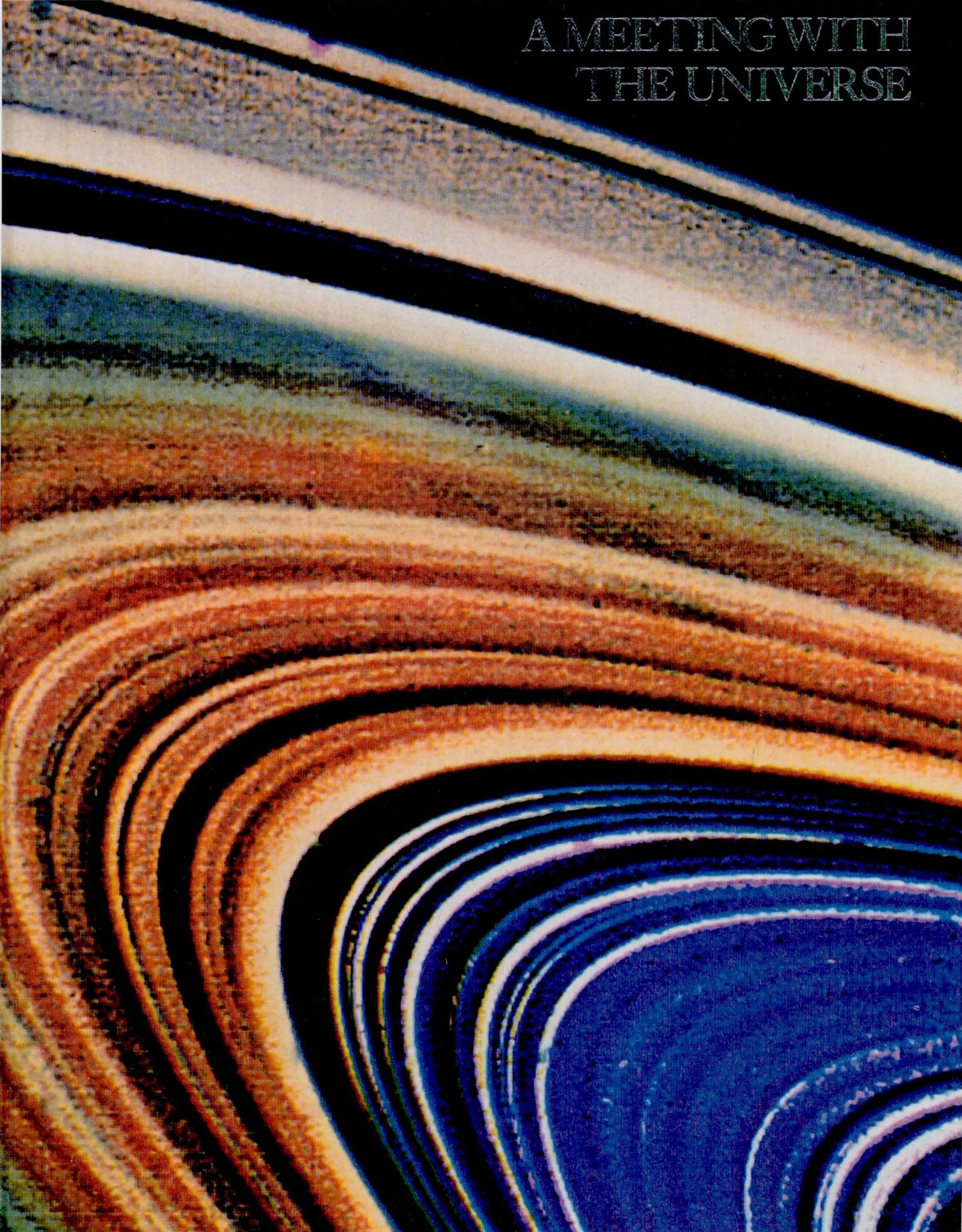
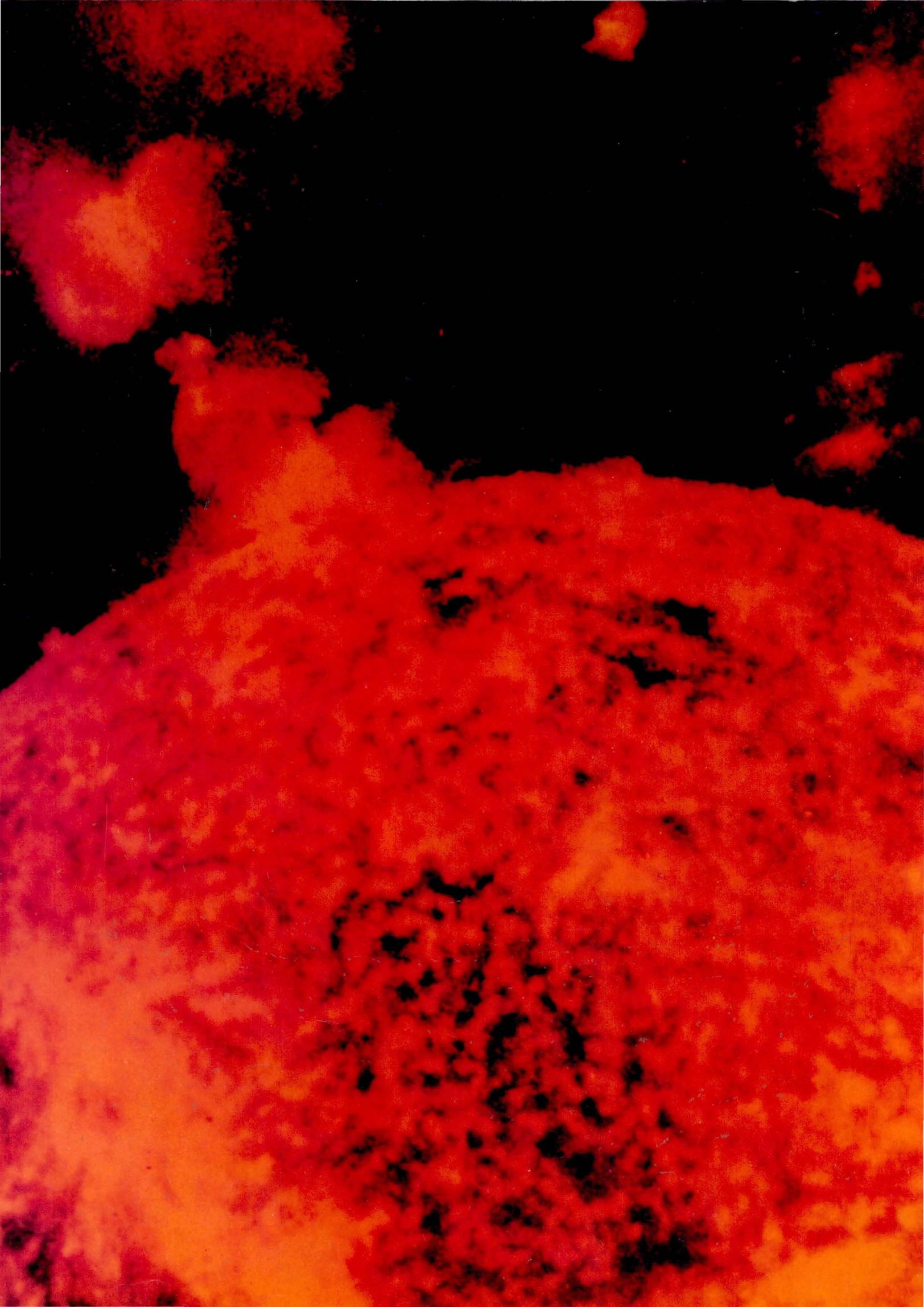
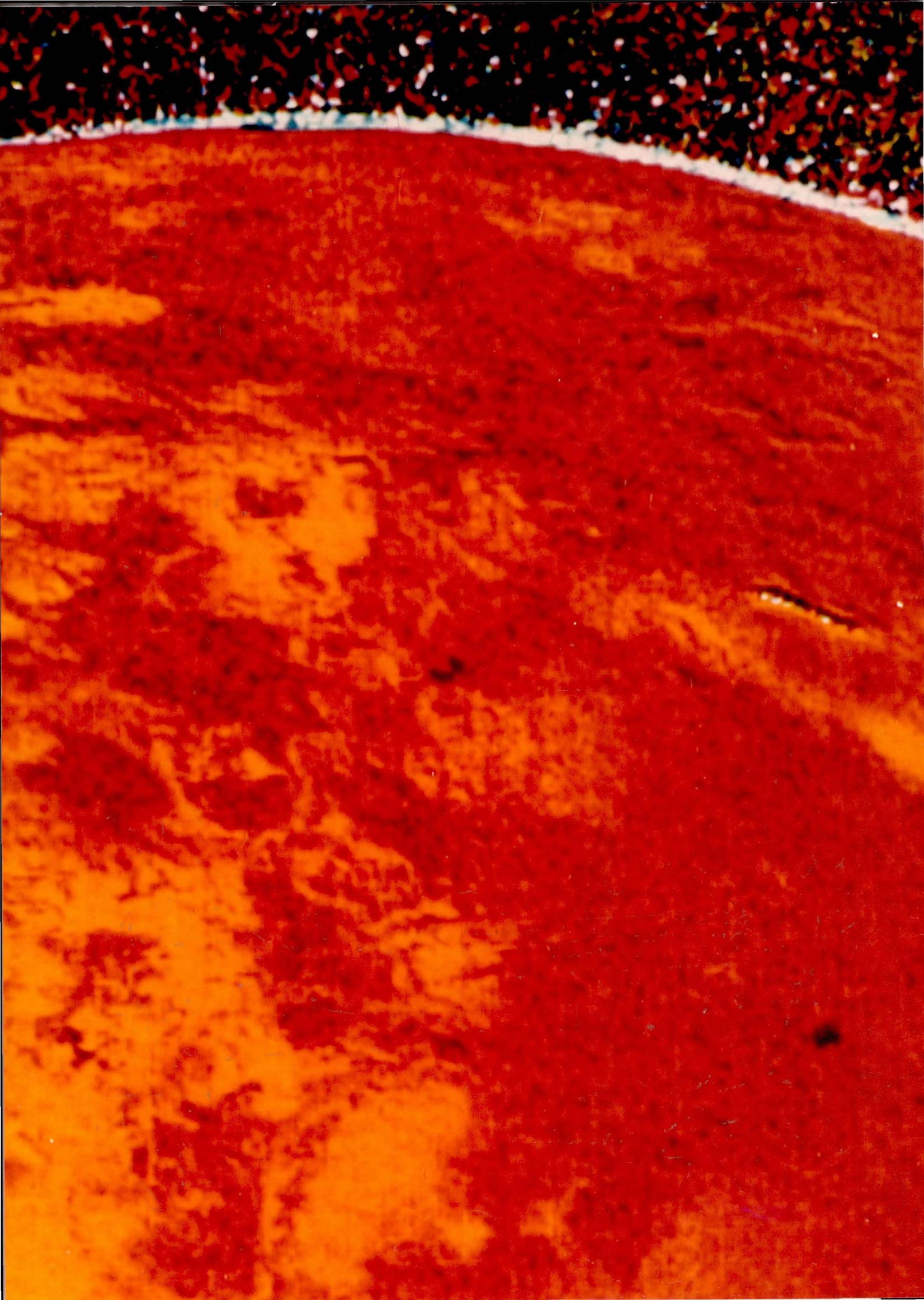
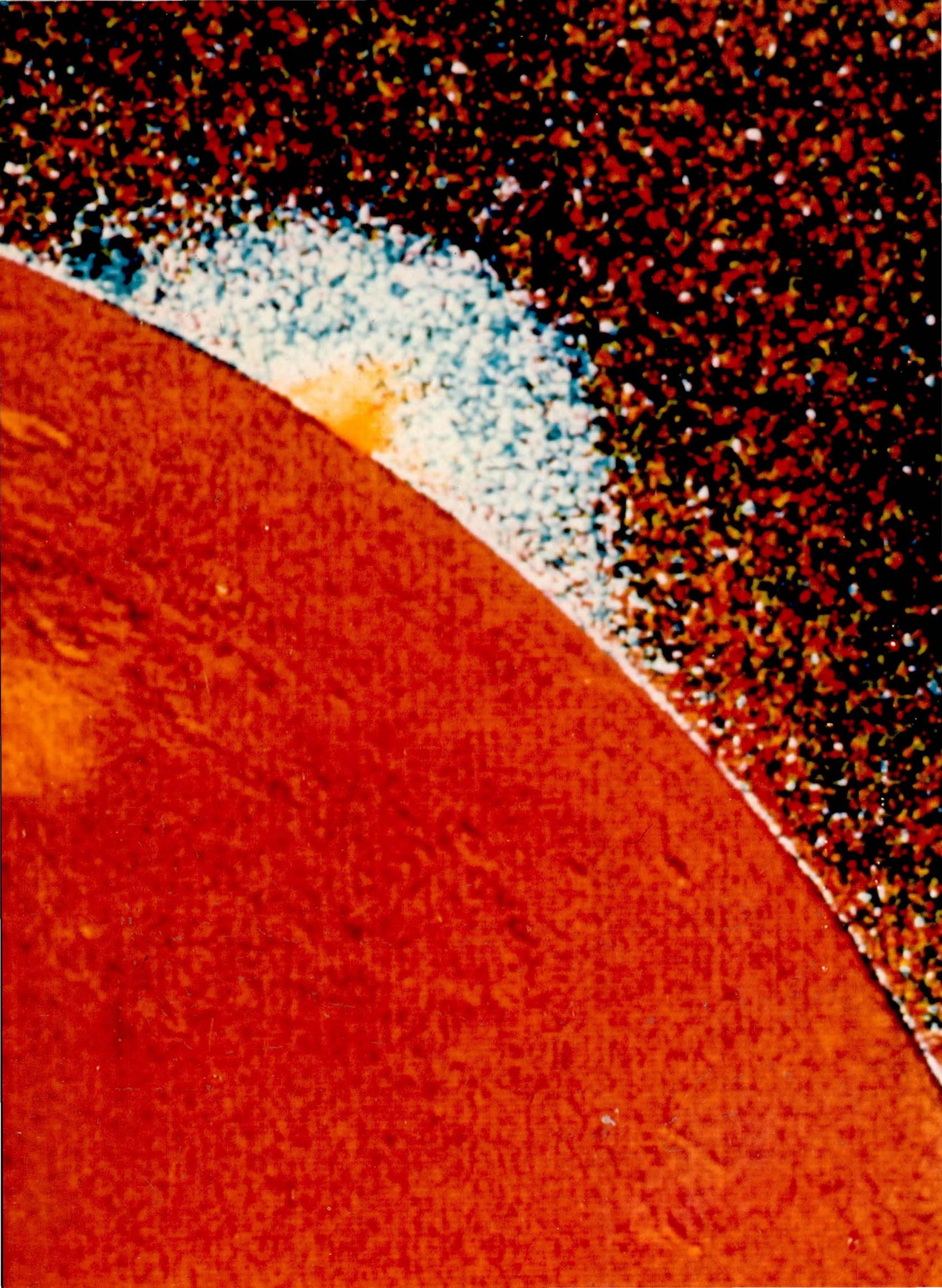


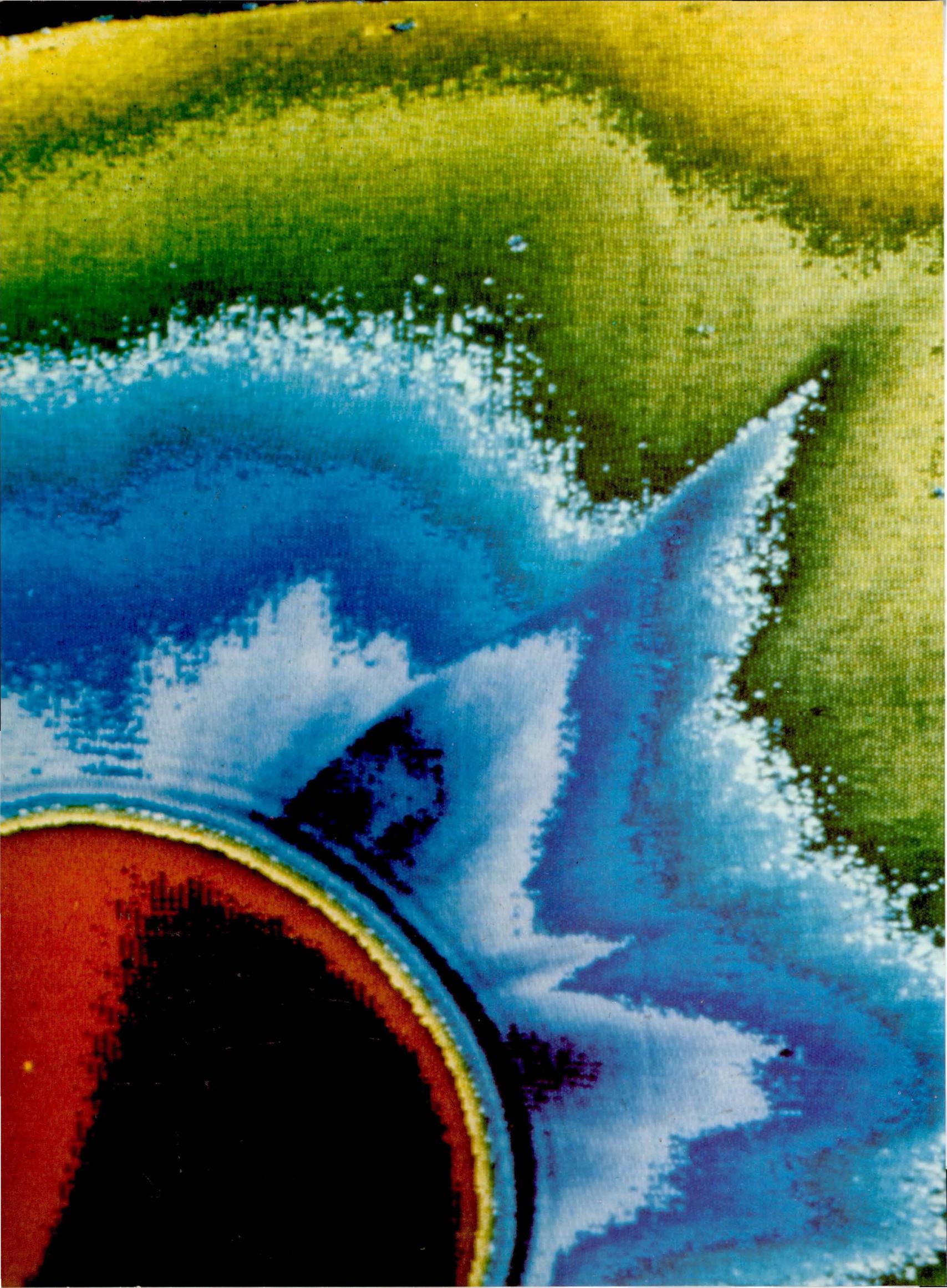
A MEETING WITH
THE UNIVERSE













A MEETING WITH THE UNIVERSE

Science Discoveries from the Space Program

National Aeronautics and Space Administration
Washington, D.C. 20546, 1981

Cover: **Spectacular rings.** Dramatic differences in Saturn's rings are revealed by computer-enhanced colors. The picture was generated from two images transmitted by the interplanetary spacecraft Voyager 2 on August 17, 1981.

Overleaf: **Solar bursts.** Violence at the Sun's limb was photographed from a Naval Research Laboratory rocket on November 4, 1969. Since then, NASA satellites have watched events as the 11-year sunspot cycle bottomed-out, then rose to a notable peak.

Overleaf: **Dwarfing Mount St. Helens.** Huge eruption on Io, moon of Jupiter, outclasses the volcanoes of Earth. The event was photographed by Voyager 1.

Frontispiece: **The Sun in action.** A great eruption on the Sun, here imaged in color by a computer, was observed by the Solar Maximum Mission satellite in 1980. The Sun influences the Earth by means of its visible light and other radiation, outward streaming atomic and subatomic particles, and magnetic phenomena.

A MEETING WITH



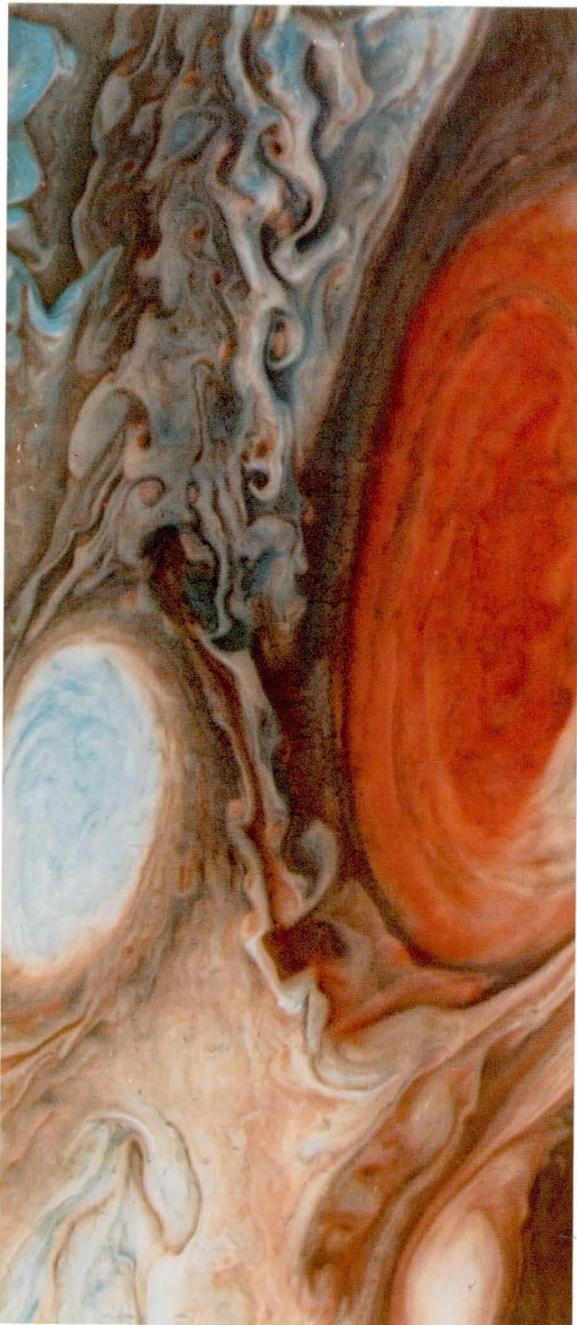
Edited by

Bevan M. French and Stephen P. Maran



NASA EP-177

THE UNIVERSE



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Dedicated to

Thomas A. Mutch (1932-1980)
NASA Associate Administrator for Space Science (1979-1980).

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Preface

People of our generation are participating in one of the greatest events in human history. Life has begun to expand its habitat, this time beyond the Earth. The last such expansion occurred hundreds of millions of years ago, when life came out of the sea to occupy the land. Humans have left footprints on the Moon and analyzed its rocks in their laboratories. Our machines have probed the surface of Mars, while other spacecraft have shown us giant Jupiter and ringed Saturn.

In past explorations, a few hardy souls ventured out, while the rest waited for months or years to hear what they had found. In the Space Age we are all explorers. Through the miracles of modern communications we have watched together as these new worlds have been revealed. Simultaneously around the world, we have seen the volcanoes of Io, counted the many rings of Saturn, and learned of Titan's cold, unworldly landscape.

The Space Age is an era of exploration, discovery, and scientific achievement without parallel in history. We have reached not one, but more than a dozen new worlds. We have observed an invisible universe with our X-ray and infrared telescopes. We are observing

our Sun with an increase in clarity comparable only to that achieved by Galileo with his first telescope. We are now studying the interactions that link our world—and its future—to this star. Beyond the Sun, we see a strange new universe of incredible, unexplainable energies, and we have heard the barely audible whisper left from the Big Bang that started it all. We have begun to understand our origin and to search for companions in the universe.

A Meeting with the Universe is the story of what we learned about the universe and ourselves by going into space. It is not a textbook for scientists. It is written for everyone who shared the excitement and wonder of the last few years—students, teachers, scientists, engineers, other professional people, and curious citizens of all kinds. It is not a NASA history. It is a history of space exploration—by NASA, by universities, by other government agencies, and by industries—all of whom have played major roles. We have not attempted to apportion credit here; space has been studied by many, and the discoveries belong to us all.

The book itself is a novel experiment in writing about science

for non-scientific readers. It was not produced by science writers or journalists, but written and edited entirely by a group of NASA scientists, all of whom are deeply involved in space science activities and many of whom actively participated in the discoveries they describe. The success of the experiment in producing a readable and exciting book reflects the skill, perspective, dedication, and downright enthusiasm of the writers and editors. Special thanks are also due to the reviewers: Kathleen Roedder (Public Library of the District of Columbia), Janet Wolfe (National Air and Space Museum), and Mary-Hill French.

We are now at a watershed in space. After 20 years of challenging and exciting activity, we have done most of the easy things and made most of the obvious discoveries. What do we do next? How do we tackle the many new questions that have arisen about the Sun, the Earth, the other worlds, the universe around us, and ourselves? These are not just scientific questions. Their answers involve the understanding of the Earth's geology, its weather, and its climate—factors that will affect the survival of our civilization, perhaps even

of our species.

Other important questions are taking form in scientific discussions and in public debates. What shall we do with our new domain of space? When will we establish permanent, self-sustaining human habitations on the Moon, on Mars, or in space itself? How will we establish these habitations? What role will machines and what role will humans play? When will we begin to use extraterrestrial resources in space and on Earth? We are acquiring the information and the technology to discuss these questions in detail and to develop plans for moving ahead—when we choose to.

“Where there is no vision, the people perish,” says the Bible.

Although we have only begun our movement into space, we have already traveled far and seen much. We have a shining vision of the universe and our future in it. Without that vision, without the will to follow it, something important in us—perhaps we ourselves—will perish.

