *Mars Rover/Sample Return* mission.