Dr. John E. Naugle
Chief Scientist
NASA

THE CLIMB INTO SPACE

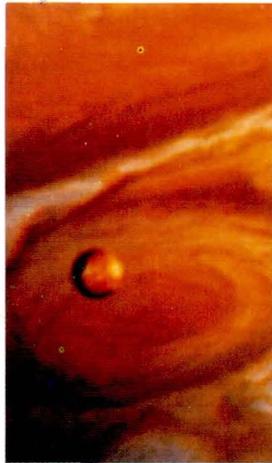


Chapter 1

3 The Quest for Answers

5 The Unfolding Universe

THE NEW WORLDS



Chapter 2

12 A New Solar System

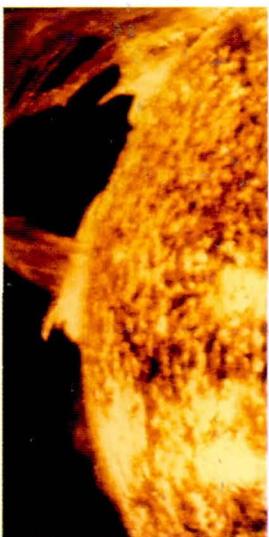
15 The Terrestrial Planets

28 The Gas Giants

51 Minor Objects in the Solar System

58 The Planetary Connections

THE SUN AND EARTH IN SPACE



Chapter 3

66 The Sun and Us

68 The Nature of the Sun

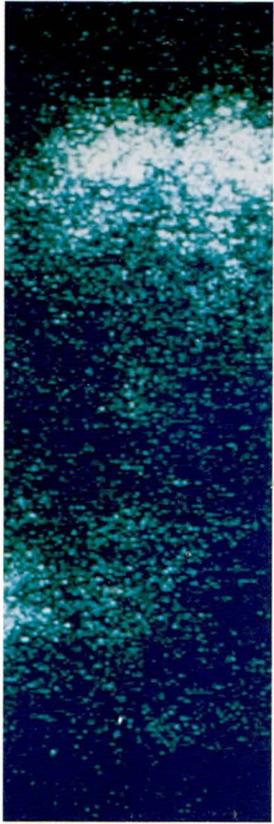
75 The Sun in Space: Magnetic Fields and the Solar Wind

80 The Magnetosphere: Our Shield in Space

84 The Sun-Weather Connection

86 Where Do We Go from Here?

BEYOND THE SOLAR SYSTEM



Chapter 4

- 90 *New Windows in the Sky*
- 91 *The Scale of the Universe*
- 93 *The New Astronomy*
- 95 *Life-Styles of the Stars*
- 100 *The End of Stars: Death and Transfiguration*
- 105 *“Empty” Space: The Birthplace of Stars*
- 108 *The Galaxies: Islands of Stars*
- 114 *Quasars and the X-Ray Background*
- 117 *The Edge of the Universe*
- 120 *What’s Coming*

THE HUMAN ELEMENT



Chapter 5

- 124 *Our New Domain*
- 126 *Weightlessness*
- 137 *Ionizing Radiation*
- 138 *Conclusion: We Can Go On*

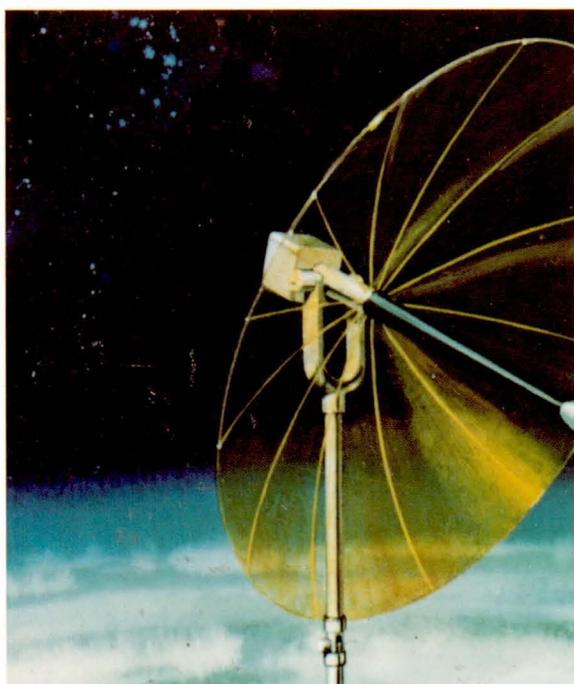
LIFE IN THE UNIVERSE



Chapter 6

- 146 A Universe of Life*
- 149 Life in the Solar System*
- 152 The Chemicals of Life*
- 155 The View from Earth*
- 158 Things to Come*

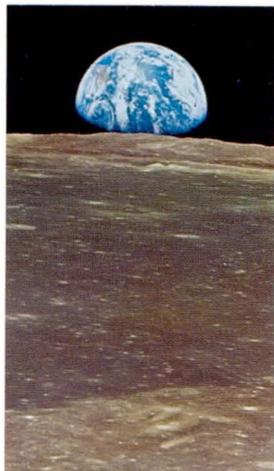
THE LONG CLIMB AHEAD



Chapter 7

- 162 The View from the High Ground*
- 163 The Worlds that Wait*
- 169 The Sun, the Earth, and "In Between"*
- 172 The Violence Around Us*
- 177 Return of the Humans . . .*
- 178 . . . And Others?*
- 180 Space Science on the Ground*
- 181 The View Ahead*

APPENDIX



184 *Lunar Exploration*

188 *Planetary Exploration*

204 *Solar-Terrestrial Physics*

208 *Astrophysics*

214 *Biomedical Research*

216 *Exobiology*

217 *Index*



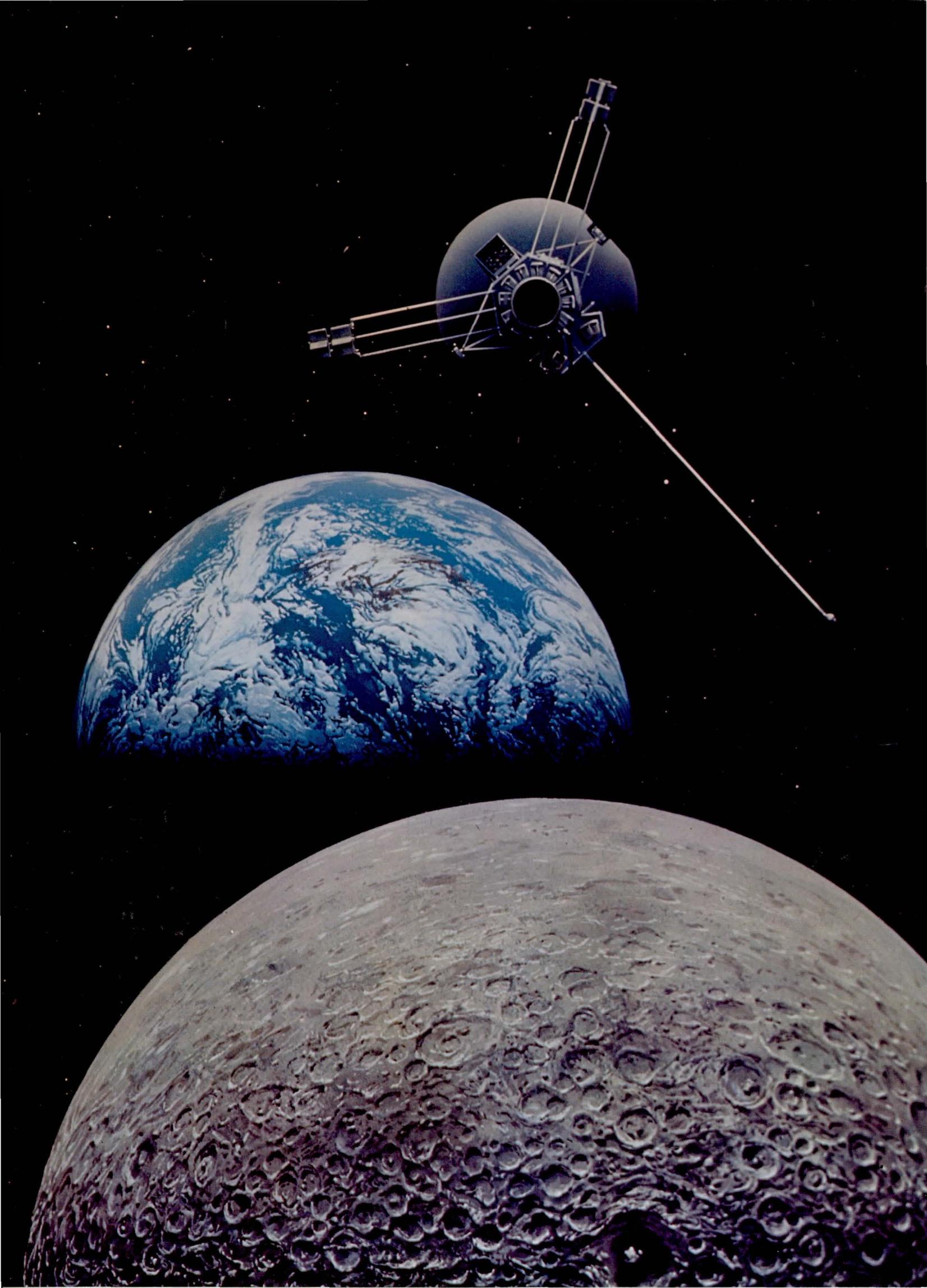


Chapter 1

THE CLIMB INTO SPACE

Bevan M. French

"We came in peace for all Mankind." The centuries-old "impossible dream" of humanity became reality on July 20, 1969 as human beings from the planet Earth first set foot upon another world—our Moon. The landing of Apollo 11, and the missions that followed it, began a new era in human exploration; we could now study new worlds close up and bring back samples of them to study in our laboratories. Here Apollo 17 astronaut Eugene Cernan stands in the Moon's Littrow Valley, flanked by an American flag and by the radio antenna of the astronauts' Lunar Roving Vehicle.



The Quest for Answers

Questions, questions, questions . . . Human beings don't accept things as they find them. They ask questions, and they search for answers. What am I? Where am I? What is my past? What is my future? From earliest childhood, people want to know things. Why is the sky blue? What makes the Sun shine? What is the Moon made of? What are the stars?

Curiosity drives us to explore our surroundings. We want to see the unseen and to learn what lies over the next hill. People have always been bothered by blank areas on the map or in the mind, and they have studied and worked and striven and sometimes died to fill them in. Over the centuries, the urge to explore has taken human beings into unknown and unreachable places: to the New World, the South Pole, Mount Everest, and the Moon. The same urge has carried the human mind outward into the realm of the galaxies and into the microscopic domain of subatomic particles.

These explorations have always been profitable. They have produced tangible riches: gold, new lands, beneficial trade, and profitable technological advances. More important is the knowledge gleaned: a better understanding of our world, its mechanisms and processes, and the basic natural laws that govern them. It is knowledge, much more than riches, that makes modern civilization possible.

When we think of exploration, we think of individuals: Marco Polo, Columbus, Lewis and Clark, Lindbergh, Neil Armstrong. But great explorations have also been an important part of the character of nations. To search for something new is an expression of a nation's confidence and enthusiasm, of its ability to organize and its willingness to innovate. It is no coincidence that the New World was discovered at the height of the Renaissance, nor that the colonization of North America accompanied the rise of Elizabethan England. In our own time, the Apollo Program manned landings and exploration of the Moon were the American response to the challenge of competition in the new ocean of space.

Outward bound to the stars. In this artist's view of Pioneer 10, launched from Earth in 1972, the spacecraft makes a close passage of the Moon as it follows a path toward the giant planet Jupiter. The blue, cloud-covered Earth is in the background. This view shows the Moon's heavily cratered far side, highlighted by the dark crater Tsiolkovsky. Pioneer 10 will never return. After its encounter with Jupiter in 1973, Pioneer 10 was moving fast enough to escape from the solar system entirely. It is the first human artifact sent out to roam among the stars, a calling card announcing our existence to any other intelligences in the universe.

The exploration of space may be only the latest episode in the long human history of wondering and seeking, but the sudden explosions of travel, new sights, and scientific discovery exceed anything that preceded them. New worlds have been discovered, not one by one, but by the dozen. Human beings have explored and sampled the Moon. Robot laboratories have dug into and analyzed the surface of Mars. The video eyes of our spacecraft are providing close-up views of planets never seen by the ancients, and more than a dozen moons have emerged in our consciousness from tiny points of light to unique, mysterious, and changing worlds.

Great as these steps have been, they have occurred in a remarkably short time. Only a single generation separates the flight of *Sputnik 1* from the first spacecraft pictures of Saturn's moons; the first geologist to explore the Antarctic is still around to talk with the first geologist to go to the Moon! Thanks to modern communications, all of us have shared in these voyages to an extent never possible before. Less than 100 people witnessed Columbus' landfall in the New World; half a *billion* watched on television as Armstrong and Aldrin stepped onto the Moon.

We have flown into space, but from this high vantage point we still feel as curious as an earthbound child. How did the universe form? How will it end? How was the solar system created? What are the other planets really like? What lies in deep space beyond the Sun? How did life originate? Is there other life out there? In the last generation, we have come a long way toward the answers. But we still have farther to reach, more questions to ask, and much more to learn. Like earlier explorers, we have painfully struggled to a high plateau from which we see new mountains and valleys beyond. The answers to our questions, the benefits from the new knowledge, still lie ahead, out of sight, but no longer out of reach.

"Liftoff! . . . We have liftoff!" A Delta rocket slowly rises from its launch pad to carry yet another payload into space. The development of rocket boosters powerful enough to overcome the gravity of our own planet was a critical step in the scientific exploration of space. This launch in 1975 placed an Orbiting Solar Observatory spacecraft (OSO-8) in orbit above the Earth to make scientific observations of the Sun.



The image shows a tall, dark, lattice-structured tower or launch structure against a bright, cloudy sky. The tower is positioned on the left side of the page, extending from the bottom to the top. The sky is filled with soft, white clouds, and the overall lighting is bright and somewhat hazy, suggesting a sunrise or sunset. The tower has a complex, skeletal appearance with many cross-braces and rungs.

The Unfolding Universe

Only 500 years ago, the universe seemed simple, orderly, peaceful, and well-understood. The Earth stood motionless at the center. The Sun, Moon, and planets circled it at no great distance. Slightly further away, the fixed stars were tiny points of light mounted on a sphere of pure crystal. It was a small, comfortable, and reassuring universe, and Man was at the center of everything.

In only a few centuries, the scale of the solar system and of the universe expanded incredibly as a result of investigation and study. The telescope and the Copernican theory replaced the Earth with the Sun at the center of the solar system. The five wandering lights (called *planetes* by the Greeks) became individual worlds. New discoveries in physics and spectroscopy made it possible to analyze and even weigh the distant stars. Still larger telescopes moved the Sun from the center of things to the fringes of the Milky Way galaxy, a huge system of 100 billion or more stars. Then the Milky Way became only one of billions of galaxies in an expanding universe. New telescopes, sensitive to radio waves, probed the universe, discovering strange objects and powerful sources of energy that our eyes could never see.

When we suddenly entered the Space Age with the launch of *Sputnik 1* on October 4, 1957, we broke through the last two barriers to our exploration of the universe: gravity and air. We now could escape from the pull of Earth's gravity, in which we had spent all of history, and reach other worlds. Astronauts and machines could stand on other planets, study them at close range, and bring back samples to analyze on Earth. Robot spacecraft could fly past other worlds, sending back closeup video pictures that brought distant planets closer to us than our own Moon.

With the Space Age, a second barrier fell away: the blurring and dimming caused by the Earth's atmosphere as we look outward from the ground. Out in space, instruments and human eyes could see the universe directly in all of its incredible violence, immensity, and variety.





Looking back at the launch of *Sputnik 1*, we realize how much that we take for granted now—only a generation later—was unknown and in many cases not even suspected then. In the universe of 1957:

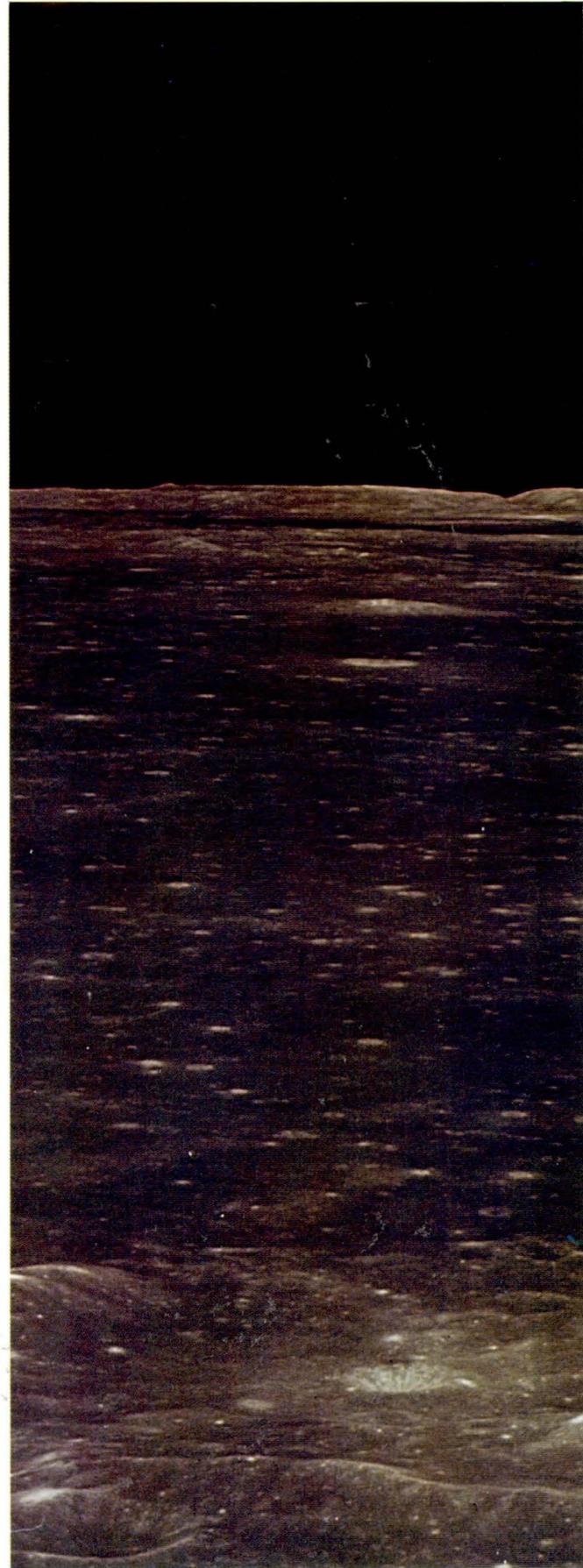
- *The Sun seemed a basically stable, steadily shining star.*
- *Mercury and Venus were just blurs in the telescope; there was no information on their remarkable geologic features.*
- *No one knew that the Earth was surrounded by belts of trapped radiation.*
- *Mars, some astronomers thought, had “canals”; perhaps it sheltered some form of life as well.*
- *The moons of Jupiter were no more than points of light, hardly more visible than they were to Galileo when he discovered them in 1610.*
- *Among the planets, only Saturn was known to have rings.*
- *Pluto had no known moon; the planet’s size and mass were hardly more than matters of conjecture.*
- *The only known volcanoes were those on the Earth.*
- *No one knew what a moon rock was like; no one had touched or studied one.*
- *Chemists had found traces of the origin of the solar system in meteorites, but no clues to earlier events.*
- *Black holes and neutron stars were creatures of the physicist’s imagination.*
- *No one had even speculated that such objects as quasars and pulsars might exist.*
- *The “Big Bang” was just one of several theories for the origin of the universe; it seemed unlikely that evidence to clearly discriminate between them would be found.*
- *No one had gone into space.*
- *It was widely doubted that human beings could survive and work in space, given the dangers of radiation, weightlessness, and meteorites.*
- *Among science fiction writers, few predicted that there would be a man on the Moon before, say, the 1990’s.*

An ear for the universe. *The dish antenna of a large NASA radio telescope located at Madrid, Spain is outlined against the sunset sky. The antenna is 64 meters (210 feet) in diameter. It is used to track interplanetary spacecraft, to send commands to them, and to receive from them the radio signals that carry scientific information and pictures of other worlds. Other, even larger, radio telescopes analyze radio waves from distant stars and galaxies. Radio telescopes have even detected a whisper of noise from the edge of the universe, an echo of the Big Bang that formed the universe 15 to 20 billion years ago. Radio telescopes like this one could also be used to detect extraterrestrial life—by listening for the communications of other civilizations in space.*

During a single generation, astronomers and space scientists have compiled a remarkable list of accomplishments and discoveries. Other planets have become individual, familiar worlds that we can see and touch, at least with the aid of remotely-controlled instruments. We have analyzed crystals from the Moon, measured the winds of Mars, and seen the violence of the volcanoes erupting unexpectedly on Jupiter's moon, Io. We have seen our own Sun in a new "light" –X-rays and ultraviolet– and have gained new insights into the character of this star that makes life possible. We have sensed the turmoil in the huge, violent universe beyond: incredible energies and fantastic objects such as quasars, pulsars, and black holes. We have even caught the whisper of creation, the tiny echo of microwave radiation from the moment, billions of years ago, when the new universe was just expanding from the Big Bang.

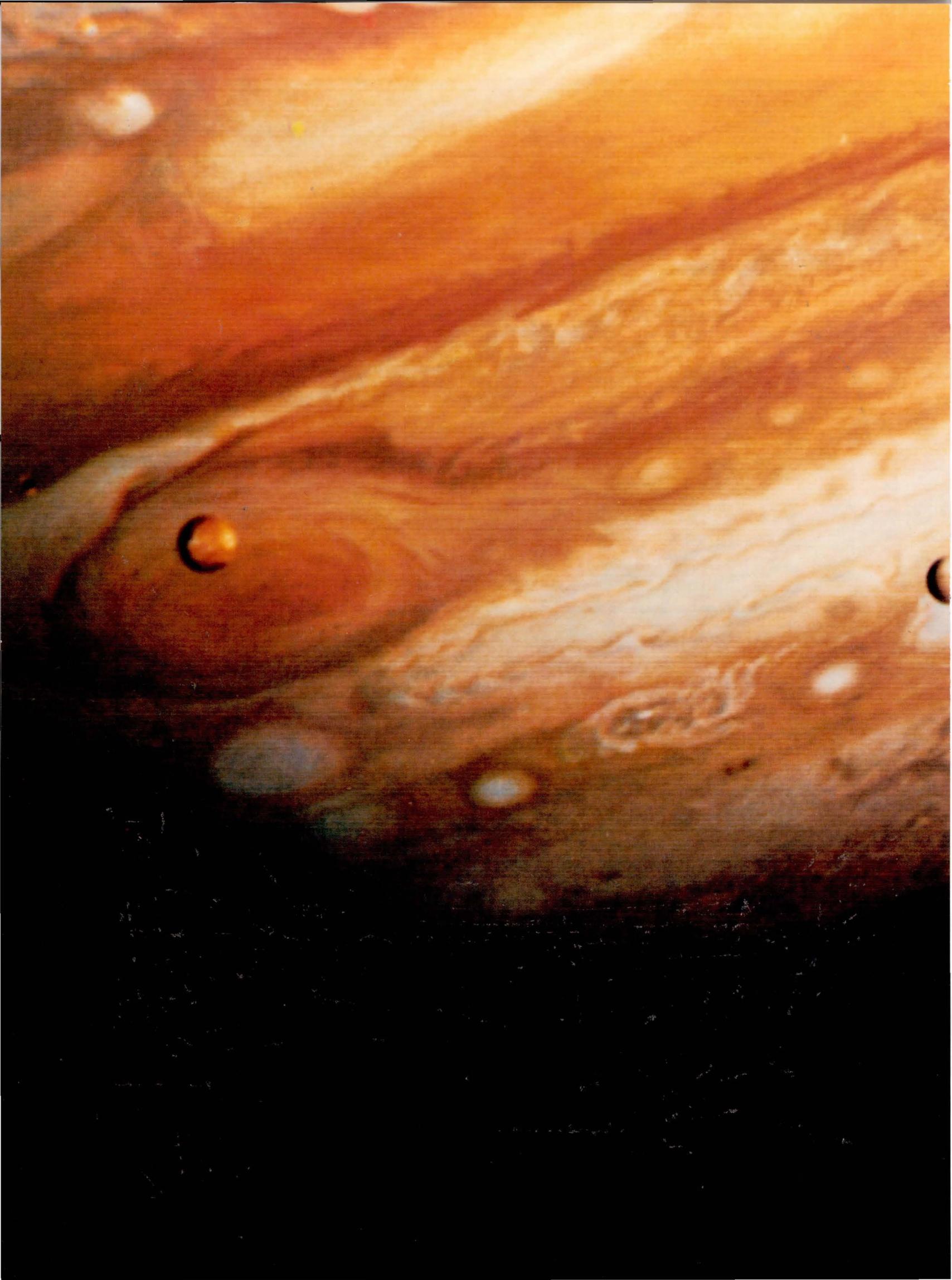
We have also gained a new viewpoint on ourselves and the Earth. We have found our own origins in the stars: carbon compounds in meteorites, organic molecules in interstellar space, the calcium and iron in our bodies that came from stars that died before the Sun was born. We have a new view of the Earth: a small, blue, habitable island in a vast, forbidding blackness. By studying the life-styles of other worlds, we are learning more about our own: its history, weather, climate, all the circumstances and conditions that are critically important, not only to science, but to our survival.

In a single generation, we have learned more about the cosmos than we did in all the centuries that went before. It seems almost unbelievable that we have been able to discover so much about objects so huge, so ancient, so complex, and so far away. Yet all this knowledge is just the basis for new explorations, discoveries, and understanding. Our current view of the universe probably is no more permanent than were the ideas people had five centuries ago. It will change just as radically as did the old concepts, as we do more and see further. All that we have done is yet a beginning, and future generations may regard our view of the universe with the same amused tolerance that we reserve today for the ancients' crystal sphere.





***The Big Blue Marble.** Earth, the home planet of humanity, rises above the scorched and cratered surface of the Moon in this photograph taken from the Apollo 11 spacecraft shortly before the astronauts set foot on the Moon. In addition to making it possible for us to see new worlds, the Space Age gave us a new view of our own planet. Astronauts, poets, writers, and average people alike were struck by the image of the Earth as a tiny, blue, hospitable, life-bearing world, floating in a vast uncaring blackness, side-by-side with the battered and lifeless Moon.*



THE NEW WORLDS

Bevan M. French

King of the planets. *Giant Jupiter, with its Red Spot and banded, turbulent atmosphere, looms awesomely behind two of its moons in this view taken by the Voyager 1 spacecraft from about 20 million kilometers (12 million miles) away. The moons, each about the size of Earth's Moon, are dwarfed by the planet, which is large enough to contain more than a thousand Earths. Even at this distance, details of Jupiter's turbulent atmosphere are visible. Io, the moon at the left, is in front of Jupiter's Red Spot. This moon's orange color may be due to sulfur compounds erupted from its active volcanoes, discovered as Voyager flew past. Europa (at center) is a whitish moon. Its surface is probably a thick icy crust overlying a rocky core.*

A New Solar System

To the ancients, the solar system consisted of a few worlds wandering through a limited region of empty space. To us, it is a huge region containing uncountable bits of solid matter and filled with great magnetic fields and streams of electrically-charged atomic particles from the Sun. One of the most visible and exciting activities of the Space Age has been the detailed exploration of this astonishing collection of matter and energy around the Sun. The inventory of solid bodies in the solar family is impressive: nine planets, at least thirty-nine moons, thousands of tiny asteroids, billions of comets, and vast numbers of meteoroids and small particles of cosmic dust.

In recent years, many spacecraft have explored the planets and their moons: over two dozen of these worlds have been studied at close range. This exploration is not a random process. It proceeds in systematic stages, each stage built on the results of earlier ones. First, there are the reconnaissance or "flyby" missions such as those to Mercury, Jupiter, and Saturn. Next come exploration missions, carried out by orbiters and landers on the Moon, Mars, and Venus. Finally, there is a stage of intensive study, involving astronaut landings and sample return, which thus far have been accomplished only on the Moon.

As of now, we have made intensive studies of only the closer worlds. Our spacecraft have not been powerful enough to push us very far out from Earth or very far inward toward the Sun. For this reason, most of our missions, especially the earliest ones, have involved the nearest worlds: the Moon, Venus, and Mars. We have only briefly surveyed Mercury, Jupiter, and Saturn. Although one interplanetary probe, *Pioneer 10*, has passed the orbit of Uranus, the outer planets beyond Saturn are completely untouched.

Even current plans involving definite missions include only a possible *Voyager 2* flyby of Uranus in 1986. To return inward to survey Mercury in greater detail than heretofore, or to go outward to study the outermost planets, we will need more powerful spacecraft than exist today.

According to current theory, the Sun and planets formed together in the collapse of a vast cloud of interstellar dust and gas (the *protosolar cloud*) about 5 billion years ago. The central part of the cloud collapsed to form the Sun, and the planets condensed in orbits around it. One feature of the solar system that all the theories have to take into account is that there are two basically different kinds of planets: the solid *terrestrial planets*, like the Earth, and *gas giants*, like Jupiter and Saturn.

The terrestrial planets (Mercury, Venus, Earth, and Mars) lie in the inner solar system, close to the Sun. They take from almost three months to almost two years to orbit around it. They are relatively small, from less than 5000 kilometers to almost 13,000 kilometers (less than 3100 miles to almost 8100 miles) in diameter, and they are solid and rocky, as if they had formed in a hotter part of the original dust cloud from which most of the gases were lost. The samples we have from the Earth, the Moon, and meteorites suggest that all the terrestrial planets are composed largely of fairly heavy elements such as silicon, aluminum, calcium, magnesium, iron, and others, combined with oxygen to make solid minerals and rocks.

Despite their common composition, the terrestrial planets are very different. Consider their atmospheres: Mercury has none, the Earth and Mars have modest atmospheres, and Venus has air so thick, dense, and cloud-filled that it forever conceals the planetary surface. The magnetism of

terrestrial planets also varies strikingly. The Earth has a fairly strong magnetic field, Mercury has a weaker one, and Venus and Mars apparently have none at all. Even more curious, the rates of rotation vary widely: Earth and Mars each spin on their axes in about one day, but Mercury takes two months to rotate once and Venus takes a full eight months. (Venus also rotates opposite to the direction of rotation of the other planets.)

The critical chemical water (H_2O) varies greatly among the terrestrial worlds. The Earth has vast quantities of liquid water, so much so that it often is referred to as "the water planet." Mars has a much smaller amount, present as ice. Venus may have almost none; only a trace of water has been found so far in its atmosphere. No water has been found on the Moon or in its rocks, although some scientists speculate that frozen water may exist in permanently shadowed regions near the lunar poles. A final mystery is that life, so far as we know, exists and has existed only on the Earth.

Further out in the solar system are the gas-giant planets: Jupiter, Saturn, Uranus, and Neptune. Great globes of dense gas, with little or no rocky material, they formed in cooler parts of the protosolar cloud, so gases and ices were preserved. These planets take from almost 12 years to almost 165 years to circle the Sun, but they spin on their axes remarkably rapidly, in 10 to 16 hours, rather than in days or months.

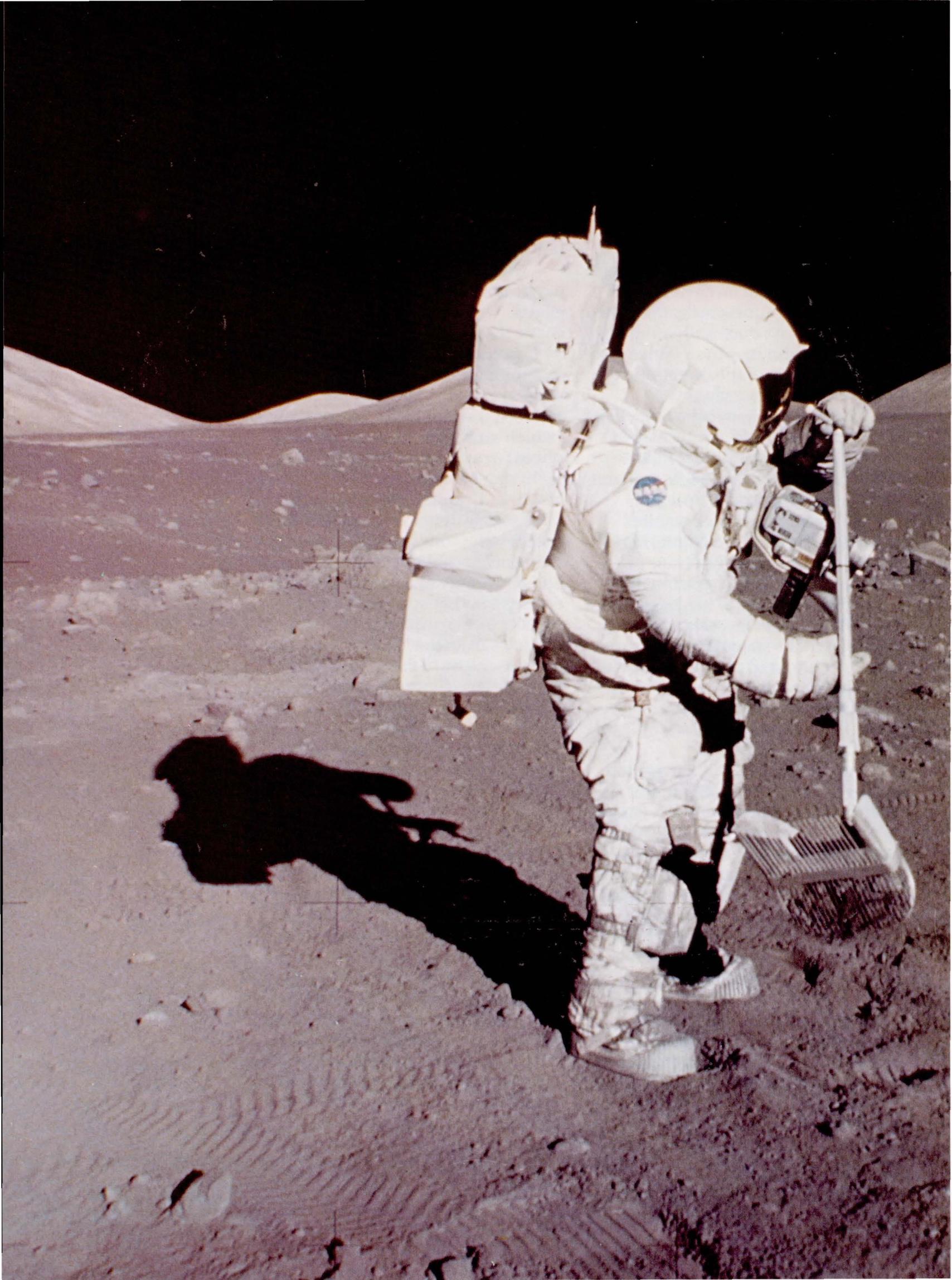
The giant planets are virtually all atmosphere. On Jupiter and Saturn, we see spectacular banded patterns of swirling, brilliantly colored clouds. At high altitudes, the clouds probably are composed of frozen ammonia crystals; in effect, there is a high layer of ammonia clouds like the high-altitude cirrus clouds of Earth. At lower alti-

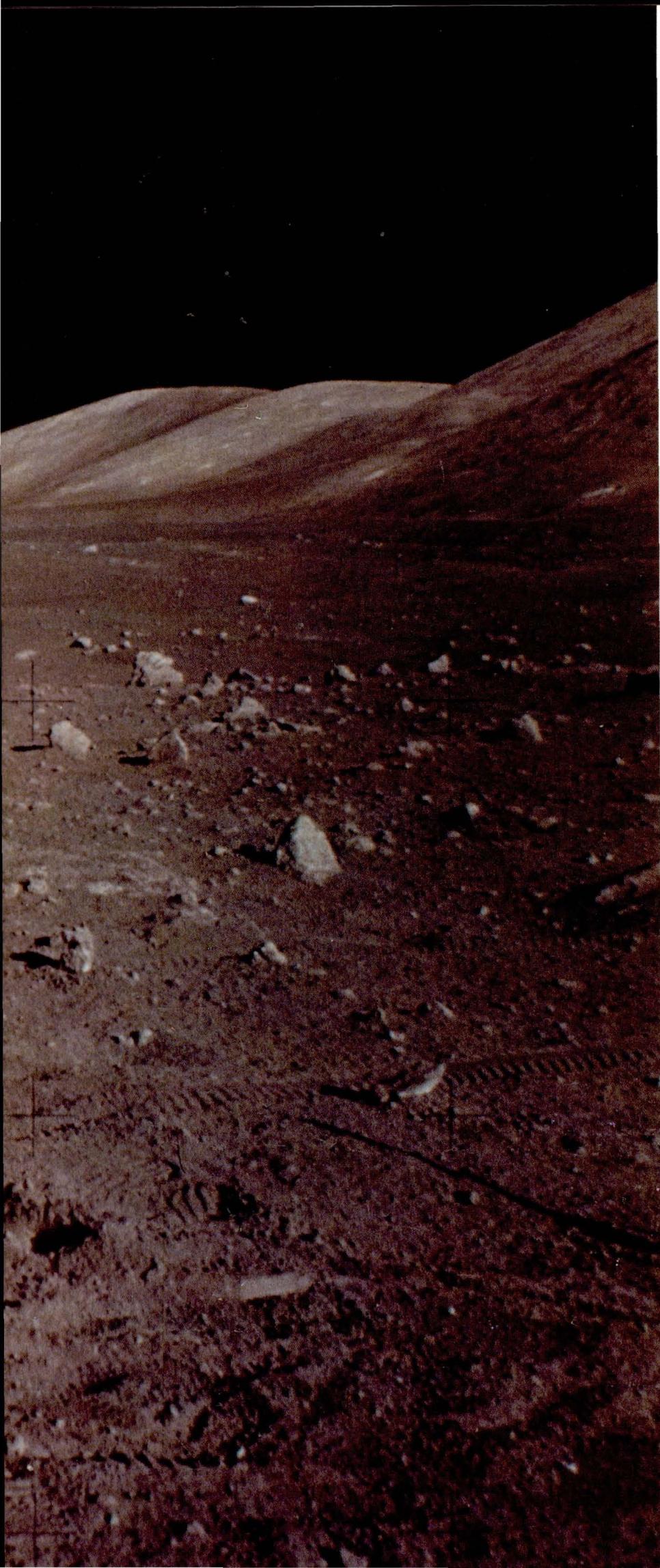
tudes Jupiter's clouds are probably made of water and complex molecules. The atmospheres of far-off Uranus and Neptune are hard to study, but show faint traces of clouds as well.

We can only make informed conjectures about the interiors of the gas giants. They may have small rocky cores; if so, the cores are surrounded by layers of solid ice. Around this ice, in Jupiter and Saturn, the enormous pressure of the overlying material has reduced the molecular hydrogen gas (which makes up most of the atmosphere) to a liquid state in which the hydrogen behaves electrically like a metal. In Uranus and Neptune, the hydrogen is dense but may not reach the metallic condition. Currents circulating in the metallic fluids of Jupiter and Saturn generate powerful magnetic fields that surround the two planets in space and trap atomic particles from the "solar wind" that streams outward from the Sun.

The gas giants have solid moons orbiting around them. Not just one or two moons, like Earth and Mars, but whole families; Jupiter and Saturn have more than a dozen moons apiece. Their moons, recently photographed by the *Voyagers 1* and *2* spacecraft, have been revealed as an astonishing collection of distinct individuals: large irregular rocks, worlds of cratered ice, and one moon of incessant glowing volcanic eruptions. The largest of Saturn's moons, Titan, is covered by a dense brownish atmosphere of nitrogen and methane, with minor amounts of other organic molecules.

Within each of the two planetary groups—the terrestrial planets and the gas giants—our space probes have revealed tremendous diversity. Each world is unique, but each also has something in common with the others, so that by studying one, it is possible to discover basic truths that relate to them all.





The Terrestrial Planets

The Moon

Is the Moon a planet? Technically no, for it revolves around the Earth rather than directly around the Sun. But the Moon is a large world, comparable in size to the planet Mercury. In composition, origin, and history, the Moon is like a terrestrial planet, resembling the Earth in many ways, different in others. These similarities and differences make the Moon an important starting point for the study of other worlds.

Because it is close to the Earth, the Moon is our most intensely studied “new” world. It has been reached by many spacecraft from both the United States and the USSR. On each of six missions, two American astronauts landed and studied the lunar surface. Manned and unmanned satellites placed in orbit around the Moon have made detailed photographs and mapped the gravity, magnetism, and chemical composition over much of its surface. Instruments placed by our astronauts on the surface have investigated the once wholly inaccessible interior of the Moon. Especially important has been the return of actual lunar samples from nine sites (six American, three Russian) on the Moon. By analyzing these samples in laboratories on Earth, we have measured the Moon’s precise composition, deduced its history, and inferred the nature and variations of the space environment around the Moon over long intervals of ancient time.

***A new world in our hands.** Apollo 17 astronaut Harrison Schmitt uses a special rake to collect rock and soil samples from the Moon’s Littrow Valley. Pieces of the Moon, brought back to Earth, yield a detailed picture of the nature and history of our nearest neighbor world. Samples from the lunar surface also bear clues to the history of the Sun: trapped gas atoms that have been sprayed out from the Sun over billions of years.*

The composition of the Moon is much like that of the Earth. Its rocks are similar to Earth rocks and contain many but not all of the same minerals. However, the Moon has no atmosphere, it shows no trace of past or present life, and its rocks contain no water.

The Moon rocks show that the lunar surface is very ancient. Its rocks are older than most of the rocks now found on Earth, and the Moon has preserved a record of the earliest history of the formation and development of the planets. In its oldest rocks, we detect indications of an intense primordial melting that left the newborn Moon covered with a seething ocean of molten lava hundreds of kilometers deep. Gradually, the lava ocean cooled and solidified, forming the light-colored crust we call the *lunar*

highlands, which still covers 80 percent of the Moon.

The newly formed lunar crust was subjected to long-term catastrophic bombardment by meteoroids and asteroids, some as large as Rhode Island or Delaware. These violent impacts formed overlapping craters and huge circular basins that can still be seen on the Moon. Then, when the bombardment subsided, about 4 billion years ago, radioactivity began to heat the inside of the Moon. The lunar rock melted at depths of hundreds of kilometers, and fresh lava rose to the surface, spreading to form the great, dark regions, or *maria*, of the Moon. The lavas from these eruptions resemble lavas found on Earth in places like Hawaii and Iceland. But, unlike terrestrial lavas, they contain no water, and the crystals in them are as

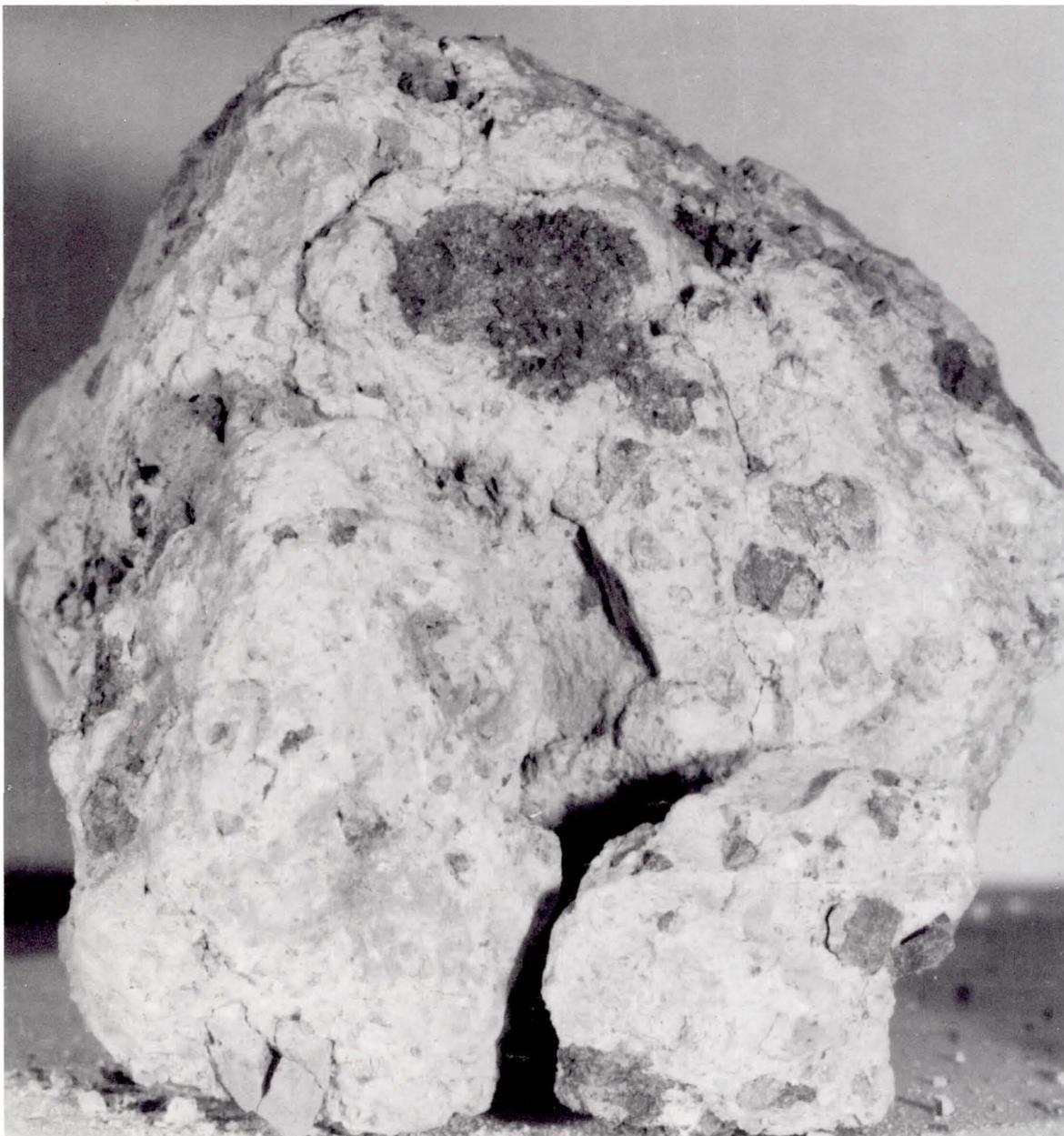


Lava from the lunar "seas." This chunk of bubble-rich lava, collected by the Apollo 15 astronauts, typifies the surface rock of the dark maria (or "seas") on the Moon. Tremendous volcanic eruptions about 3.5 billion years ago flooded much of the Moon with molten lava resembling the volcanic rocks found in Hawaii and Iceland. Unlike Earth rocks, the lunar specimens contain no water; the nature of the gas that made the bubbles remains a mystery.

clear and gemlike as if they had been erupted yesterday rather than 3.5 billion years ago.

For the last 3 billion years, the Moon has been a very silent world. A steady, gentle bombardment by tiny meteorites has gradually chipped away at the lunar bedrock, creating a slowly stirred surface layer of powdery rubble, the lunar "soil." During these billions of years, the soil par-

ticles have been recording the space environment, retaining traces of the steady bombardment of the Moon by cosmic dust, by charged atomic particles from the Sun, and by cosmic rays from the stars. Unlike the geologically active, continually changing Earth, the Moon has been a virtual "museum world," a key to understanding the history of the Sun and the planets.



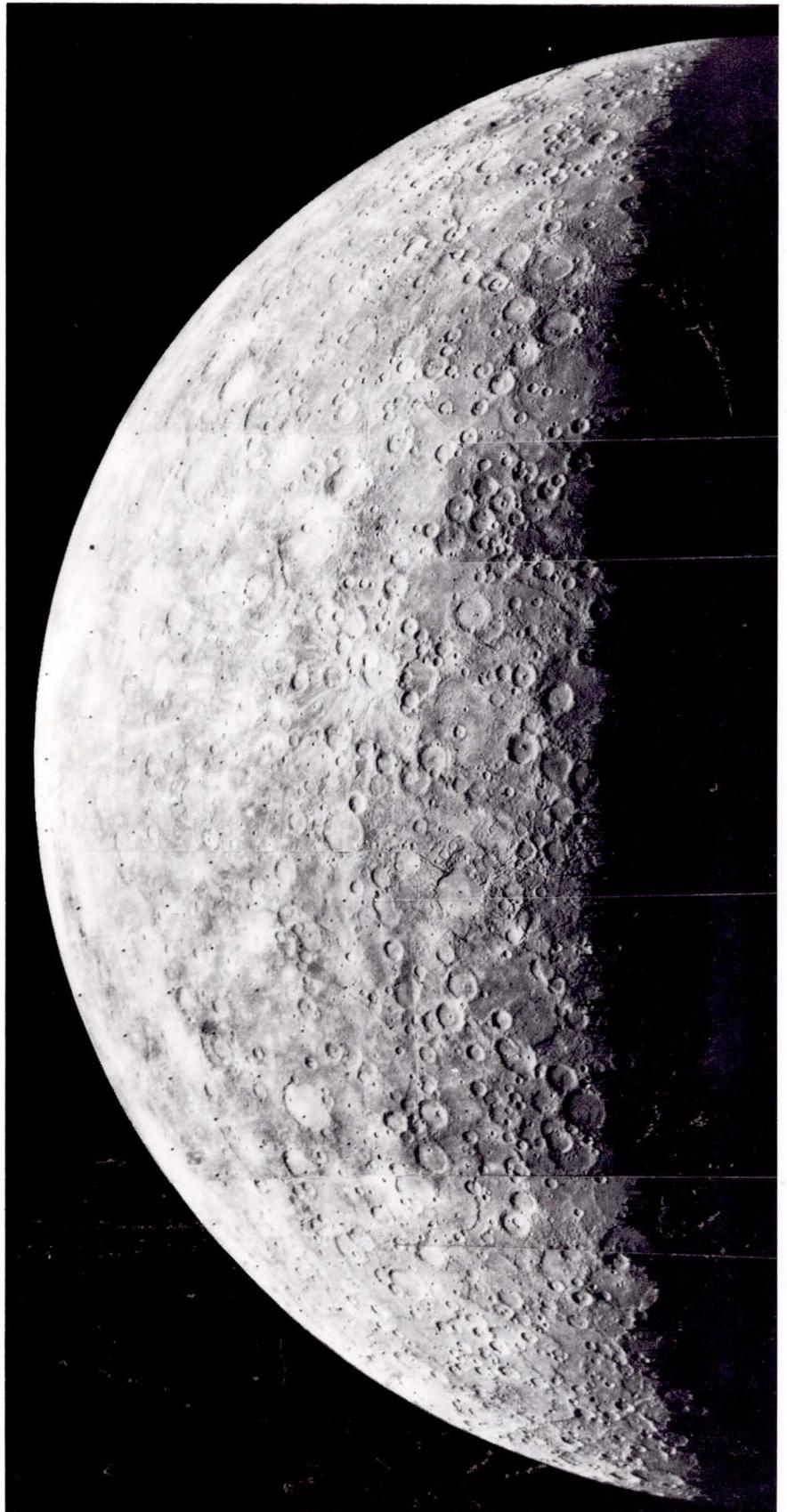
The rubble of ages. Collected by Apollo 16 astronauts on the lunar highlands, this light-colored rock (or breccia) was formed from pieces of many different rocks, shattered, melted, and mixed together by the great meteorite impacts that rocked the Moon during its early years. The complex breccias are the key to understanding how the Moon and other planets developed. Some fragments in this specimen may be pieces of the original lunar crust that formed 4.5 billion years ago.

Mercury

Only 40 percent larger in diameter than the Moon, Mercury is the closest planet to the Sun, and its sunlit surface is hot enough to melt lead. The planet is so small and so far away from Earth that it was only a dull white blur in telescopes before the Space Age. Its surface finally was revealed during three flybys of a single space probe, *Mariner 10*.

Mercury is a planet much like the Moon. It has no atmosphere, and its surface is covered with circular impact craters and huge, round basins. Most of Mercury looks much like the lunar highlands; apparently it was subjected to the same bombardment that shaped the Moon in primordial times. Yet Mercury is different. It seems to lack the dark deposits of lavas that engulfed much of the Moon between 3 and 4 billion years ago. Unlike the Moon, Mercury has great cliffs, thousands of kilometers long, that may be wrinkles formed as the planet cooled and shrank. Mercury is denser than the Moon, and it seems to have a large iron core, the source of a weak but detectable magnetic field, a feature the Moon lacks.

Mercury is a scorched, primordial world which must retain traces of how planets were formed in a part of the solar system remote from the Earth and Moon. But we cannot reach it yet for detailed exploration. Deep in the gravity field of the Sun, Mercury lies beyond the reach of even today's most advanced spacecraft. To send orbiters and landers there, more powerful interplanetary spacecraft will be needed. Until then, Mercury waits just out of reach, its secrets baking in the light of a huge and searing Sun.





A world revealed. The planet Mercury, once only a white blur in Earth bound telescopes, reveals a moonlike face to the cameras of Mariner 10. The heavily cratered surface seen here resembles the highlands of the Moon; the largest craters are up to 200 kilometers (125 miles) in diameter. The surface of Mercury, like that of the Moon, displays the effects of meteorite bombardment, suggesting that such impacts shaped many of the terrestrial planets. This mosaic was assembled from eighteen separate pictures, snapped at a distance of 200,000 kilometers (125,000 miles).

The landscape of Mercury. In this close-up view from Mariner 10, an airless, cratered surface is revealed as it might appear to an astronaut in orbit around Mercury. Surface temperatures can reach 425°C (about 770° F) in the searing light of the nearby Sun. The irregular dark line on the distant horizon is a unique feature of Mercury, a huge scarp (or cliff), several kilometers high and several hundred kilometers long, that may have been formed as the young planet cooled and shrank. This picture was taken from 77,800 kilometers (48,000 miles) as Mariner sped past Mercury; the distance along the lower edge of the picture is about 580 kilometers (360 miles).



Mars

Mars is larger than Mercury, slightly over half the diameter of the Earth. For centuries it has been a mystery planet, a blurred red globe in the telescope, splashed with patches of white and dark. Even before spacecraft ventured there, we knew that Mars had a thin atmosphere, winds, water, clouds, and polar ice caps. There was a continuing debate over whether the so-called "canals" were really there and whether Mars might in fact have life. In science fiction, Mars was the destination for spacefaring humans and also the main source of extra-terrestrials, hostile or friendly, who visited Earth.

A new Mars has been revealed by several unmanned spacecraft: flybys, orbiters, and finally landers. Mars is now recognized as a kind of "halfway" world. Part of the Martian surface is ancient like those of the Moon and Mercury, and part is more evolved and Earth-like. The southern Martian hemisphere is heavily cratered, so it too bears the traces of the primordial bombardment that engulfed the Moon and Mercury. But the Martian craters are different: Their rims are low; they are shallow, eroded, and filled with wind-blown dust accumulated over millions of years.

The northern half of Mars is more like the Earth. Huge volcanic mountains climb as much as 25 kilometers (15 miles) into the sky, three times as high as Mount Everest, and the remnants of ancient lava are seen on

their slopes. A huge chasm, wider in places than the Grand Canyon is long, runs east-west for about 4500 kilometers (2800 miles). Elsewhere on this younger half of Mars, surprising, twisted channels meander across the surface. These are not the straight "canals" once seen from Earth; those turned out to have been tricks of perception produced by viewing Mars at the limit of Earthbound vision. The real twisted, braided channels seem to have formed catastrophically in huge, sudden floods more than a billion years ago. The water has vanished; no liquid water is now found on Mars. But huge reservoirs of frozen water apparently remain in the Martian polar caps, and in permafrost beneath the Martian soil. The white polar caps are largely made up of water, with a frosting of "dry ice" or frozen carbon dioxide. The caps themselves lie on layered sediments, perhaps the evidence of past ice ages on Mars.

Two places on Mars have been examined on the surface by the two *Viking* landers (one of which is still operating since its landing in 1976). The robot spacecraft sent back pictures of a pink sky, colored by fine, red, windblown dust. Lander instruments measured mild winds in the thin Martian air and detected a thin frost that formed on rocks and soil during the Martian winter.

The atmosphere of Mars is very thin; the barometric pressure is less than one percent that of the Earth at sea level. Unlike our air, Mars' atmo-

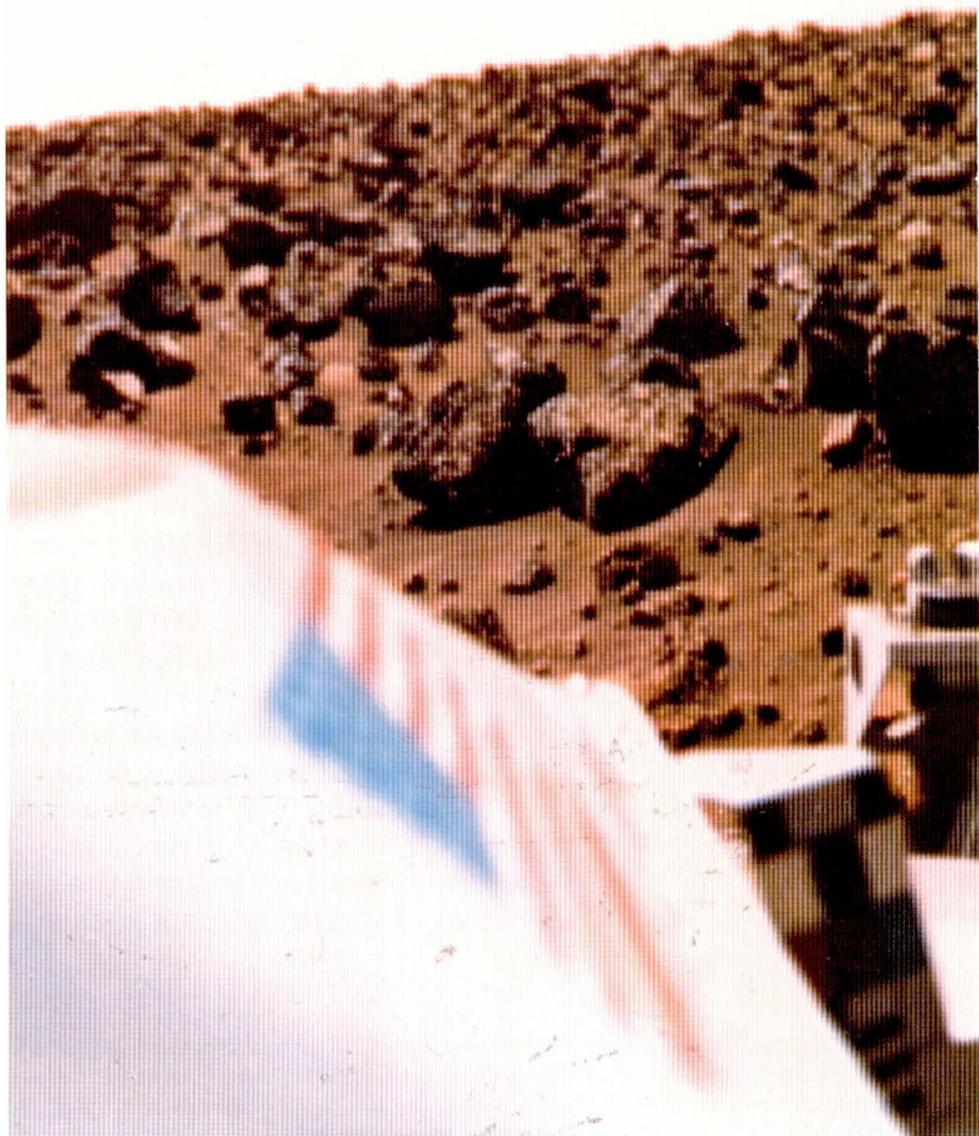
The face of Mars. The different regions of the Red Planet are shown in this single picture taken by Viking 1 at a distance of 560,000 kilometers (348,000 miles). The dark spots are huge volcanoes, which characterize the younger, more geologically active northern hemisphere. The largest Martian volcano, Olympus Mons, is the isolated dark spot at the upper right. It is more than 600 kilometers (373 miles) across and rises about 25 kilometers (16 miles) above the surface. The more ancient, heavily cratered southern hemisphere is mostly in shadow here, but the large circular feature, Argyre, probably formed by a great meteorite impact, can be seen at the bottom, its shape emphasized by a thin layer of frost or ground fog within.

sphere is not predominantly composed of nitrogen and oxygen, but consists almost exclusively of carbon dioxide (CO₂), with minor amounts of nitrogen and argon and just a trace of oxygen.

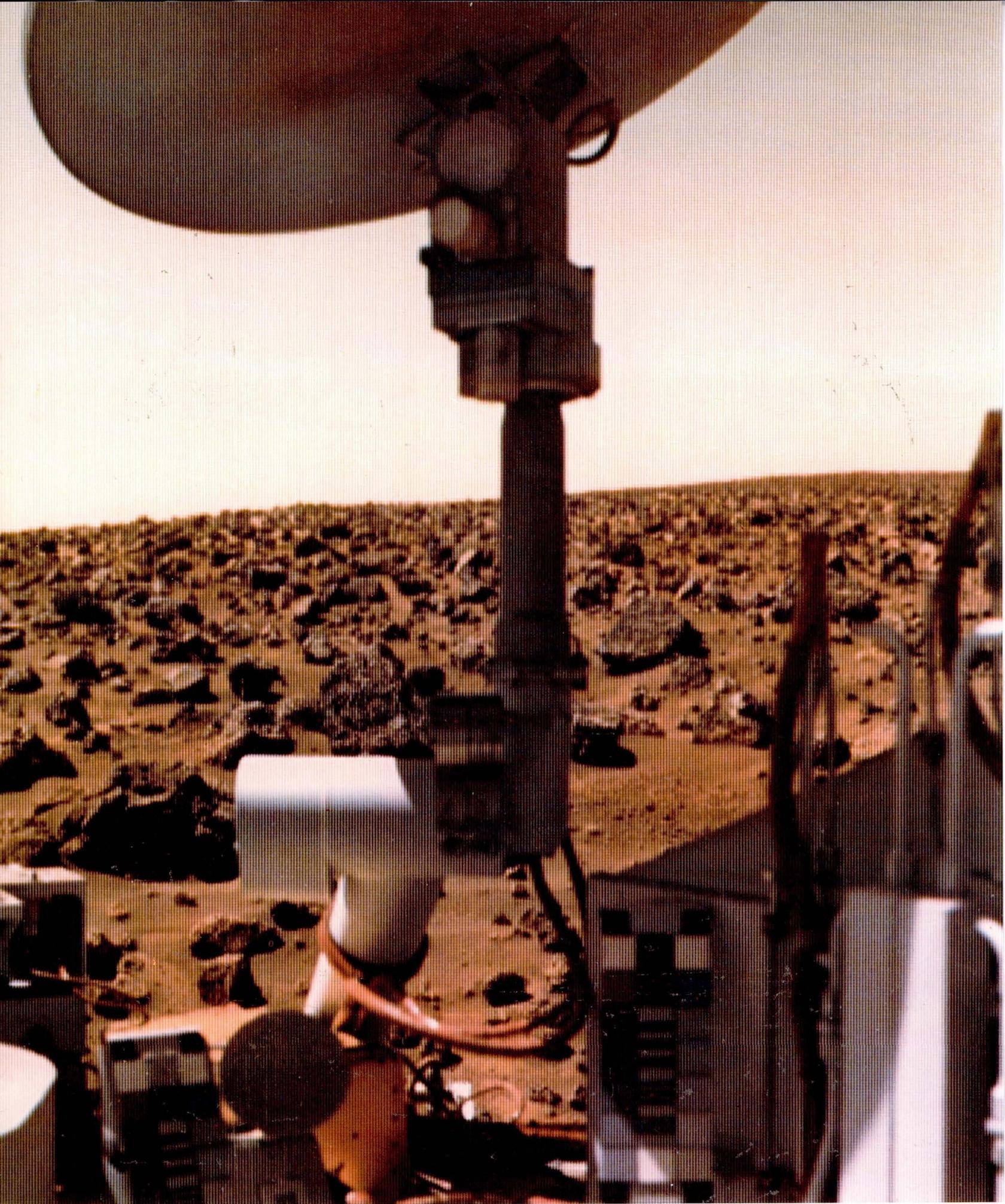
The rocks of Mars are porous and jagged, like the volcanic lavas of the Earth and the Moon. The Martian soil, analyzed by the *Viking* landers, has a composition very much like weathered lava. The red color of Mars is in fact caused (as generations of science fiction writers had written) by the presence of oxidized iron, a kind of exotic rust.

The greatest mystery of Mars: Is there life?—remains a mystery. Several experiments on the *Viking* landers tried to detect life in the soil, and some unusual reactions were encountered. But the reactions probably were due to the unusual chemistry of the soil rather than to the presence of any microscopic life forms. It seems that we will need to carry more sophisticated experiments to Mars—or bring a sample of Mars back to laboratories here on Earth—before we can answer the question with certainty.

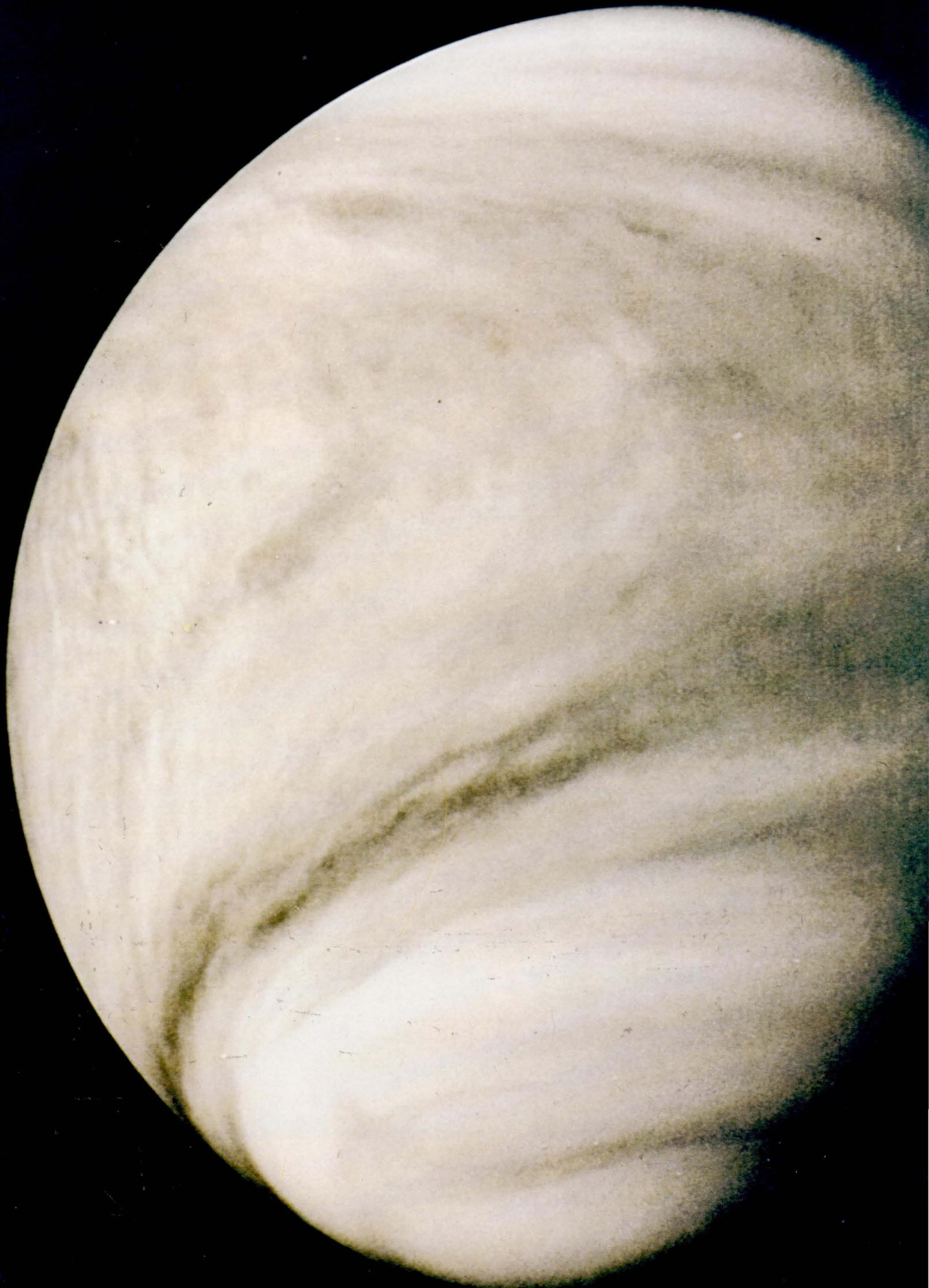
Mars is a more developed planet than the Moon and Mercury. The evidence of massive volcanism is obvious. In addition, some geologists consider the vast chain of canyons in the northern hemisphere to be the result of rifting, perhaps the beginning of continent-building. Mars has made and retained an atmosphere. But, like the Moon, Mars apparently stopped evolving 1 or 2 billion years ago and has not gone as far geologically as the Earth. On the other hand, like the Earth, it is a world with weather and climate. The records of its past climates, floods, and ice ages remain in the layered sediments of the polar regions, photographed in detail, but as yet unreachable.



Rocks of the Red Planet. A geological welcoming committee, Martian rocks up to a meter (3.3 feet) across surround the *Viking 2* lander in the Utopia region of Mars. Dark, sometimes banded, and often bubble-rich, the rocks resemble volcanic lavas (basalt) found on the



Earth and Moon. The red soil is colored by oxidized iron; its chemical composition resembles that of weathered basalt lava. The surprising pink sky of Mars draws its hue from fine red dust carried aloft by the winds.





Venus

Second from the Sun, closest planet to the Earth, Venus has long been known as the bright morning and evening star. Called "Earth's Twin" because it is almost the size of Earth, Venus is surrounded by a thick, yellowish-white, opaque atmosphere. All we can see in telescopes are fuzzy images of its perpetual cloud cover.

Probed and scanned by spacecraft, however, Venus has revealed itself as no twin of Earth, but rather as a strange and hellish inferno. Its thick atmosphere is composed mostly of carbon dioxide, with a little nitrogen and traces of water, oxygen, and sulfur dioxide. At the surface, the pressure of Venus' atmosphere is 90 times that of Earth's, equal to the pressure half a mile down in the ocean! The thick atmosphere traps the Sun's heat, producing a "greenhouse effect" that keeps the surface of Venus at a scorching 480° C, literally hot enough to fry eggs. Above the surface, entry probes of the *Pioneer Venus* mission detected several distinct regions, two of them, and possibly even four, constituting separate cloud layers. The top-most cloud layer, revealed in photos made from spacecraft and dimly perceived from Earth, consists not of water clouds as on Earth, but rather of sulfuric acid droplets, far more potent than the mild "acid rain" that

Earth's cloudy "twin." Planet-wide swirls and waves appear in the thick atmosphere of Venus, as photographed by Pioneer Venus Orbiter. This view shows a pronounced dark band (lower left), two bright areas ("polar rings") near the north and south poles, and a complex, turbulent region at the left. These large-scale patterns are strikingly different from the numerous smaller circulation patterns of the Earth's atmosphere. The Venus patterns are remarkably stable and circle the planet in only four days, although the planet itself takes about 244 days to rotate on its axis.

concerns us now in the United States. A haze of aerosol particles extends upward from this layer and sometimes even veils the clouds themselves from view.

The surface of Venus has been photographed at two locations by Russian *Venera* landers that briefly survived the hot, high-pressure environment and photographed the surrounding rocky slabs and rubble. Another *Venera* lander gave us our first chemical analysis of the surface of Venus, indicating a unique composition resembling that of terrestrial granite.

Until other camera-carrying spacecraft land and survive, the rest of the surface of Venus will remain unseen. But the clouds that block telescopic investigation do not stop radar waves. Powerful radar transmitters, both on Earth and on a *Pioneer Venus* spacecraft in orbit around Venus, have scanned and located the

major topographic features of the veiled planet's surface.

Venus revealed by radar apparently lacks the great number of high mountain ranges and the interlocked systems of deep oceanic trenches that run for thousands of kilometers on the Earth. But it has its own remarkable features. Among them are two great plateaus, each as large as a small continent, which rise as high as 17 kilometers (11 miles) above the surface. One, called Ishtar Terra, is about the size of the continental United States and contains a more elevated region that is higher than Earth's Tibetan plateau and more than twice as large. Elsewhere on Venus is Beta Regio, a prominent landform that contains two huge, adjoining shield volcanoes, together more extensive than the Hawaii-Midway chain. Among the rifts found in the Venus crust are a canyon deeper and longer than the Grand Canyon of Arizona and a long

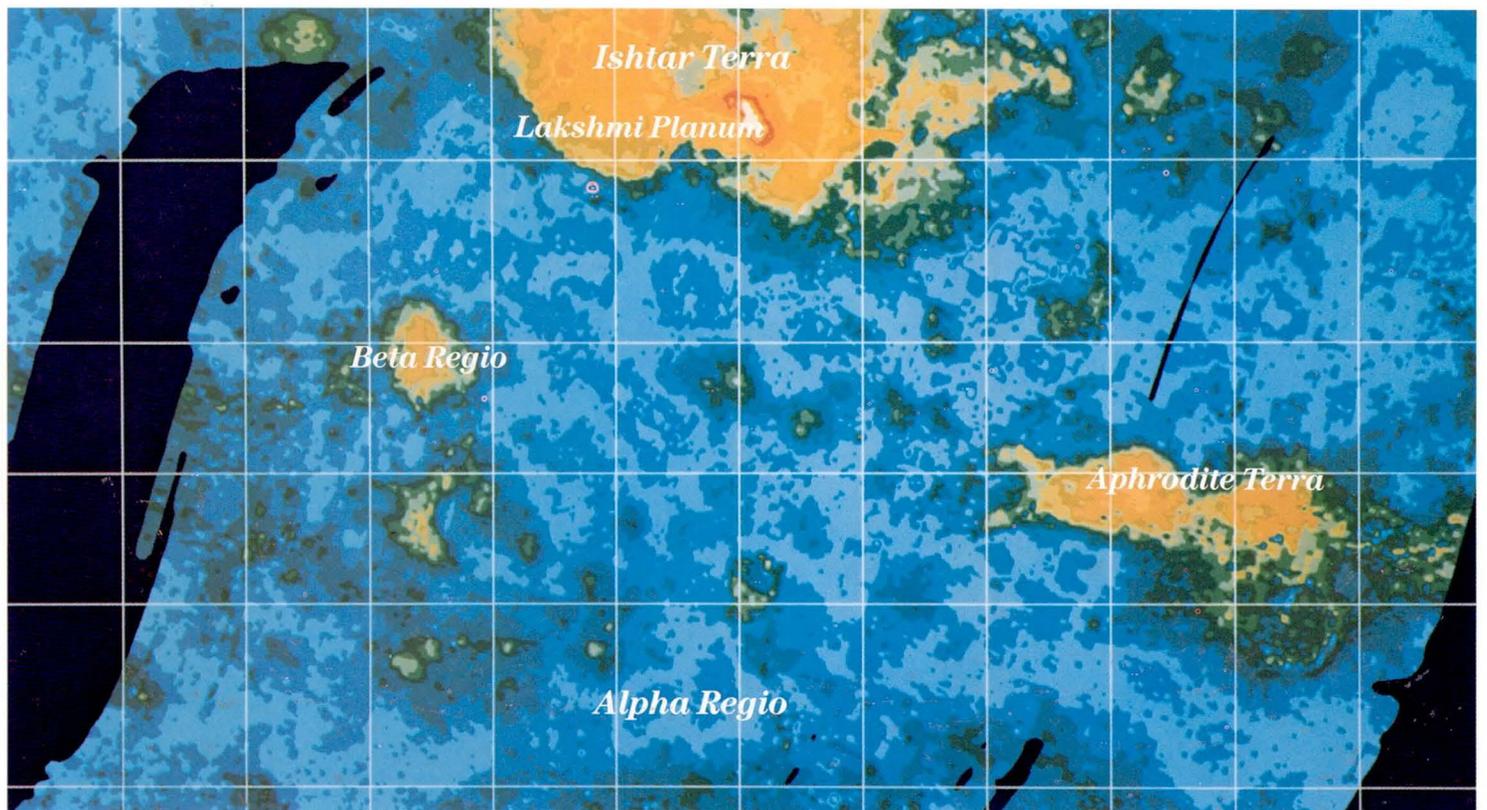


Hot rocks of Venus. Scorched to nearly red heat under the thick hot atmosphere of Venus, the planet's surface was photographed by two successful, but short-lived, Russian *Venera* landers. In this picture, jagged slabs of rock extend to the horizon (upper right). The nature of the rock is unknown. The images are curved by optical effects in the television cameras. Parts of the spacecraft are seen, out of focus, at lower center and lower right.

valley that apparently is flanked by large mountains. Do these chasms of Venus indicate that its continental masses are separating? There also are large circular depressions, perhaps great meteorite craters like those found on other terrestrial planets. However, these basins are unusually shallow, as though the hot crust of Venus has flowed into them like hot, soft wax.

The surface of Venus seems to have been shaped by internal geo-

logical activity, but we do not know what kind of phenomena were involved, nor how long they went on. Is Venus now dead and quiet, as Mars appears to be? Or is it more evolved, and still geologically active, perhaps approaching Earth in its development? We have no detailed maps of Venus to guide our thinking, unlike the case of the other planets. The surface of Venus, the nearest planet to Earth, is still one of the largest unexplored lands in the solar system.



Highs and lows of Venus. This crude relief map of the cloud-shrouded surface of Venus is based on radar observations made from Earth and from the Pioneer Venus Orbiter. Low elevations are shown in greens and blues, higher altitudes in yellows and reds. Most of Venus is much flatter than Earth, but a few plateaus the size of small continents rise up to 17 kilometers (11 miles) above their surroundings. There is no clear indication of anything resembling the global system of trenches and mid-ocean ridges that characterizes our geologically active Earth.

The Gas Giants

Jupiter

Jupiter is where the action is. The planet is big enough to hold 1400 Earths and is almost 2.5 times more massive than all of the other planets put together. It is a huge, rapidly spinning blob of cold gases—hydrogen, helium, a little methane, water, and ammonia—all colored by traces of more complex but largely unknown chemicals. The outer part of the atmosphere is all that we see of Jupiter. There, clouds form in belts and stripes, in consequence of the fast rotation. This planet, 11 times the diameter of Earth, spins on its axis in less than half an Earth day.

Deep inside Jupiter's atmosphere, the pressure becomes enormous, and hydrogen, a gas at the higher altitudes, is condensed to a liquid. At about 25,000 kilometers (16,000 miles) below the cloud tops, the pressure attains a value 3 million times that of the Earth's atmosphere at sea level. At this pressure, the liquid hydrogen transforms to a metallic state.

Great storms of Jupiter. *An exercise in cosmic modern art, huge whirling storms and sawtoothed, turbulent flows spread out in Jupiter's atmosphere as pictured by Voyager 2 from 6 million kilometers (3.7 million miles). The Red Spot (right center) is a huge storm system, big enough to hold three Earths, that has persisted for at least three centuries. It whirls counterclockwise, producing highly contorted patterns at its left, where cloud banks moving left to right are blocked and forced to squeeze past it. Smaller white oval storms, about the size of Earth, create similar turbulent effects below the Red Spot. Most patterns in Jupiter's atmosphere are constantly changing; the structures shown here have changed significantly since Voyager 1 photographed them four months previously. Jupiter's atmosphere is composed almost entirely of colorless hydrogen and helium; the colors come from small amounts of unknown substances, perhaps compounds of sulfur and phosphorus.*





Currents circulating through the metallic hydrogen fluid generate a magnetic field that is about 14 times stronger at Jupiter's cloud tops than the field at the surface of the Earth. Disturbances in the magnetic field around Jupiter produce powerful bursts of radio waves, making Jupiter the noisiest radio transmitter in the solar system, other than the Sun.

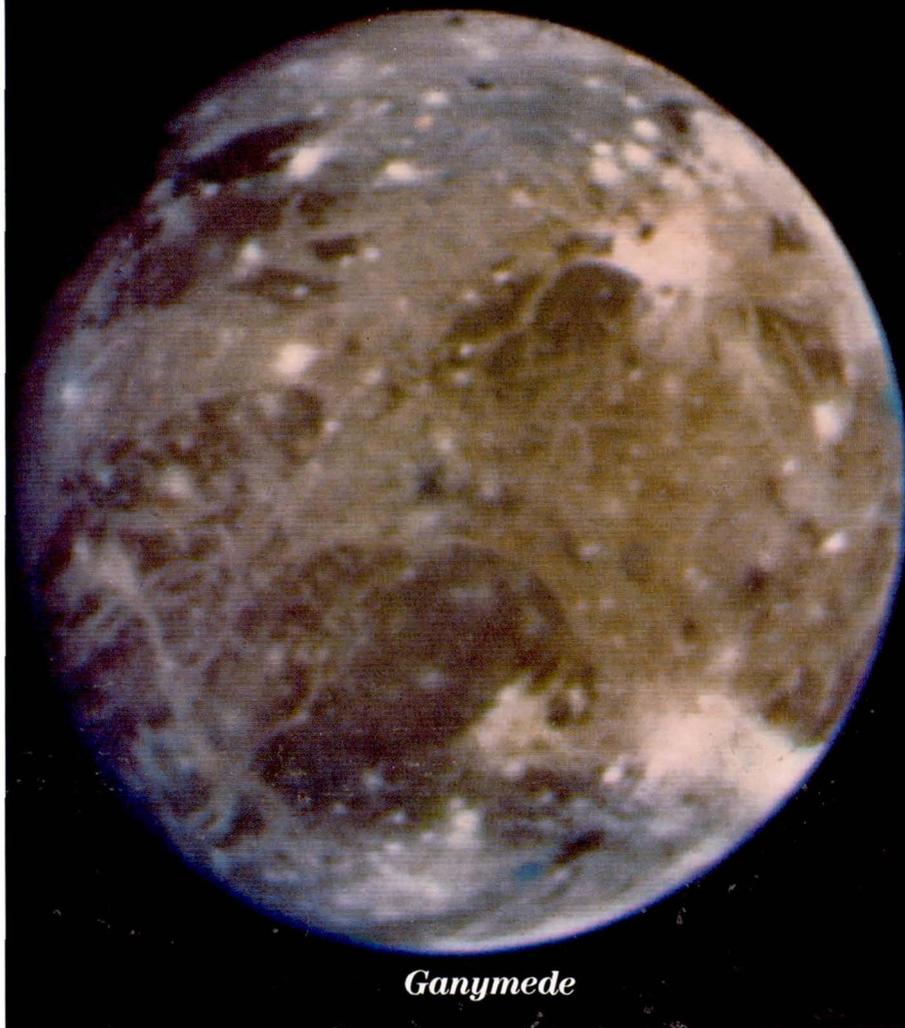
Jupiter's magnetic field is much stronger than the Earth's, and it is much less compressed by the solar wind, the stream of charged atoms that pour out from the Sun. Jupiter's field forms a huge magnetosphere around the planet, and the field sweeps out on the side opposite the Sun to give Jupiter a fat "magnetic tail" at least 150 times wider than the diameter of the planet itself.

Jupiter's composition of hydrogen and helium is the same as the Sun's. Recent theoretical studies have carried the similarity even further, suggesting that if Jupiter had been only a little larger, it might have become another Sun, the gas at its center compressed so much that nuclear reactions would have begun. Thus, Jupiter is a sort of "star that failed," although it still radiates, by compressing its own core, twice the amount of energy that it receives from the Sun. The most striking resemblance, however, is that Jupiter is the center of a miniature solar system, surrounded by an array of at least 16 moons, just as the Sun is surrounded by planets, comets, and a belt of asteroids.

Jupiter, remarkable even as observed from Earth, revealed even more wonders as our spacecraft sped past it in recent years. Cameras gave us a close view of its banded atmosphere,



Io

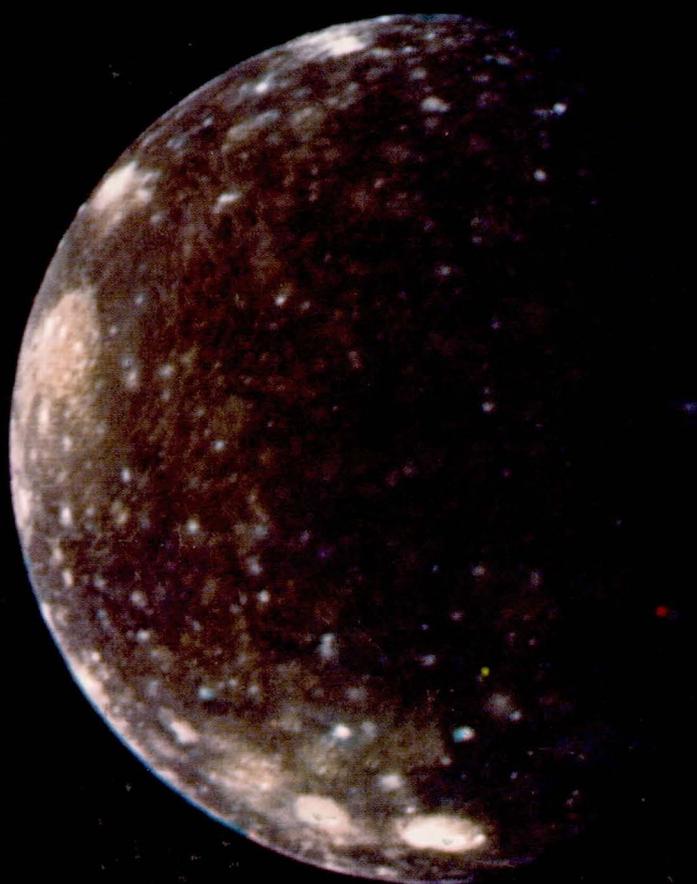


Ganymede

A menagerie of moons. Jupiter's four largest moons, first seen as tiny dots of light in Galileo's telescope, are revealed as strange new worlds by the cameras of Voyagers 1 and 2. Seen here in their relative proportions, they show a bewildering variety. Each is different from our own Moon and different from the others. Io is a red-orange world, pitted by the craters of active volcanoes that constantly renew its surface with sulfur and sodium compounds. Europa is a yellowish,



Europa



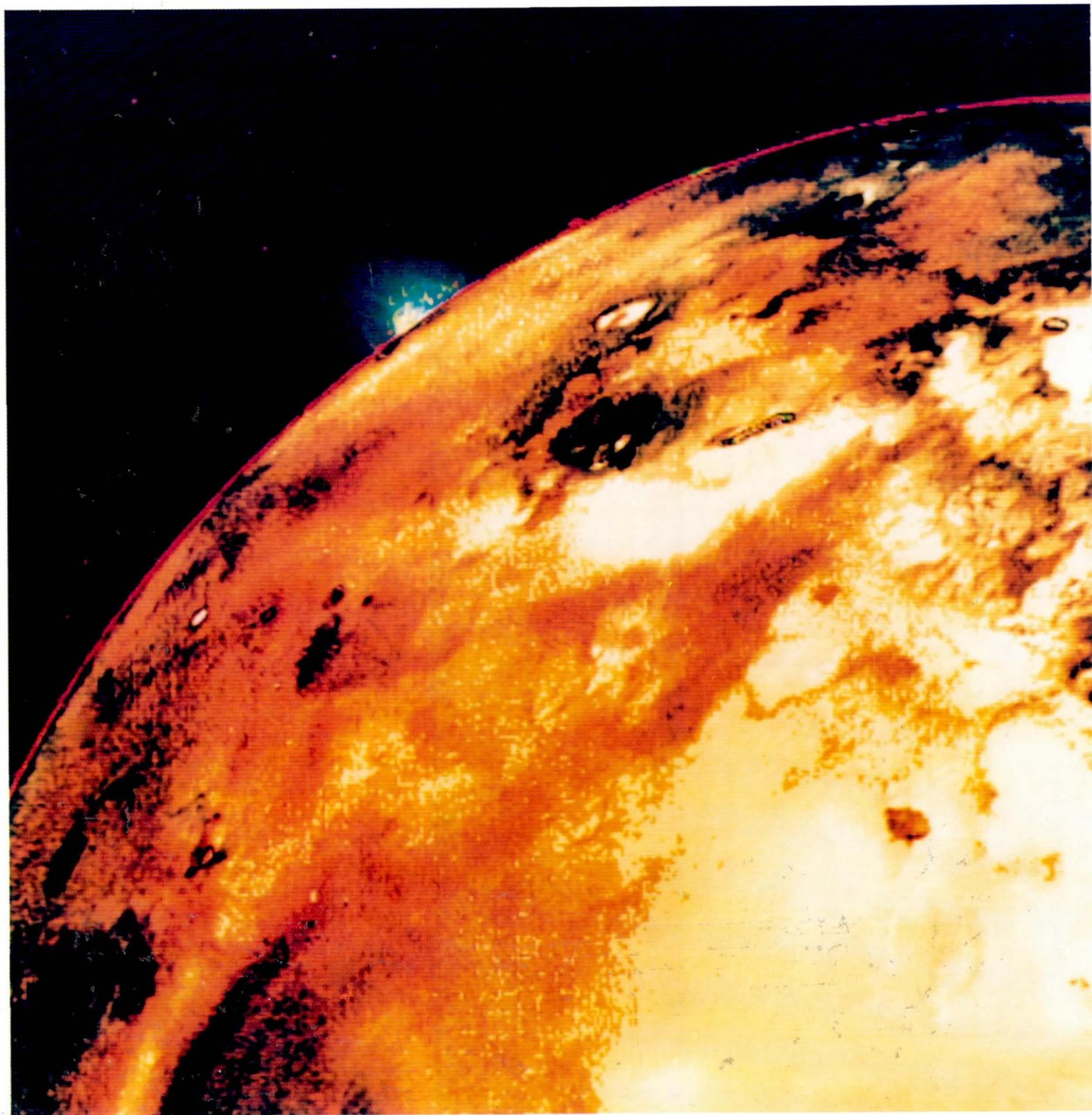
Callisto

and we learned that the seemingly smooth belts of color were actually separated by zones of violent turbulence. Earth-sized blobs of colored gas travel along huge "jet streams," spin, and collide. Great plumes rise from deep in the atmosphere and leave trails 10,000 kilometers (over 6200 miles) long across the planet. The great Red Spot, a long-lived oval as big as three Earths (it was first seen at least 300 years ago), is a complex, swirling hurricane. Even the night side of Jupiter is alive with the flash of lightning superbolts and the glowing bands of huge aurorae.

The spacecraft passing Jupiter discovered three new moons, adding to the 13 already observed from Earth. Inside the orbit of the innermost moon they found a ring, a thinner version of the rings of Saturn, never seen from Earth. The ring, made of tiny particles, apparently reaches right down to the cloud tops of Jupiter, and it has stimulated a major debate about how it formed and how it continues to exist so close to Jupiter.

The moons of Jupiter are equally spectacular, remarkably different from our own Moon and from each other. The two *Voyager* spacecraft discovered that they are very unlike what astronomers expected. Amalthea, once considered Jupiter's innermost moon, is an irregular rock about 270 kilometers (170 miles) long, but only about 155 kilometers (96 miles) wide along one axis. Beyond it are the four *Galilean satellites* (so-called because Galileo discovered them). Three of them are larger than our own Moon, including Ganymede, which is even bigger than the planet Mercury.

smooth globe, crisscrossed with dark lines that may be the fractures of an icy crust. Ganymede, larger than our Moon, has light and dark regions dotted by bright impact craters that may have exposed a subsurface ice layer. Callisto, brownish and heavily cratered, has perhaps the oldest planetary surface yet discovered, its landscape sculptured by an intense meteorite bombardment during the formative stages of the solar system.



***Volcanoes of Io.** Jupiter's moon Io displays the only active volcanoes found outside the Earth. Driven by tidal heating as Io circles mighty Jupiter, the volcanic eruptions are still shaping the moon's surface. They spray sodium and sulfur atoms, making a cloud that surrounds Io's orbit. In this computer-enhanced picture from Voyager 1, a blue plume on the horizon consists of material hurled upward from a volcano to more than 150 kilometers (about 90 miles) above Io's blotchy red-orange landscape.*



Io, the innermost Galilean satellite, was one of the biggest surprises of the Space Age, a brilliant red-orange world with more than 100 volcanoes. The two *Voyagers* saw seven of the volcanoes in continual eruption, shooting umbrella-shaped plumes of sulfur particles high above Io's surface. These unique volcanoes, the only active ones known outside the Earth, seem to be ejecting molten sulfur at a temperature of a few hundred degrees, not molten rock at more than 1000° C. The heat comes, not from radioactivity as in the Earth, but from tidal forces and perhaps also huge electric currents that act on Io as it swings around Jupiter.

Europa, the next moon out, resembles a smooth, yellowish billiard ball and comprises perhaps the flattest real estate in the solar system. It is crisscrossed with thin lines, some several thousand kilometers long, that remind some observers of a kind of modern art. The lines may be the traces of a shifting icy crust, but we have no idea of what forces have acted, and continue to act, to keep this world so flat.

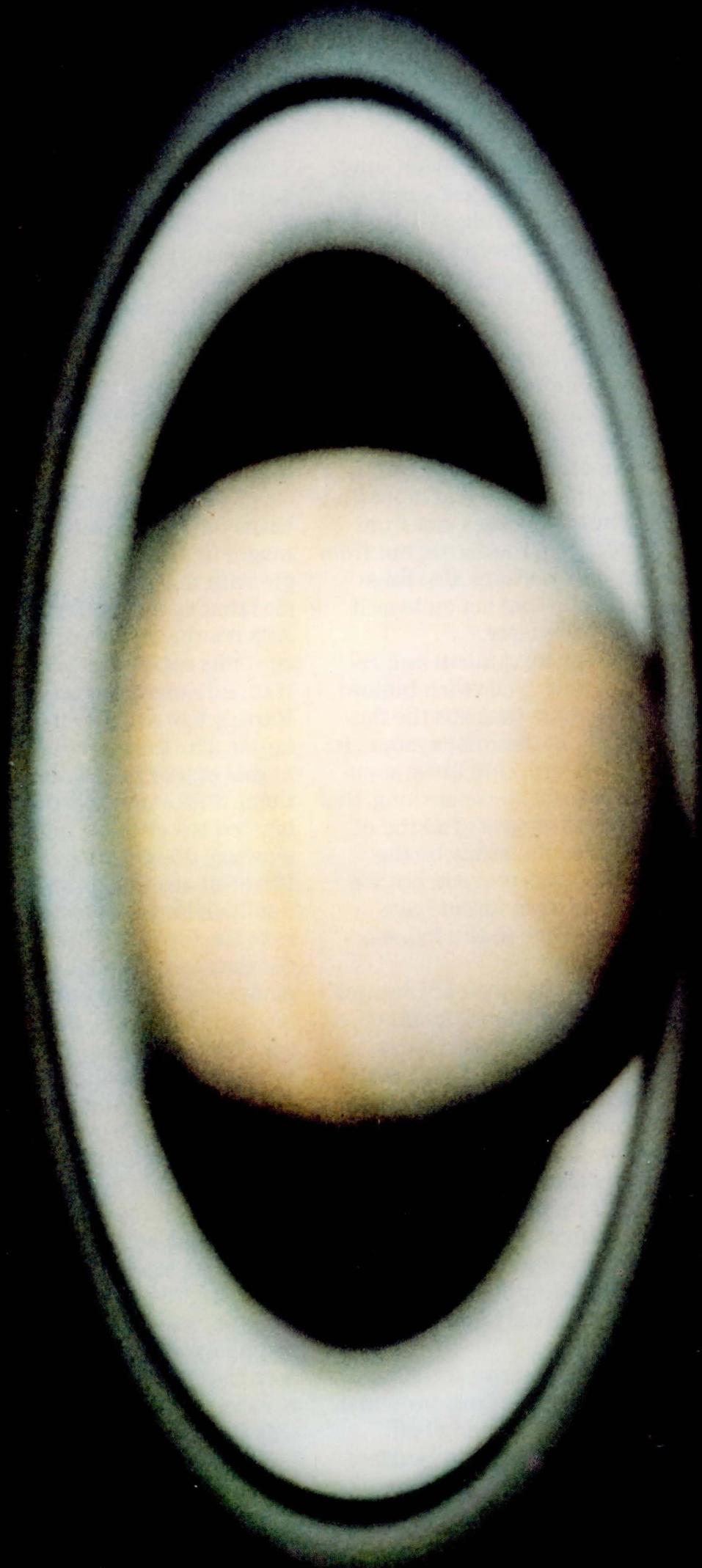
Ganymede, the largest of Jupiter's moons, looks a little more familiar. Like our own Moon, its surface is divided into light and dark regions, and we can see craters. There the similarity ends. Ganymede is a lightweight moon, a "snowball" of mixed ice and rock. Bright rays extend from the craters, perhaps consisting of fresh ice. The light areas of Ganymede display long bands of parallel grooves, unique and puzzling structures which indicate that internal forces have shaped the surface.

Callisto, the outermost Galilean moon, is a heavily cratered, brownish world. It seems to be a snowball moon like Ganymede, but its surface

is uniformly cratered and preserves a long history without any disruption. Callisto may have the oldest surface yet observed in the solar system, its craters perhaps dating back to an ancient era of bombardment, which ended about 4 billion years ago. Callisto also bears what may be the largest crater anywhere in the solar system, a huge, multi-ringed basin more than 2500 kilometers (1600 miles) across.

Even the space around Jupiter turns out to be exciting. Jupiter's huge magnetic field is in a constant struggle with the streams of charged particles that speed outward from the Sun. As a result, the jovian magnetosphere contains regions of highly charged trapped radiation particles, like the Earth's Van Allen belts, but much larger. The four large moons lie within this belt of radiation, and it affects them. Sulfur and sodium atoms blasted out of Io by volcanoes form a glowing, doughnut-shaped band in Io's orbit around Jupiter. An intense 3-million ampere electric current links Io to the top of Jupiter's atmosphere, continuously flowing from moon to planet and back again. Further out, beyond the moons, there is a region of space where the atomic particles are so energetic that their temperature has risen to about 3 million degrees, the hottest place in the solar system except for the Sun.

The Jovian system of Jupiter and its moons is a place where all the forces of the solar system—atmospheres, volcanoes, cratering, magnetism, charged particles, radiation—are present on scales so vast that they inspire excitement and awe. We have seen only partially and briefly the wonders that exist there, and we are only beginning to understand it all.



Saturn

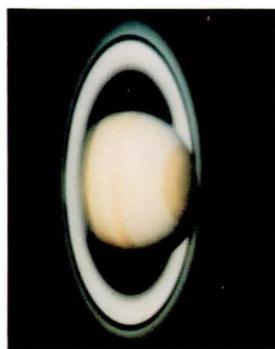
To ancient astronomers, Saturn was a wandering light near the edge of the known universe. The planet and its rings have been objects of beauty and wonder ever since Galileo noticed the "cup handles" that seemed attached to a round world.

Saturn is a smaller version of Jupiter, made up of a similar mix of gases, mostly the very light hydrogen and helium. Like Jupiter, all we see of Saturn is the tops of its clouds. With their subdued hues of yellow, gray and brown, they lack the sharp, brightly

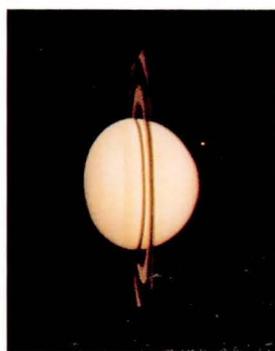
Saturn comes of age. Saturn, the most distant planet known to the ancients, was finally reached by spacecraft in 1979 and 1980. These three pictures show how our ability to see the details of the mysterious ringed planet has grown dramatically in the last few years as we have moved from Earth-based telescopic observations (1 and page 34) to pictures returned from spacecraft that actually flew past Saturn, Pioneer Saturn (2 and page 36) and Voyager 1 (3 and page 37).

The telescopic view from Earth (1) shows the planet, which is about 115,000 kilometers (71,000 miles) in diameter and is distinctly flattened at the poles. Faint colored bands are visible in the atmosphere, and the multiple nature of the rings can be seen. The Pioneer Saturn picture (2) was taken from about 2.5 million kilometers (1.6 million miles) away; it shows one of Saturn's moons (Rhea, lower right) as a tiny dot. In this picture Saturn's rings are illuminated by sunlight scattered through them, so that only the thin rings appear bright; the thickest ring (the B ring) appears as a dark band between the two bright ones. The shadow of the rings is a dark band on Saturn's equator.

The Voyager 1 TV picture (3), taken from a distance of 34 million kilometers (21 million miles), shows details in the rings that are invisible to Earth-based telescopes or to Pioneer Saturn. A new gap has appeared in the dark inner C ring, and material is now visible within the surrounding empty Cassini division that separates the two largest rings (the A ring and the B ring). The dark band on the planet's equator is the shadow of the rings. Some of the details of the structure of the rings can also be seen in the shadow. The small dot below Saturn is its moon Dione. (Photo 1 courtesy of Catalina Observatory, Arizona.)



1



2



3

colored belts of Jupiter. Above the clouds there seems to be a high haze of frozen ammonia crystals. Saturn's rings, its best known feature since Galileo's time, stretch far out around the planet, extending to more than half the distance from the Earth to the Moon. They actually consist of a series of individual rings separated by small gaps and composed of huge numbers of small particles. Saturn has at least 15 moons, some only recently discovered by passing spacecraft. Among those that have long been known is Titan, one of the largest moons in the solar system, massive enough to retain a thick, cold atmosphere that obscures any view of its surface. Organic compounds are present on Titan, and it has occasionally been speculated that life may exist there.

Saturn is far out. A billion miles from Earth, the planet was not reached by any spacecraft until September, 1979, when *Pioneer Saturn*, after a six-year trip by way of Jupiter, flew past the rings to within 21,000 kilometers (13,000 miles) of Saturn's cloud tops. *Voyager 1*, with better, more sophisticated instruments (which had explored Jupiter in 1979) reached Saturn slightly more than a year after *Pioneer*. On November 12, 1980, *Voyager 1* ducked under the rings, passed Saturn at 124,000 kilometers (77,000 miles) above the cloud tops, crossed the ring plane again, and headed out of the solar system at 90,000 kilometers per hour (56,000 miles per hour). In a few hectic days, the television cameras and other instruments of *Voyager 1* told us more about Saturn, its rings, and its moons than was learned in all the centuries that people have studied this strange and beautiful world.





These closeup looks at Saturn revealed several properties that the ringed planet shares with Jupiter, as well as some differences. Like Jupiter, Saturn is radiating away about twice as much energy as it receives from the Sun, but its frigid cloud tops have a temperature of about -183°C . *Pioneer Saturn* discovered that Saturn has a magnetic field. The field is much weaker than that of Jupiter, but it is probably produced in the same way, by circulating flows of liquid metallic hydrogen deep within the planet that generate electric currents and thus create a magnetic field. Saturn's magnetic field fills a smaller volume of space than does Jupiter's, and its radiation belts are correspondingly weaker. In fact, Saturn's radiation belts are comparable in intensity to the Van Allen Belts of Earth.

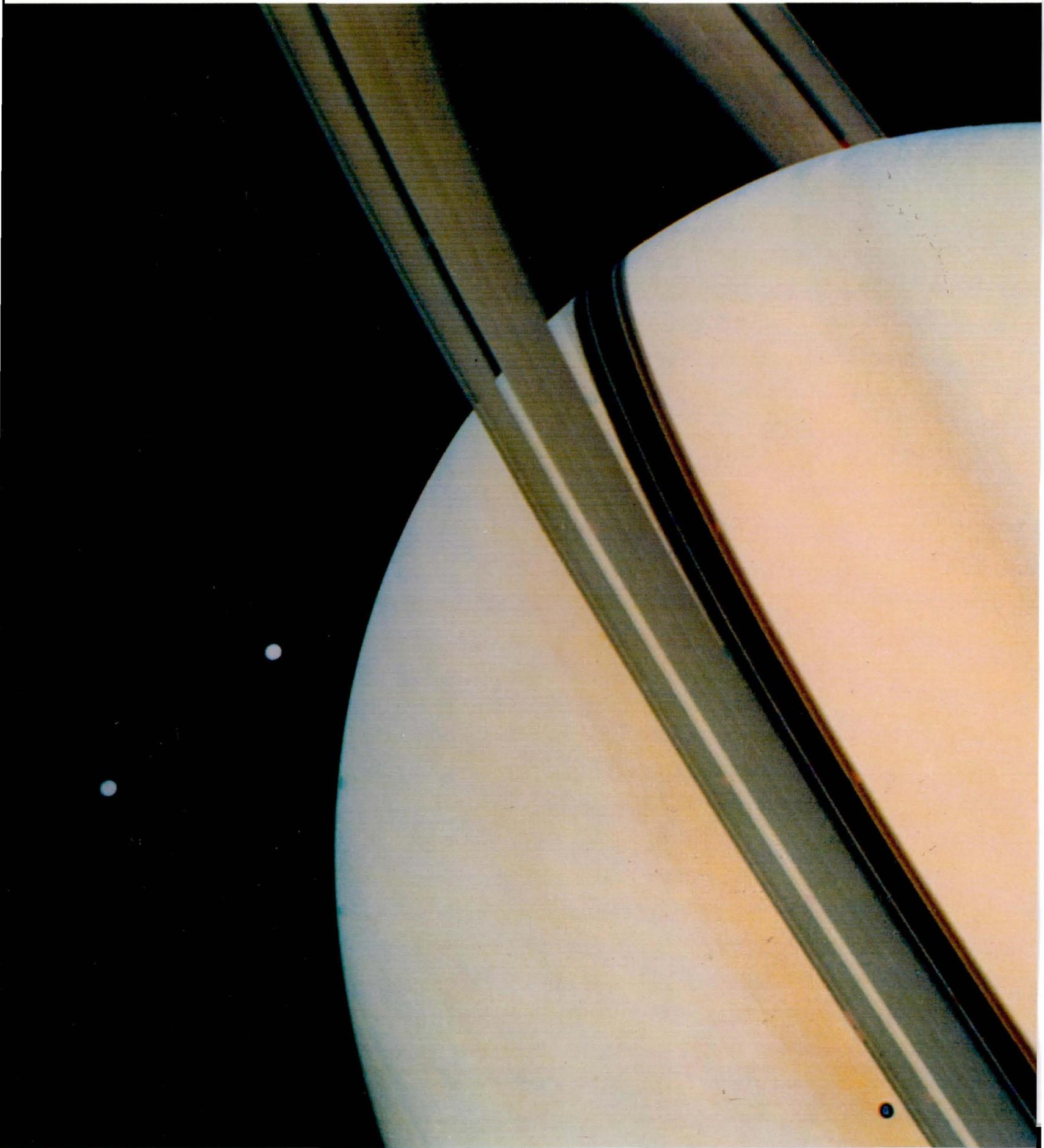
As *Voyager 1* approached Saturn, the planet's atmosphere began to show structural details within the indistinct, faintly colored bands. The television cameras peered through the frozen ammonia haze, down to the thicker clouds. At this still fairly distant range, Saturn looks more like Jupiter. Turbulent belts and streams of clouds stretch east-west across the planet. Cloudy jet streams were photographed that move four times as fast as the winds of Jupiter, as much as 1500 kilometers per hour (930 miles per hour). A red oval was found in the clouds, a swirling storm like Jupiter's Red Spot, but much smaller (only about the size of the Earth!).

Saturn's rings are a landmark of the solar system. They seem solid, but we have long known that they are made up of innumerable particles of water ice and perhaps frozen ammonia, a few centimeters to a few meters in size. Nevertheless, in close-up, the

rings were one of the biggest surprises in the history of planetary exploration, far more numerous, complex, baffling, and beautiful than ever was expected. From Earth, we could clearly see only three rings. *Pioneer Saturn* discovered three more. But as *Voyager 1* drew close, the once seemingly uniform rings separated into dozens and then into hundreds of distinct, thin rings separated by narrow gaps. As *Voyager 1* flew under Saturn, the rings stretched above the spacecraft like a huge rainbow and the *Voyager* cameras photographed perhaps a *thousand* separate rings, looking like the grooves of a cosmic phonograph record. Even in the Cassini division, a dark, seemingly empty band as seen from Earth, *Voyager 1* photographed over 50 of the thin rings, floating within what had long been regarded as a permanent empty space in the ring system.

The rings are far more complicated than anyone had imagined. For some unexplained reason, a few rings are not circular but appear elliptical, as though some force has pulled them a little out of round. The thin, outer F-ring was resolved by *Voyager 1* into several distinct strands that apparently are braided about each other. Equally mysterious and unexpected are the so-called "spokes," radial bands cutting right across the rings

A close look at a large planet. The looming shape of Saturn stretches across this picture taken by Voyager 1 from 13 million kilometers (8 million miles) away. Nearby and to the left are two of Saturn's moons, Tethys (above) and Dione (below), each about 1000 kilometers (622 miles) in diameter. Saturn's rings stretch from upper left to lower right. The Cassini division, the narrow gap between the large A-ring and the B-ring, is clearly visible, and Saturn's cloud tops can be seen through it. The shadow of the rings is a series of light and dark bands that stretches across the planet. The small black dot at the lower right is the shadow of the moon Tethys.





Spokes in Saturn's wheel. The dark, finger-like area which cuts across Saturn's bright B-ring is one of the many baffling spokes detected in Voyager 1's close-up pictures. The spokes rotate around Saturn with the rings, and individual spokes may persist for several hours. The existence of such objects that cut radially across the rings is baffling. Inner ring particles move around Saturn faster than outer ones, and the radial structure of the spokes should be quickly destroyed as the particles move past each other. The spokes appear dark in reflected sunlight (as in this picture, taken when Voyager 1 was between Saturn and the Sun), but they appear bright when photographed by forward-scattered sunlight from the other side of Saturn. This behavior suggests that the spokes are actually clouds of fine dust that are carried around Saturn by its magnetic field, but there is still no definite explanation. This Voyager 1 photograph was taken from a distance of 51 million kilometers (32 million miles).



A rainbow of rings. The intricate baffling details of Saturn's rings are spread out in this computer-enhanced view taken by Voyager 1 at a distance of 8 million kilometers (5 million miles). At least 95 separate rings are clearly shown, far too many to be explained by our current theories of simple gravitational forces between Saturn's nearby moons and the ring particles. At the upper left, the thin outer F-ring appears as a narrow curved streak beyond the main body of the rings. The tiny dot nearby is a small moon discovered by Voyager 1, one of a pair that seems to act like shepherds, keeping the thin F-ring in place.



much like the spokes in a wagon wheel. They may be clouds of fine dust, held in place by electrical forces generated around the rings, but no one really knows.

The *Voyager 1* pictures demolished all existing theories about Saturn's rings. Previously, the structure of the few known rings and gaps was explained in terms of the gravitational influence of some of Saturn's adjacent moons on the small ring particles. Indeed, *Voyager 1* did show how this mechanism may work on a small scale: Two small moons were discovered, one on each side of the thin F-ring. The pair may be "shepherds," their gravity keeping the ring particles from moving in or out of their present orbits. A third small moon, discovered just outside the large A-ring, may have a similar stabilizing effect.

These examples are helpful, but they are not enough. No theory involving only a few moons can explain the presence of a thousand narrow rings, the elliptical rings, the ring braids, or the spokes. Nor can we yet explain how the delicate rings apparently have survived over the 4.5-billion-year age of the solar system. The

problems of the rings are now seen more fully and clearly, and unfortunately, they are more complex. New theories are needed to understand the entire fantastic Saturn system.

In its dash past Saturn, *Voyager 1* photographed seven of the planet's large moons, previously unexplored worlds that had been only tiny spots of light in earthbound telescopes, despite their fanciful mythological names: Mimas, Enceladus, Tethys, Dione, Rhea, Titan, and Iapetus. Even before *Voyager 1* arrived, we thought that these moons would be different. In this cold, distant region of the solar system, water does not exist as a liquid but as ice, in effect a brittle kind of rock. Saturn's moons are huge icebergs, perhaps with small cores of true rock, and they may be more like huge versions of the nucleus of a comet than like our own rocky Moon.

Just like the moons of Jupiter, Saturn's moons displays a variety of weird landscapes. Mimas, Dione, Tethys, and Rhea all have heavily cratered terrain, presumably the result of bombardment by smaller objects shortly after the moons formed about 4.5 billion years ago. On Mimas there is one large crater that makes the moon resemble a huge, staring eyeball. The crater is so big that the impact that formed it must almost have shattered Mimas into pieces. The landscape of Rhea, photographed close up as *Voyager 1* skimmed past only 72,000 kilometers (45,000 miles) above its north pole, resembles the cratered lunar highlands and the battered surface of Mercury, but Rhea's craters have been cut in *ice*, not in rock.

The craters are caused by an external force, the cosmic bombardment of Saturn's moons, but some of the moons have clearly also been modified by internal forces. Tethys has a huge

Iceworld. *The ancient, cratered surface of Saturn's moon Dione may record an intense bombardment by smaller objects (planetesimals) when Saturn and its moons formed. Dione, which is about 1100 kilometers (684 miles) in diameter, is composed largely of ice, though it may have a small amount of denser rocky material scattered through it or forming a small core. The largest crater in the picture is about 100 kilometers (62 miles) in diameter and shows a prominent central peak. White streaks on the left side may be rays of material thrown out of a crater on the other side of Dione. Similar cratered landscapes were photographed on other moons of Saturn—Mimas, Tethys, and Rhea. Dione's surface shows evidence of internal forces as well. A long crack at the lower right near the shadow may have been produced by spreading of the moon's icy crust.*

trench, 60 kilometers (37 miles) across and about 750 kilometers (470 miles) long, perhaps a great crack in a spreading crust. Rhea and Dione display strange streaks and swirls, side-by-side with heavily cratered regions, as though the icy crusts shifted and deformed after the craters were made.

The moon Enceladus was a surprise of a different kind; its surface is smooth and crater-free, even though it orbits Saturn between the heavily cratered moons Mimas and Dione. Perhaps Enceladus is heated by tidal forces imposed by nearby Dione. (Similar tidal heating of Jupiter's moon Io is strong enough to power Io's constantly erupting volcanoes.) Such heating could warm Enceladus' icy crust, deforming it and removing the traces of once-present craters. Perhaps the heating is so strong that icy volcanoes erupt from time to time and floods of molten "lava"—in this case just water—pour briefly across the surface of Enceladus.

Saturn's distant moon Iapetus, photographed at long range by *Voyager 1*, is even more of a mystery. Telescopic studies from Earth show that Iapetus has two different sides, one dark and one bright. *Voyager 1* pictures showed the two regions and their sharp boundary but as yet provide no explanation of the mystery.

Titan is a unique, giant moon, a world about the size of the planet Mercury. It is the only moon in the solar system known to have an atmosphere. Already from Earth we had detected methane and other organic compounds, so *Voyager 1* was carefully programmed to take an especially close look at Titan. It flew past Titan

only 4000 kilometers (2500 miles) above the atmosphere, the closest flyby past any cosmic object in the history of space exploration. The accuracy involved is comparable to shooting a billiard ball 3200 kilometers (2000 miles) across a giant table and sinking it in the right pocket.

Titan's atmosphere is so thick, perhaps more than 200 kilometers (125 miles) deep, that the *Voyager 1* cameras could not see to the surface. Surprisingly, the atmosphere is not rich in the methane detected from Earth. Instead, the most common gas is nitrogen, just as on the Earth itself. Methane makes up only about one percent of the air of Titan. More complex organic molecules, formed by the action of sunlight on the atmospheric gases, produce a natural smog not too different from the choking haze found over many of our cities. At Titan's surface, the atmospheric pressure is two or three times that on Earth, but the temperatures are as low as -150° to -200° C.

The unseen surface of Titan may be a bizarre, frozen swamp, with murky streams and lakes of liquid nitrogen and a cold rain of nitrogen and organic chemicals sleeting down. There may be no life in that incredible cold after all, yet Titan may preserve in its deep freeze a sample of what other primitive atmospheres (including Earth's) resembled before they were changed by phenomena that probably have never affected Titan: volcanoes, oceans, and life.

Saturn and its moons still have much to tell us and doubtless more surprises in store.





The Lord of the Rings. In this montage of individual Voyager 1 pictures, Saturn is surrounded by the newly revealed faces of six of its moons. Below Saturn at the right is Tethys, a heavily cratered moon with a long mysterious trench running along its surface. To the left of Tethys, just below Saturn's rings, is Mimas, a tiny, pockmarked moon on which one huge crater can be seen. Enceladus is just below the left-hand edge of Saturn's rings;

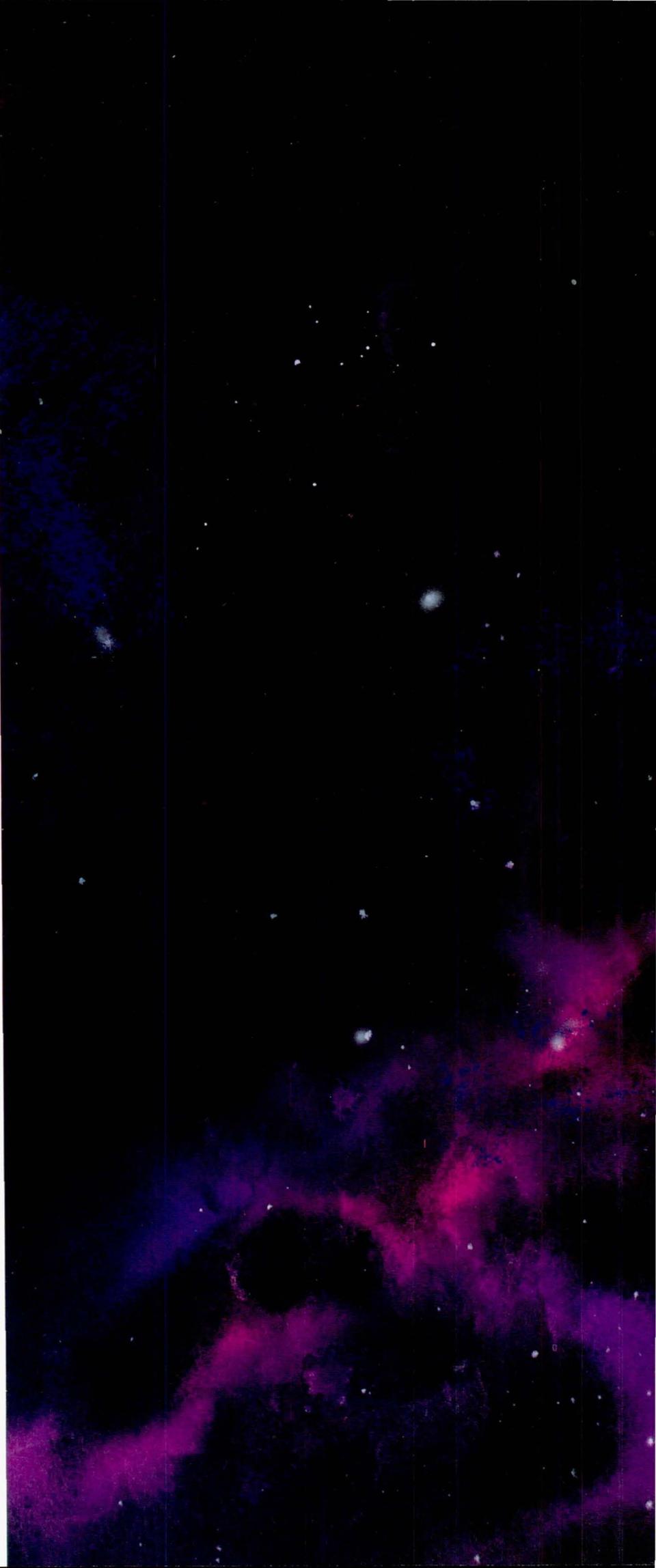
this moon displays a puzzling surface, smooth and apparently uncratered. In the lower left corner is Dione, a brownish moon with a heavily cratered surface. Rhea, at the far left near Saturn's rings, shows a faint bluish tinge and strange patterns of white, wispy swirls on its surface. Titan, Saturn's largest moon, is shown in its distant orbit at the upper left. Titan's thick orange-brown atmosphere completely conceals its surface.

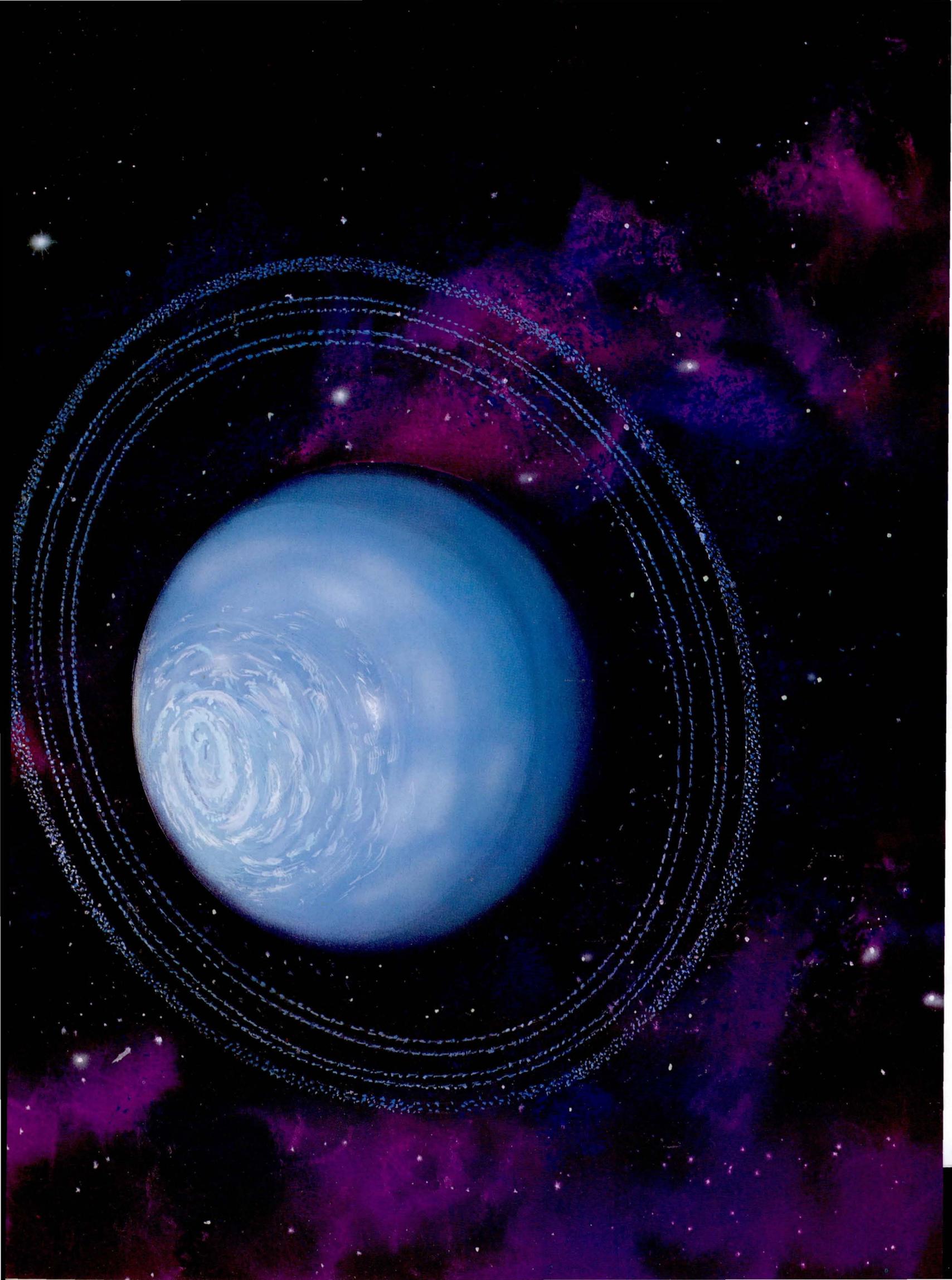
Uranus

The ancients knew of five planets in the sky. In less than a generation, all five have been brought close to us by spacecraft. Further out in space, three more planets await our inspection. Uranus, the first outward beyond Saturn, is nearly 3 billion kilometers (nearly 2 billion miles) from the Sun and takes 84 years to make one orbit around it. *Pioneer 10* passed the orbit of Uranus, but did not come near the planet. Uranus is another gas giant, smaller than Saturn, a cold world that is a distant greenish disk even in the largest telescopes. From Earth, we can see five moons circling the planet. Uranus has one unique property: its axis of rotation lies in the plane of its orbit rather than nearly vertical to it as is the case with the other planets. Because of this curious orientation, Uranus moves around the Sun, not so much like a top spinning on its end, but like a barrel rolling along on its side.

The greatest Space Age discovery about Uranus was made in 1977, not from a spacecraft but rather with a telescope mounted in a high-altitude jet aircraft, the Kuiper Airborne Observatory. Like many great discoveries, it was entirely unexpected, and the scientists were looking at Uranus

***Dark rings of Uranus.** Discovered by telescopic observations from a NASA aircraft in 1977, the rings around the planet Uranus are painted here as they might appear from a spacecraft approaching the planet. The thin narrow rings, composed of dark particles, are invisible from Earth. They were discovered when they blocked the light of a distant star on a night when Uranus passed in front of it. The rotation axis of Uranus lies almost in the plane of its orbit around the Sun, so the ring system (in the plane of the planet's equator), appears like a gigantic bullseye as Uranus rolls around the Sun. Uranus is so distant that no spacecraft has yet reached it. Voyager 2 may go on to Uranus after passing Saturn in 1981; it would get there in 1986.*



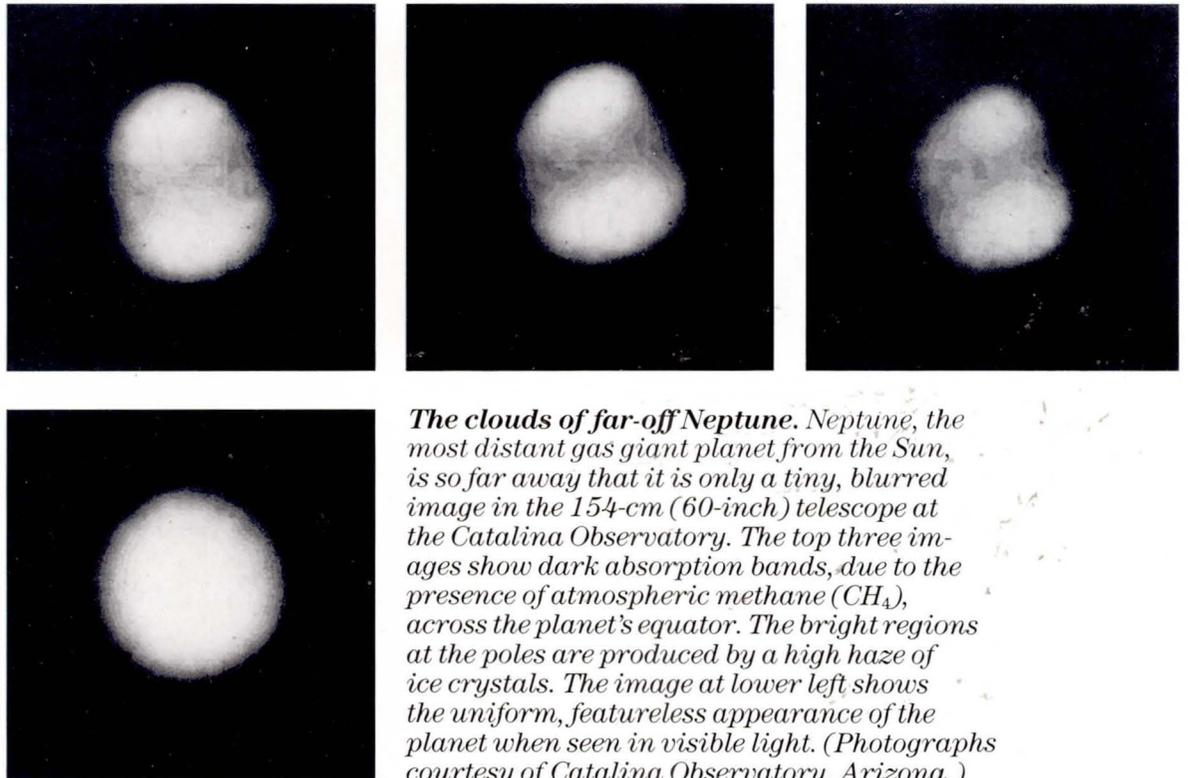


for something entirely different. They intended to study Uranus' atmosphere by measuring the light from a distant star as the planet passed slowly in front of it. What happened was that the star seemed to flicker on and off several times, long before *and* long after the planet had passed in front. The only explanation was that Uranus—like Saturn and now Jupiter—has rings! The planet is surrounded by at least five and perhaps nine rings. The rings are dark, thin, narrow, and invisible from Earth, but they were thick enough to block out the light from the star.

Uranus may soon have its first visitor from Earth. The spacecraft *Voyager 2* is now following a path that will take it past Uranus in 1986.

Neptune

Neptune is even further out, 4.5 billion kilometers (2.8 billion miles) from the Sun. Through the telescope it is a green, featureless world, about the size of Uranus. Two moons have been detected. Neptune has remained untouched by the activity of the Space Age, although clouds have been detected in its atmosphere. The planet remains an enigma, too far away to see well from Earth, almost too far away to reach.



The clouds of far-off Neptune. Neptune, the most distant gas giant planet from the Sun, is so far away that it is only a tiny, blurred image in the 154-cm (60-inch) telescope at the Catalina Observatory. The top three images show dark absorption bands, due to the presence of atmospheric methane (CH₄), across the planet's equator. The bright regions at the poles are produced by a high haze of ice crystals. The image at lower left shows the uniform, featureless appearance of the planet when seen in visible light. (Photographs courtesy of Catalina Observatory, Arizona.)

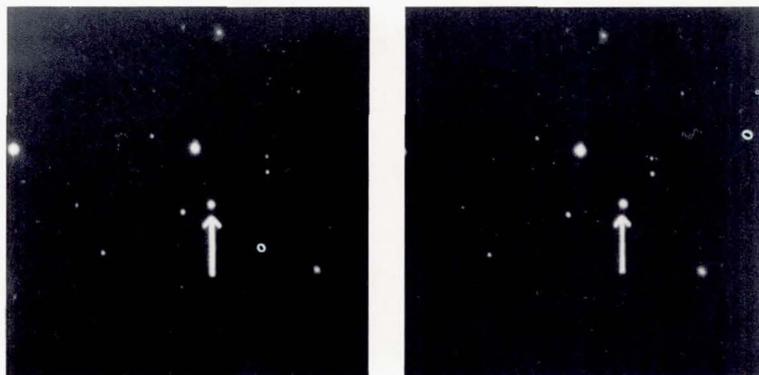
Pluto

Pluto is a planetary oddball, a strange world that has baffled scientists ever since it was discovered in 1930. It is not the large gas giant that one might expect to find in the outer reaches of the solar system. Instead, it is a small world, much smaller than the Earth, and in fact roughly as large as our Moon. It is probably composed of a mixture of rock and ice. It even has been suggested that Pluto is not a genuine planet, but simply a moon that somehow escaped from Neptune.

Pluto is usually the farthest known planet from the Sun, its mean distance almost 6 billion kilometers (almost 4 billion miles) out. It takes 248 years for Pluto to complete one orbit around the Sun, but the orbit is so elongated that it actually spends about 20 years of this time inside the orbit of Neptune. (In fact, Pluto is inside Neptune's orbit now, and will be until 1999, so that *Neptune* is temporarily the furthest planet from the Sun.)

Despite Pluto's distance and the extreme difficulty of observing it, our view of the faraway planet has changed greatly in the last few years. As we have looked more carefully, Pluto has become an even smaller and brighter object than we thought it was. It seems to have a bright layer of frozen methane ("marsh gas," chemically CH₄) on its surface. Even more surprising, reexamination of old photographs revealed that Pluto is not alone; it has a moon. Pluto now seems to be about 3000 to 3500 kilometers (1900 to 2200 miles) in diameter. Pluto's moon, Charon, is large by comparison, about 1200 to 1500 kilometers (750 to 930 miles) in diameter, so that the two bodies form a kind of unique double planet.

Pluto will hold its secrets for a long time yet. It is simply too far away for our current spacecraft to reach it in a reasonable length of time. It will be many years before any machines or humans see Pluto up close, dimly lit by a Sun so distant that it seems like just a rather bright star in the blackness of space.

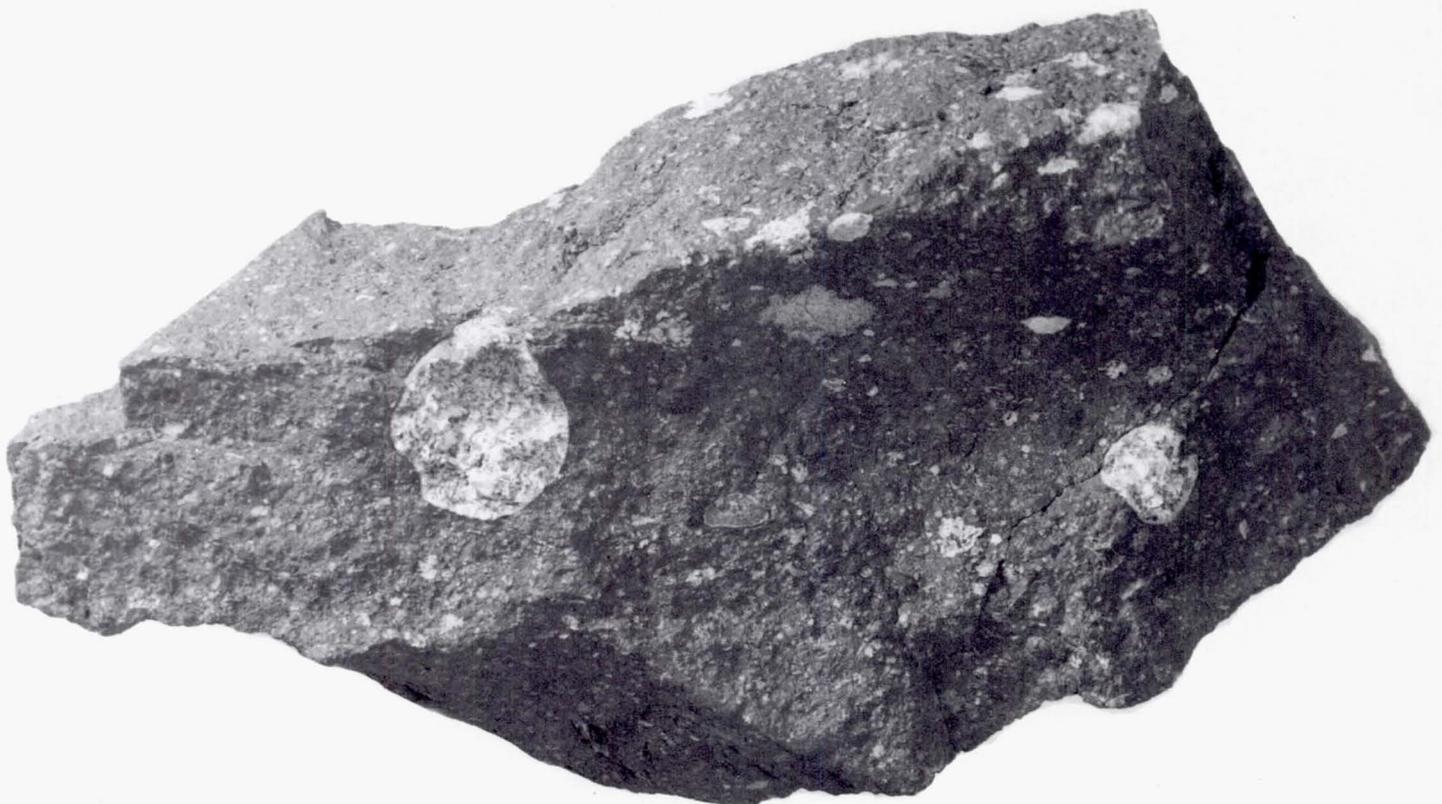


***The last planet?** Tiny, mysterious Pluto is so far from the Sun that it appears only as a tiny speck of light (arrow) that moves slowly against the background of the fixed stars. So inconspicuous that it was not discovered until 1930, Pluto is not a gas giant planet like all the others in the outer solar system. Instead it is a small, rocky world about the size of Earth's Moon. Recent examinations of old photographs, combined with new observations, indicate that Pluto itself has a moon.*



New member of the family. A tiny trail of light across a field of fixed stars reveals the track of a recently discovered member of the small group of asteroids that cross the orbit of the Earth. The new arrival, Ra-Shalom, was 29 million kilometers (18 million miles) from Earth when this picture was taken. The grainy background is due to the great enlargement from the original negative. (Courtesy of Eleanor F. Helin, California Institute of Technology.)

Rare chunk of cosmic history. White fragments in this dark, carbon-rich meteorite that fell on Mexico in 1969 contain minerals formed at high temperatures, perhaps among the first substances to condense as the solar system began to form from a huge cloud of hot gas and dust. Some of the white pieces also contain material that is chemically different from the rest of the meteorite, and which may have come from a nearby star that exploded shortly before the solar system was born. (Courtesy of Brian Mason, National Museum of Natural History, Smithsonian Institution.)



Minor Objects in the Solar System

The nine planets and at least 39 moons are only a tiny part of the population that circles the Sun. There are huge numbers of smaller objects: comets, asteroids, large cosmic rocks and small pebbles, and innumerable particles of dust. Each object makes its own contribution to the solar scenery, and each has its own secrets to reveal. These small objects have been less studied, and none have yet been visited by a spacecraft. Our main source of information has been observations through the telescope and study of meteorites, which are part of the extraterrestrial materials that fall to Earth at a rate of several hundred tons per day.

Asteroids and meteorites

There is no planet between Mars and Jupiter. Instead, there are a great many small objects called *asteroids* where a planet might have formed. About 2000 have been observed sufficiently so that their orbits are known. Most of them are irregular rocks a few kilometers across, but a dozen are about 250 kilometers (160 miles) or more in diameter. The largest, Ceres, has a diameter of about 1000 kilometers (about 600 miles) and is roughly the size of Texas. It has been estimated that there may be a half-million asteroids larger than one kilometer (0.6 miles) in diameter, nearly all too small to be observed by current methods.

Most asteroids have orbits that remain between Mars and Jupiter, in a region called the asteroid belt, but a few have orbits that cross the orbit of the Earth. These "Earth-crossers" are called the Apollo-Amor asteroids (named after two of their number). The most famous member of the group is Icarus, discovered in 1949, and so named because it actually goes closer

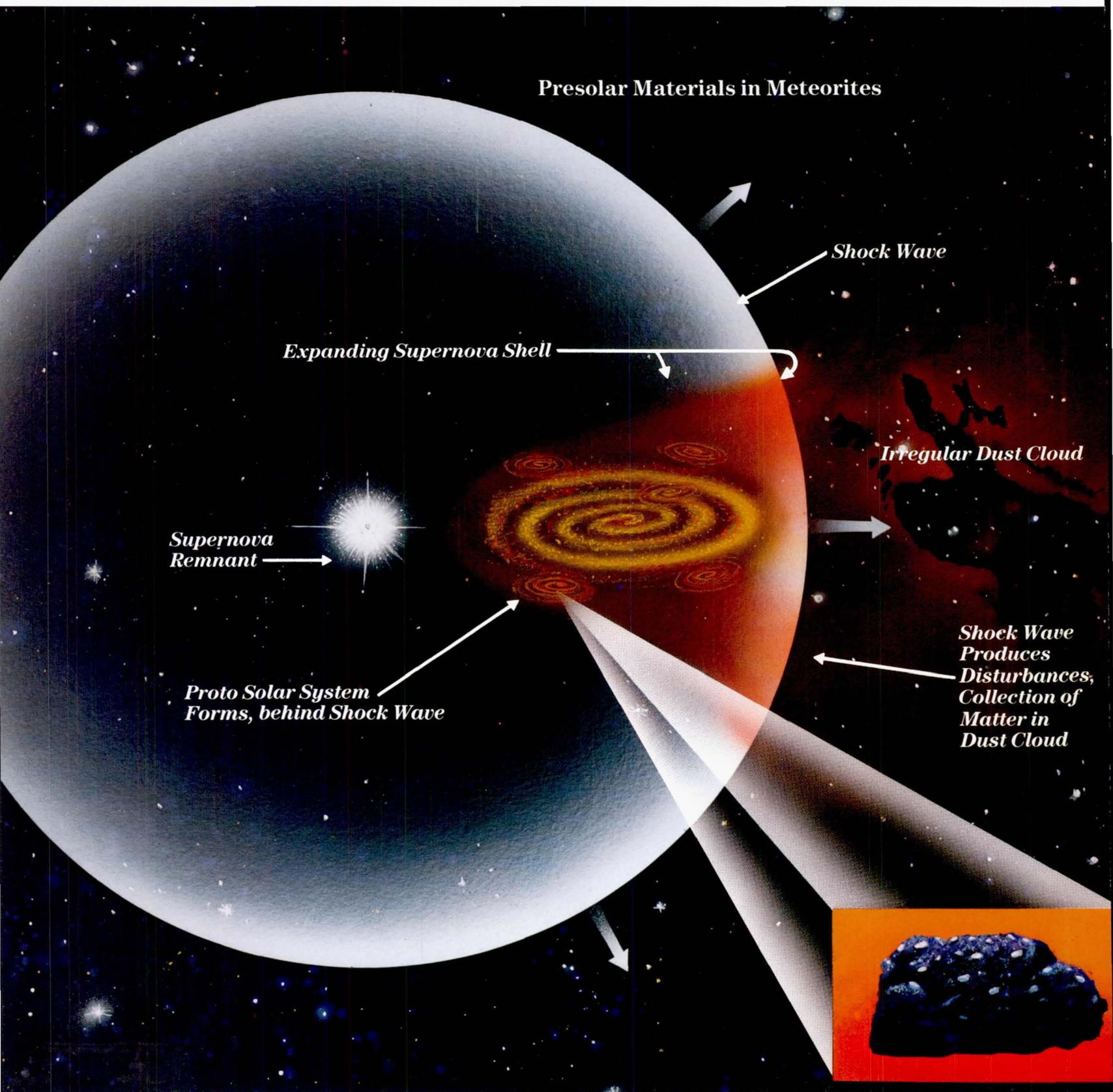
to the Sun than Mercury. It came within 6.5 million kilometers (4 million miles) of the Earth in June, 1968.

Recent observations have detected other members of this Apollo-Amor group in the sky. The geological record on Earth also bears witness to these Earth-crossers, for about 100 ancient meteorite impact craters have been detected, each one possibly representing an asteroid that didn't quite make it past the Earth. Some of these collisions must have been unbelievable catastrophes; the two largest known craters, one in Canada and one in South Africa, are more than 100 kilometers (60 miles) in diameter.

Smaller bits of asteroids also collide with the Earth, although less violently and more frequently. These objects, called meteorites, have provided us with extraterrestrial samples for centuries, long before we were able to collect rocks from the Moon. We think that they come from the asteroid belt. If this is right, then there must be a great variety of objects out there, for meteorites are very different. Most meteorites are stones containing many glass droplets, but others are pieces of lava flows, chunks of solid nickel-iron, and even bits of dark, carbon-rich materials containing significant amounts of water.

Meteorites are among the most ancient solar system samples we have. They date from the formative stages of the solar system 4.5 billion years ago, and they are the only source of direct information about the physical and chemical processes that went on as the Sun and the planets grew from a collapsing cloud of dust and gas.

Studies of meteorites during the Space Age provide specific details about the solar system's birth and early years. Some meteorites seem to be pieces of actual lava flows that poured from ancient volcanoes on



Presolar Materials in Meteorites

Supernova Remnant

Expanding Supernova Shell

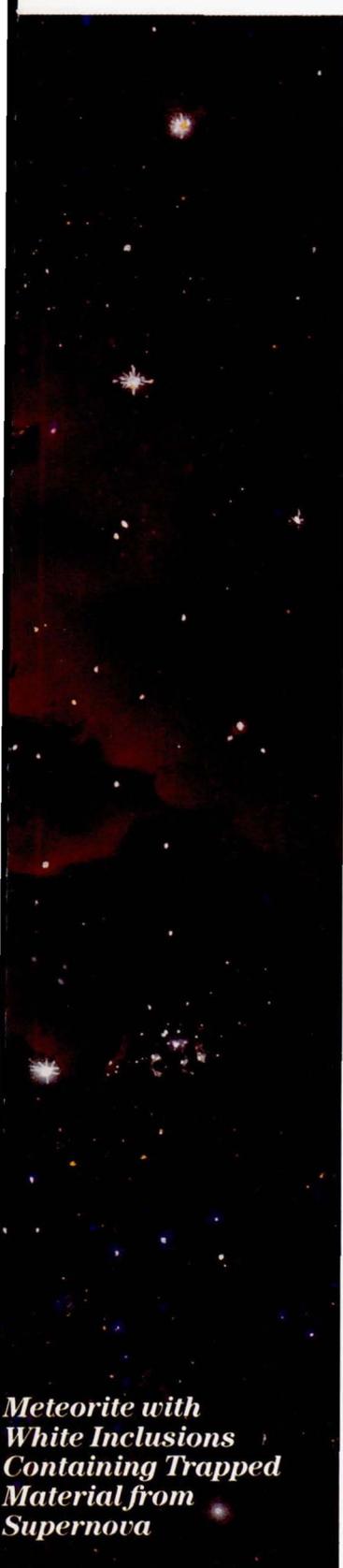
Shock Wave

Proto Solar System Forms, behind Shock Wave

Irregular Dust Cloud

Shock Wave Produces Disturbances, Collection of Matter in Dust Cloud

Sample from the stars. An artist's impression shows how material from another star might have been trapped in meteorites as the solar system formed. The explosion of the star (supernova) sends a shock wave through interstellar dust clouds. Material from the star, carried along by the wave, is trapped in the first meteorites formed and thus preserved before it is strongly diluted with other solar system materials. It is possible that passage of the shock wave also induced the cosmic cloud to begin the condensation that gave birth to the solar system.



small asteroids heated by primordial radioactivity. The carbon-rich materials in some meteorites contains amino acids—so-called “building blocks” of life—which give us new insight into the possible occurrence of life in the universe. White rock fragments from a meteorite that fell in Mexico in 1969 are composed of high-temperature minerals that may have been the first materials to form as the solar system came into being.

The white fragments document more than just the beginning of the solar system: They may contain records that actually date from “before the beginning.” Some of the fragments contain anomalous material that is chemically unlike the matter that makes up the solar system. (The chemical elements are the same, but the abundance patterns of certain elements are different.) This chemically unusual material did not come out of our own Sun. It may have come from another nearby star, perhaps flung out in a violent supernova explosion to enrich the cloud of gas and dust where the solar system later formed. The discovery also suggests that shock waves from the supernova passed through the cloud, triggering the condensation that eventually produced the Sun and the planets. Thus, through laboratory analyses of the meteorites, we can now see back in time beyond the formation of the solar system itself.

Meteorites also tell much about what the asteroids are like. Using ground-based telescopes and spectrometers, we are able to make crude chemical analyses of individual asteroids by analyzing the light that they reflect. Comparing these data with the results of meteorite studies, we have determined that the asteroids can be divided into families that are similar to the different groups of meteorites, although we have not yet been able to link a meteorite group uniquely to a specific asteroid.

The origin of asteroids has also been illuminated by meteorites. The asteroids were once thought to be the remnants of an exploded planet. Meteorite studies have disproved this idea, and the asteroids are now thought to have formed as small objects in a region where the gravitational tug-of-war between Jupiter and the Sun prevented a larger body from coming together.

We now know enough about asteroids to ask some exciting questions. Do they hold records of the actual formation of the solar system? How can such small bodies have developed with such a variety of compositions and histories? Among the unanswered questions are some that may be of more than scientific importance. How many asteroids are there? How many undiscovered ones cross the Earth’s orbit? When might another catastrophic collision occur?

*Meteorite with
White Inclusions
Containing Trapped
Material from
Supernova*

Comets

Comets are the shining wanderers of the solar system. With their glowing tails that may stretch 100 million kilometers (60 million miles) through space, they are conspicuous, remarkable, and exciting objects. Their appearances often have been superstitiously associated with disasters and (more recently) with brief periods of intense scientific study.

Most comets reside in the outer fringes of the solar system, far beyond Pluto. In fact, the solar system probably is surrounded by a huge cloud of more than a hundred billion comets that may stretch a third of the way to the nearest star. Almost all remain there in the frozen darkness, but on rare occasions they are perturbed (perhaps by the gravity of a nearby star) and a comet may be sent on a long trip down to the Sun and back out again.

For all their apparent size in the sky, comets are actually fairly small objects. When a comet begins its trip down past the Sun, it is probably a chunk of "dirty ice," a mixture of rock dust and ice a few kilometers across, much smaller than the typical observed asteroid. As it speeds toward the Sun, the heat from the Sun evaporates the ice, and the gases thus released blow dust particles outward from the solid body or *nucleus*. Radiation from the Sun ionizes the released atoms, producing a tail that glows in the sky like a neon sign; the

dust particles reflect sunlight and form another, smoother tail. The tails seem white to the eye, but color photography reveals that the ionized gas tail is blue and the dust tail yellow. Although the tails may be bright, they are thin, and stars show through.

The small nucleus, the only even near-permanent part of a comet, is surrounded by the *coma* or head of the comet, a large, hazy structure formed by the liberated gas and dust. From the coma, the tails sweep back in the direction opposite the Sun, driven by the pressure of sunlight and by the solar wind. In 1970, an instrument on the Earth-orbiting satellite OAO-2 (named the *Orbiting Astronomical Observatory*) revealed that comets are surrounded by huge clouds of hydrogen gas, produced when ultraviolet light from the Sun decomposes the cometary gas. Later, the hydrogen cloud of the bright Comet Kohoutek was scanned by a photometer on *Mariner 10*, and the comet was photographed in ultraviolet light from *Skylab*. Aboard *Skylab*, astronaut Ed Gibson was able to view the comet when it was very close to the Sun, and he discovered a unique "anti-tail" pointing toward, rather than away from, the Sun.

Of the 100 billion comets that may exist, less than 1000 have been observed thus far as they make the long journey down to the heat of the Sun. Some comets now are trapped in smaller orbits, taking from a few to a few thousand years to complete one

Shining wanderer. A visitor from far beyond Pluto, Comet West seems to hover above Table Mountain in California shortly before sunrise in March 1976. The bright head of the comet is seen just above the mountains, while its long broad dust tail sweeps up and back from the nucleus, pushed outward by the pressure of sunlight. Comet West passed within 118 million kilometers (73 million miles) of Earth and will not return for another 560,000 years. (Courtesy of the Jet Propulsion Laboratory.)

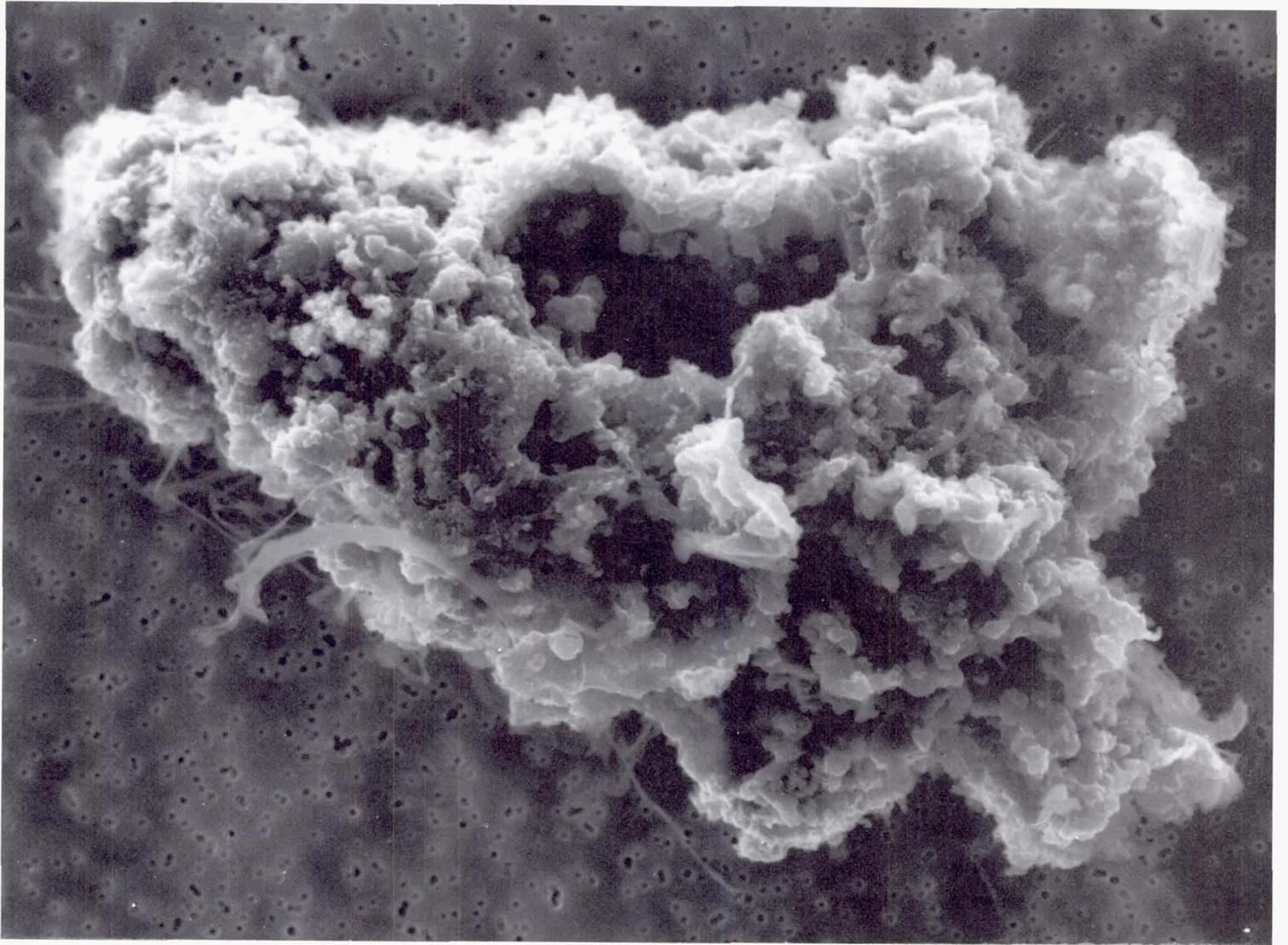
lap. Even so, most of them spend the bulk of their time in the cold, dark, outer solar system and just a tiny portion of their lives speeding in glowing splendor past the Sun.

Comets probably formed in the freezing darkness beyond Jupiter and perhaps beyond Pluto where they spend most of their lives. As a result, comets are probably the most primitive and the most unchanged original solar system materials that we can ever hope to sample and to study.

We have never yet sent a spacecraft to a comet. What we have learned

during the Space Age has come from ground-based telescopes, from a few unmanned satellites and sounding rockets, and from studies made in the *Skylab* space station. But excitement is building for a major event: the reappearance of Halley's Comet in 1985. Swinging on a long orbit that brings it by the Sun every 76 years, Halley's is one of the best-known and brightest comets, and scientists are already planning observing programs and possible spacecraft missions that may remove much of the mystery from this famous visitor.





***A speck from a comet?** Displayed in a close-up under an electron microscope, this tiny bit of cosmic dust may be our first sample of a passing comet. Less than one-tenth of a millimeter across, the particle is composed of millions of even tinier crystals. Although chemically similar to some meteorites, its fluffy, crystalline structure is unlike that of any known meteorite. Interplanetary dust particles like this are trapped in special collectors flown aboard high-altitude aircraft. Their interplanetary origin is established by analyzing the gases that they trapped from the Sun while still in space. The interplanetary dust is believed to come from comets, which shed material as they are warmed by the Sun. It may be possible to collect material from a particular comet when one passes close enough to the Earth some day.*

Dust

There is no lower limit to the sizes of the solid particles that move around the Sun. Small asteroids grade downward into large meteoroids and then into smaller pebbles and so on down to the tiniest particles of dust. The most numerous particles are the smallest ones. A particle larger than a millimeter (about one twenty-fifth of an inch) in diameter is a relative rarity in space, but even smaller particles exist by the uncountable billions. There are enough of them to reflect sunlight in a faint glow, called the *zodiacal light*.

Unlike planets and other large objects, dust particles are not permanent residents of the solar system. They spiral slowly inward toward the Sun. Over a million years or so, a typical particle will fall into the Sun, so that the current dust population must consist of fairly new arrivals, presumably shed from comets.

Because interplanetary dust particles may be actual samples of comets, strenuous efforts have been made to collect them. Many efforts failed

because of the rarity of the particles and the contamination of collecting devices by terrestrial dust. Recently, however, extraterrestrial dust particles have been successfully trapped with collectors mounted on high-flying aircraft.

The yield has been small so far: only about a hundred particles a few thousandths of a millimeter across. But recently developed instruments are so sensitive that even these tiny objects can be usefully studied. They are definitely extraterrestrial, for their chemical composition is like that of common meteorites (and not like that of the Earth), but they are fluffy, fragile objects, each particle a mosaic of millions of tiny crystals.

As we look ahead to the reappearance of Halley's Comet, we are continuing to collect and study the dust that may have been shed by comets in the past. Perhaps when Halley does appear, we may be able to do more than just look at it. We may be able to collect and analyze the very dust that it sheds as some of those tiny fragments drift down to our planet.

The Planetary Connections

If our goal in planetary exploration were simply to accumulate a list of impressive discoveries, then we have succeeded beyond our wildest expectations. But there is a larger purpose to our search through the solar system: to discover not just *what* planets are like, but also *how* they got that way. What forces formed and shaped young planets in the ancient past? What processes sculptured their surfaces, made or failed to make atmospheres, and brought forth or failed to bring forth life?

We cannot discover the general laws that govern all planets by studying only the Earth. We would never know whether things that are common on Earth (oxygen, water, and life) were abundant or absent elsewhere, and so we have gone to other worlds to find out. A new scientific discipline has arisen, *comparative planetology*, in which we study as many worlds as possible, looking for common characteristics amid the riot of individuality.

Finding how planets form and grow is motivated by more than just scientific curiosity. The Earth is a planet too. Our world and its life are the results of complex forces operating for billions of years. The more we learn about all planets, the better we can understand our own: its geologic past, the behavior of its atmosphere, and future climatic trends.

By going into space, we have discovered that certain basic planetary characteristics occur throughout the solar system, manifesting themselves in different ways on different planets. These general features include phenomena that affect the Earth itself: volcanism, meteorite bombardment, magnetism, atmospheric evolution, and weather and climate.

Volcanism

Volcanic eruptions seem to be a normal process in the development of terrestrial planets. The Moon is covered with dark lavas that have been identified, analyzed, and age-dated through samples brought to the Earth. Photos of as-yet-unsampled Mars reveal both huge volcanoes and surface rocks that resemble lavas. Mercury shows large surface features that also could be lava flows. Our blurred and indistinct radar views of Venus show some landforms that probably are large volcanoes. The asteroids also seem to have volcanic histories, for some of the meteorites that we find (themselves presumably asteroidal fragments) are pieces of ancient lava flows erupted at the very beginning of the solar system. Even Jupiter's moon Io has its own collection of strange, sulfur-spouting volcanoes.

Meteorite bombardment

Before we went into space, meteorite bombardment seemed an unimportant process. Only about a dozen small meteorite craters were known on the Earth, and many scientists thought that the Moon's craters were all ancient volcanoes. Now we know that intensive bombardment by meteorites in the past was the rule, not the exception, among the planets. The Moon suffered a violent bombardment in its earliest years, more than 4 billion years ago, and the traces are still seen in the heavily cratered lunar highlands.

Other planets show traces of the same ancient cosmic battering. The whole surface of Mercury resembles the lunar highlands, saturated with overlapping craters. The southern half

of Mars likewise was battered, although its large craters have been deeply eroded. Venus bears traces of what may have been large impacts. Even Callisto, the icy moon of a gas giant world, displays much the same cratered surface that Mercury does.

Is the Earth unique? It shows no obvious large meteorite craters. Did it somehow escape the bombardment? No. The ancient Earth must have been pounded and shaped by meteorite impacts just like the worlds near it. But the ancient craters, like the Earth's oldest rocks, have been destroyed by the continuous volcanism, erosion, and mountain-building that characterize our planet. Nearly 100 ancient craters, now identified in the geological record, show that the Earth has been, and still presumably is, subject to meteorite impacts.

Meteorite impact has continued through time, though at a much lower rate than in the early bombardment. Smaller craters occur in profusion on the relatively young, dark, lava flows on the Moon, and even tinier microscopic craters, made by bits of cosmic dust, dot the surfaces of exposed lunar rocks. On the Earth, Meteor Crater in Arizona, the best-known impact scar, is less than 50,000 years old. The Tunguska event in Siberia, a violent explosion probably caused by the entrance of a comet into the Earth's atmosphere, occurred within living memory, in 1908.

Planetary magnetism

We have studied and used the Earth's magnetic field for centuries, but it remains a mystery in many ways. It surely is caused by huge electric currents in Earth's iron core. But we still do not know the details of how it is

produced, why it varies, and why it completely reverses itself every million years or so.

Space probes have discovered magnetic fields elsewhere in the solar system, extending outward from the Sun and surrounding both some terrestrial and some gas giant planets. Where these fields are present, they shield the planet from the solar wind that pours out from the Sun, and in the region where the solar particles encounter the planetary fields, there arise other remarkable effects: trapped radiation belts, planetary magnetic tails, magnetic storms that cause aurorae, and bursts of radio noise that can be heard across the solar system. In truly great magnetic fields like those of Jupiter, atomic particles may be heated to millions of degrees, and a great electric arc flows between the planet and its moon Io. Indeed, one of the curiosities of the solar system is that two planets as different as Jupiter and the Earth—one terrestrial, one a gas giant—should have similar magnetic properties. Each has a magnetic field, aurorae, radiation belts, and naturally-generated radio noise.

Magnetic properties vary widely and unpredictably among the terrestrial planets. The Earth has a metal core and a strong magnetic field. The Moon, with no detectable metal core, has no field, but it may have had a strong field in the past because a strange "fossil" magnetism has been detected in many lunar rocks. Mercury has a large metal core, but only a weak magnetic field. Venus probably has a metal core, but it has no field. Mars, which may or may not have a metal core, has no field. The gas giant planets, at least the two visited by spacecraft, seem to be more uniform.

Both Jupiter and Saturn have strong magnetic fields, although their "metallic" interior regions probably are made of hydrogen rather than of nickel-iron.

Our studies of planetary magnetism have so far produced more questions than answers. Why do some terrestrial planets with metal cores have magnetic fields (Earth, Mercury) while others (Venus, Mars) do not? If the planet's rotation rate is a factor, why does one slow rotator (Mercury) have a magnetic field while another (Venus) does not? More puzzling is the evidence from Moon rocks that the Moon's magnetic field "turned off" about 3 billion years ago. How could this happen? Might the Earth, or another planet, lose its magnetic field in the future?

Atmospheres

Long before the Space Age, we knew that other worlds have atmospheres. But only recently have we been able to make accurate analyses of these atmospheres or to understand something of their histories.

There seem to be two types of atmospheres: *original* ones, formed from gas present in the primordial dust cloud, and *evolved* or outgassed ones, whose gases have gradually come out of the interior of the planet, probably as the result of volcanism.

The atmospheres of the gas giant planets are largely original. Their compositions are close to that of the Sun itself (largely hydrogen and helium), and the crushing gravity of these huge worlds would prevent any original gases from escaping. The gases that collected into Jupiter 4.5 billion years ago must be there still.

The terrestrial planets seem to have atmospheres of the outgassed type. Somehow, most of the original gas seems to have been swept away from the terrestrial planets and replaced by other gases from their interiors, such as nitrogen, carbon dioxide, and water.

These outgassed atmospheres differ greatly. Mars and Venus have atmospheres rich in carbon dioxide, but the pressure of Venus' atmosphere is 10,000 times that of Mars. Although Venus has a thick, heavy atmosphere, its composition suggests that the planet has not outgassed as much as has the Earth. The atmosphere of Mars has been modified continuously since formation because the low gravity of the planet has allowed much of the nitrogen to escape into space.

Earth's oxygen-rich atmosphere seems unique, but we know that it has been drastically modified by an agent not detected on the other planets: life. Studies of other planets suggest that, just before life developed, Earth's atmosphere may have been much like that of Mars and Venus: probably rich in carbon dioxide and nitrogen. In such an atmosphere, with oxygen lacking, simple organic molecules could combine into more complex ones without being destroyed by oxygen. Eventually, about 4 billion years ago, these complex molecules united to produce simple life forms. At some later time, simple plants began to turn the carbon dioxide into oxygen, and the process has continued to the present, producing the air we now breathe.

It is ironic that the development of life on Earth has finally produced an atmosphere so rich in oxygen that the original chemical reactions that

led to life can no longer occur. If life suddenly vanished from the Earth, it might not reappear again. Because living things produced the atmosphere in which we now live, there is a real cause for concern that another kind of life (human beings) could change the atmosphere even further. It happened once before.

Weather and climate

Earth is probably the worst place to learn the laws that govern Earth's weather. Our weather patterns are complicated; they are modified by the planet's rotation, by high mountain ranges, by the huge oceans, and by the water that rises as clouds and falls again as rain. Because of these complications, it is difficult to study the weather and almost impossible to predict it.

We have to examine other worlds with simpler weather patterns in order to learn about our own. Fortunately, the solar system provides a wide variety to study. There are planets that rotate slowly (like Venus) and rapidly (like Jupiter). There is a flat world (Venus), a somewhat mountainous world (Mars), and a world that may have no solid surface whatever (Jupiter). There are thick, dense atmospheres (Venus, Jupiter) and thin ones (Mars). There are atmospheres of carbon dioxide (Venus, Mars) and of hydrogen and helium (Jupiter, Saturn). The atmospheres range from superheated (Venus) to freezing (Mars).

We have found similarities to Earth's weather in unlikely places. The circulation of the thin Martian atmosphere is similar to the effects found over Earth's deserts. High-ve-

locity jet streams like our own also run along the belts of Jupiter's atmosphere. Jupiter's Red Spot, three times the size of Earth, bears a strong resemblance to an overgrown terrestrial hurricane.

The atmospheres of other planets give us another important opportunity: to learn how our own atmosphere might change in the future. We can look at other worlds to see how their atmospheres are affected by certain important substances: dust, carbon dioxide, sulfuric acid. In this way, we can understand what will happen to Earth's atmosphere if natural or human activities continue to introduce these materials into it.

We have already found several examples worthy of study and concern. Dusty Martian sandstorms may imitate the heating or cooling effects of dust, produced by volcanoes or by human beings, in our own air. The fine particles (aerosols) of sulfuric acid that form the corrosive clouds of Venus may help us to understand acid rain and other kinds of sulfur pollution here on Earth. The atmospheres of Mars and Venus, rich in carbon dioxide, may teach us to predict what will happen to our own atmosphere as the burning of fossil fuels continues to pour more carbon dioxide into the air. Will Earth warm considerably or not at all?

Climate is simply the weather of a planet over long periods of time. We know that the Earth's climate has not been stable. It has been both hotter and colder in the geological past, and the recent Ice Ages are only the latest events in these variations. We do not know what caused these climate changes: gradual changes in the Earth's orbit around the Sun, changes

in the Earth's oceans and atmosphere, or perhaps even changes in the Sun itself? We know even less about what climatic changes may occur in the future. Yet civilization is dangerously vulnerable to these changes. Will the climate grow warmer, melting the ice-caps and flooding our seacoasts? Or will it grow colder, freezing the seas and wiping out agriculture?

Again, other planets can help us find the answers. We now know that other planets have experienced climate changes, so that the Earth is not unique in this respect. Mars shows the traces of a warmer, wetter time, a period when its atmosphere was thick and great floods scoured channels across its surface. Mars may also have been colder in the past than it is now. The layers of sediment around the polar caps suggest that those caps may have been larger in the past. If we could show that Mars' hot and cold climates had occurred at times responding to the Earth's, then the underlying cause might be ascribed to variations in the light from the Sun itself.

Venus, our other neighbor world, is not too helpful yet. We do not know enough about its surface to understand if there are traces of previous climates. In a cooler time, Venus might really have been "Earth's Twin," with rivers cutting winding channels across it; those channels may remain. We need to explore in great detail both Mars and Venus, those worlds that bracket the Earth, before we will fully understand the development of the Earth's climate.

The flood of data and discovery in the Space Age has given us our first

glimpse of the mechanisms that control the birth and development of planets. We have found that worlds which seem totally different at first glance are actually linked by common bonds: volcanoes, meteorite craters, magnetism, and atmospheres. But further investigation and exploration are required to clearly define the forces that make planets what they are.

From what we have already done and learned, we can suggest and plan the next steps:

- *We should map the hidden surface of Venus, so that we can compare it closely with the other terrestrial worlds.*
- *We need to return to Mars, a world which we now see as tantalizingly Earth-like in some ways, strangely different in others. We should monitor its weather in detail, bring back rock samples to study, and carry out a more thorough search for life.*
- *The outer gas-giant planets are still largely unexplored. Jupiter's huge atmosphere and its strange and varied moons are now ready for close inspection and study.*
- *We should expand the investigation of comets and asteroids to study these strange, small objects at close range, and to seek in them a more complete record of how the solar system, and ourselves, came to be.*

The more we understand about other worlds, the more we will learn about the past and present nature of the Earth. Did huge meteorite impacts

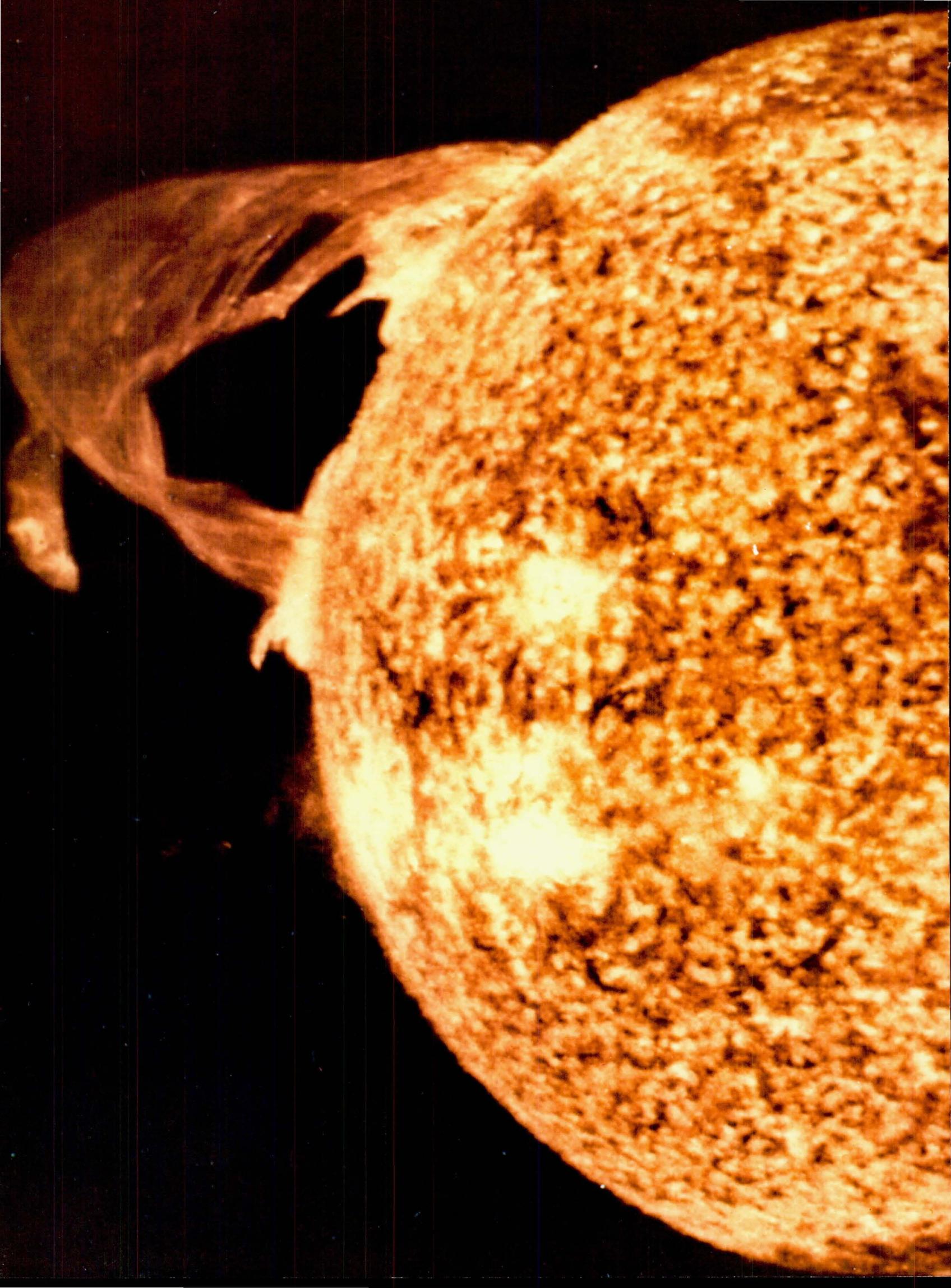
begin the process by which the Earth produced continents and ocean basins? Why is the Earth a highly evolved planet, with active volcanoes and mountain-building, while the other terrestrial planets seem quiet and dead? Why has the Earth developed a temperate environment where life has flourished, while nearby Venus and Mars seem lifeless and inhospitable?

There are other questions about the Earth's *future* that we must also answer. How are we changing our atmosphere, and what will these changes do to us? Will the Earth's climate change soon, and how? Is the Earth's magnetic field decreasing? What will happen to us if it vanishes, even for a short time? When will an asteroid hit the Earth, as many have done in the past? These are questions of more than just scientific interest. Their answers may determine the survival of people and civilization.

The Space Age has given us a new view of many worlds, but most especially of our own Earth. On our first trips to the Moon, the Earth suddenly appeared to human eyes as a tiny blue world of life, isolated in a vast, uncaring blackness. Now that we have explored further, we see that the Earth is not alone. It is one of a family of worlds, all different, each an individual, but all formed at the same time, shaped by the same forces, and developing in related ways. We can no longer hope to understand the Earth, its past, and its future, without studying and understanding its companions in space around the Sun.

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THE SUN AND EARTH IN SPACE

Eric G. Chipman

Gigantic prominence. An ultraviolet telescope aboard Skylab photographed this huge erupting prominence, one of the largest seen in a decade, as it lifted off the Sun on December 19, 1973. The ultraviolet radiation was produced by electrified helium atoms at a temperature of about 70,000° C.

The Sun and Us

Nothing is more important to us on Earth than the Sun. Without the Sun's heat and light, the Earth would be a lifeless ball of ice-coated rock. The Sun warms our seas, stirs our atmosphere, generates our weather patterns, and gives energy to the growing green plants that provide the food and oxygen for life on Earth.

We know the Sun through its heat and light, but other, less obvious aspects of the Sun affect Earth and society. Energetic atomic particles and X-rays from *solar flares* and other disturbances on the Sun often affect radio waves traveling the Earth's ionosphere, causing interference and even blackouts of long-distance radio communications. Disturbances of the Earth's magnetic field by solar phenomena sometimes induce huge voltage fluctuations in power lines, threatening to black out cities. Even such seemingly unrelated activities as the flight of homing pigeons, transatlantic cable traffic, and the control of oil flow in the Alaska pipeline apparently are interfered with by magnetic disturbances caused by events on the Sun. Thus, understanding these changes—and the solar events that cause them—is important for scientific, social, and economic reasons.

We have long recognized the importance of the Sun and watched it closely. Primitive people worshiped the Sun and were afraid when it

would disappear during an eclipse. Since the early seventeenth century, scientists have studied it with telescopes, analyzing the light and heat that manage to penetrate our absorbing, turbulent atmosphere. Finally, we have launched solar instruments—and ourselves—into space, to view the Sun and its awesome eruptions in their every aspect.

Once, when we looked at the Sun by the visible light that reaches the ground, it seemed an average, rather stable star. It was not exactly constant, but it seemed to vary in a fairly regular fashion, with a cycle of sunspots that comes and goes in about eleven years. Now the Space Age has given us an entirely different picture of the Sun. From space we have seen the Sun in other forms of light—ultraviolet, X-rays, and gamma rays—that never reach the ground. This radiation turns out to be far more responsive to flare eruptions and other so-called solar activity.

We now see the Sun as a place of violent disturbances, with wild and sudden movements above and below its visible surface. In addition, the influence of solar activity seems to extend to much greater distances than we had believed possible. New studies of long series of historical records reveal that the Sun has varied in the past in strange and unexplained ways. Scientists wonder how such variations might affect the future climate on Earth.

We have obtained a clearer picture about the scope of the Sun's effects. Its magnetic field stretches through interplanetary space to the outer limits of the solar system. Steady streams and intense storms of atomic particles blow outward from the Sun, often encountering the atmospheres of our Earth and the other planets.

The spectacular photos of the Earth from space show only part of the picture. Instruments carried on satellites reveal a wide variety of invisible phenomena—lines of magnetic force, atomic particles, electric currents, and a huge *geocorona* of hydrogen atoms—surrounding the Earth. Each is as complex and changing as the visible face of the globe. The Earth's magnetic field extends tens of thousands of miles into space, and many different streams of electrons and protons circulate within it. Huge electric currents flow around the Earth, affecting their high-altitude surroundings as well as our environment at ground level.

Space observations have greatly expanded our ability to look at the Sun, at interplanetary space, and at the immediate surroundings of the Earth itself. We can now "see" many phenomena that are completely undetectable from the Earth's surface, and we now have a much better, more complete and more coherent picture of how events in one part of our solar system relate to activity in another.

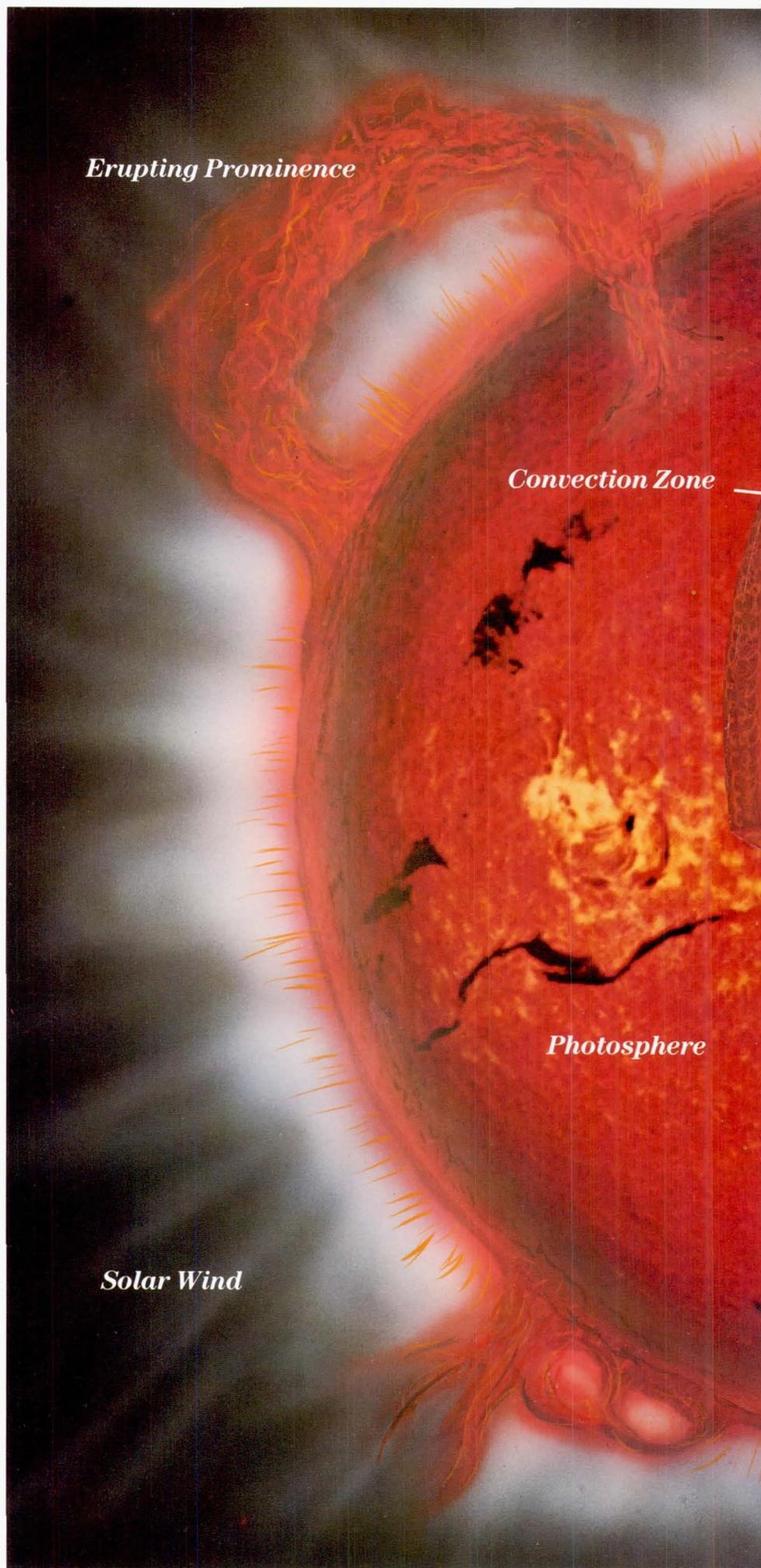
The Nature of the Sun

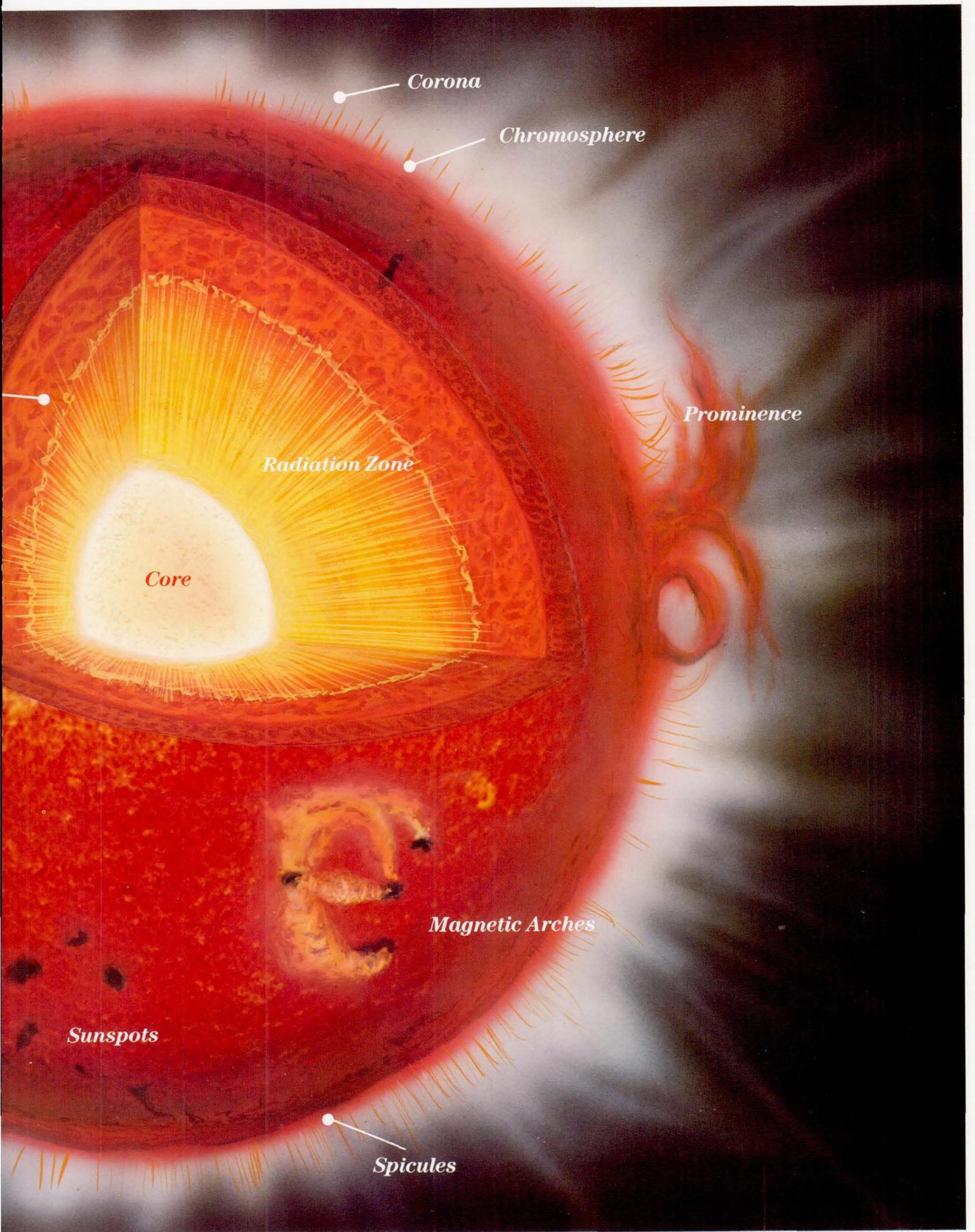
What is the Sun?

Human beings have always looked upon the Sun as the most important celestial body. Even primitive people realized that the light and heat from the Sun sustain all life on Earth, and they knew that any disturbance to the Sun's daily motion through the sky would have serious effects. Over the years, they devised many rituals to ensure the reliability of the Sun. Later, Greek philosophers declared that the Sun is a flawless sphere, its motions governed by perfect perpetual clockwork. Sunspots glimpsed dimly by the ancients when thin cloud or thick mist made it possible to stare at the Sun were dismissed as unrelated objects passing in front of the glowing sphere. This idea was accepted throughout the Western world until after the invention of the telescope, when Galileo proved that sunspots were true markings or structures (hence, "blemishes") on the surface of the Sun. Not only was the Sun imperfect, but it was changeable; the spots came and went over days and weeks. Later, astronomers discovered that the number of sunspots varies in a cycle, showing a maximum and a minimum about every eleven years.

More recently, the combination of nuclear energy theory, laboratory experiments, and better solar observations has enabled scientists to obtain a good picture of the overall structure of the Sun. It is a ball of gas, composed of about 90 percent hydrogen,

From core to corona. Artist's cutaway drawing of regions and structures of the Sun includes both the observed phenomena and layers of the exterior and the hypothesized energy-generating and transmitting zones of the interior. Many surface features are shaped by magnetic field patterns. Interior regions are calculated from conditions necessary for the observed solar energy to be produced by nuclear fusion of hydrogen deep inside the Sun.





9 percent helium, and only 1 percent of all the other elements such as carbon, nitrogen, oxygen, silicon, and iron. The diameter of the Sun is about 1,390,000 kilometers (865,000 miles), or about 109 times that of the Earth, and the Sun is 300,000 times as massive as the Earth.

At the Sun's center, theory predicts that the temperature reaches an incredible 15 million °C. This is the temperature of an exploding hydrogen bomb; it is hot enough to sustain the thermonuclear reactions that convert hydrogen atoms into helium, thus powering the Sun. In this way the Sun consumes about 5 billion kilograms (5 million tons) of its nuclear hydrogen fuel every second. Yet the Sun is so large that it has been burning hydrogen at this rate ever since it formed some 5 billion years ago, and it will continue to burn steadily for at least another 4 billion years.

The energy released by nuclear fusion in the heart of the Sun is eventually radiated away in all directions into space. A tiny fraction reaches the Earth, powering every process necessary for life. Even this tiny fraction is enormous. The solar energy striking the Earth is equal to 800 billion megawatts of power, an amount vastly more than the entire capacity of all of our power plants. Someday, we will learn to harness it effectively.

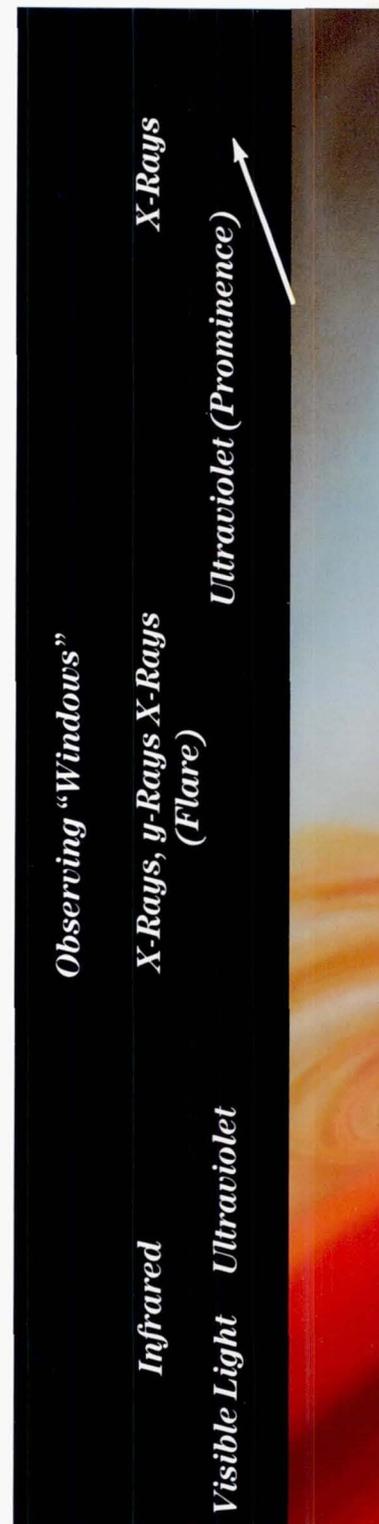
The solar interior may burn hydrogen at a steady rate, but a close look at the surface and outer layers shows that the Sun is not stable at all. Examined with modern techniques—especially space instruments—the solar atmosphere is seen to seethe with constant motion and vio-

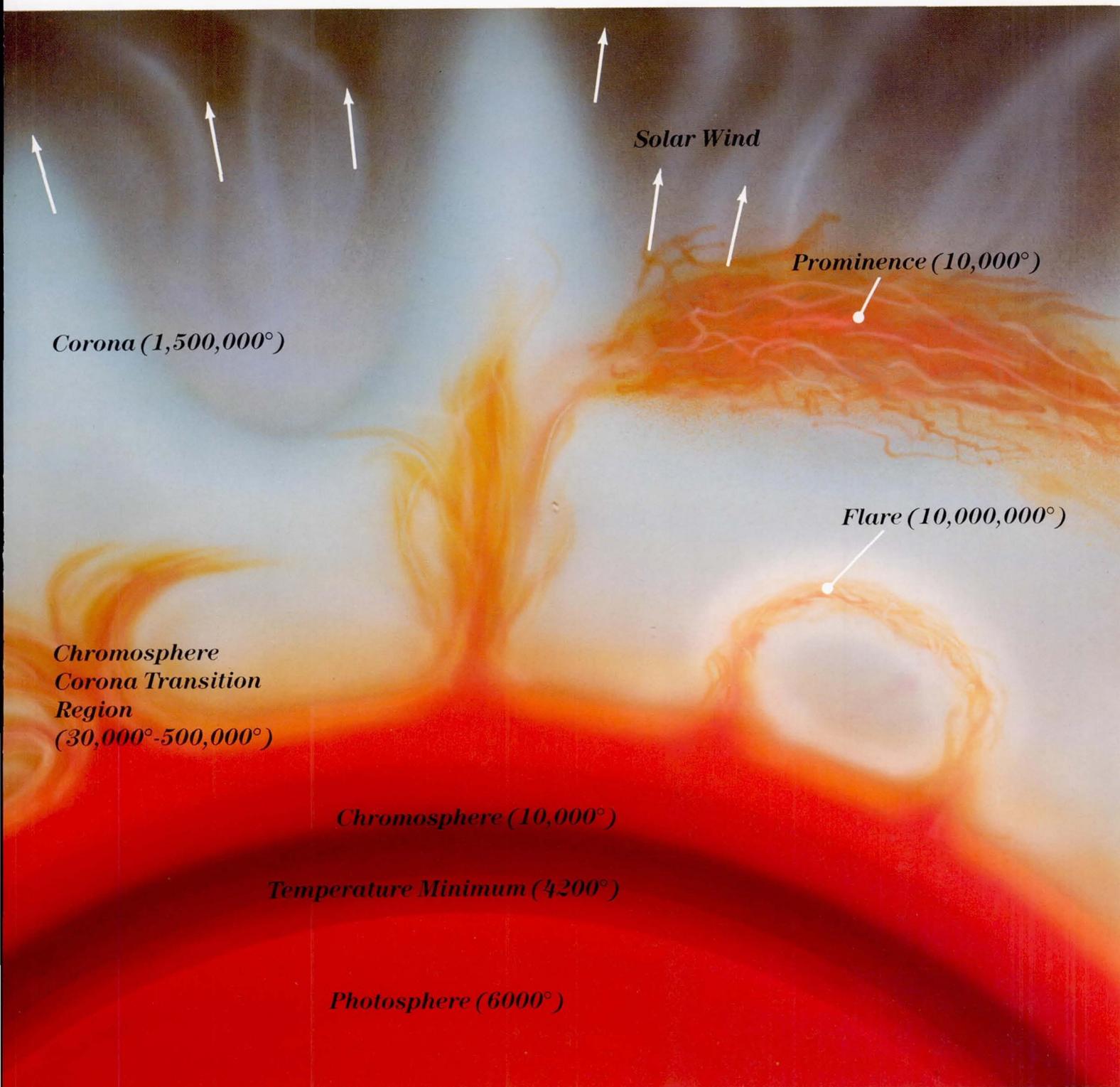
lent activity. Solar disturbances of diverse kinds occur on time scales ranging from years down to thousandths of a second, involving regions ranging in size from the entire solar atmosphere to the smallest detail visible in our most powerful telescopes.

Space observations allow us to see the Sun in many wavelengths, or "colors," of light that are totally absorbed by the Earth's atmosphere and cannot be seen from the ground. High-energy gamma rays and X-rays, ultraviolet light, and much of the infrared and radio regions of the spectrum can be observed only from above most of our atmosphere. Each of these newly explored spectral regions, or "windows," yields unique information about physical processes and phenomena on the Sun which are inaccessible with ground-based telescopes.

Through these new windows that open for telescopes above the Earth's atmosphere, we can see radiation emitted from many different parts of the Sun. Each solar region has its own temperature, density, and other characteristic physical conditions and emits its own kind of light. We have measured temperatures on the Sun ranging all the way from a mere 4200° C in the coolest regions to over 50 million° C in the hottest solar flares.

The apparent surface of the Sun, the *photosphere*, has a temperature of about 6000° C, which decreases with height to a minimum value of 4200° C. The solar gas in this region shines mostly in visible and infrared light. Above the minimum temperature region, the gas gets hotter. The *chromosphere* (the next higher part





Rays from the Sun. Solar features at different temperatures emit characteristic radiation of different forms, ranging from radio and infrared waves to visible light, ultraviolet, X-rays, and gamma rays. Drawing shows typical temperatures, while legend at the left indicates corresponding radiations. Infrared and visible light are suitable for study of coolest layers, while much information on the hot corona can only be gleaned from X-rays. Energetic atomic particles from solar flare explosions produce gamma rays.

of the Sun's atmosphere) has a temperature of about $10,000^{\circ}\text{C}$ and glows brightly in ultraviolet light. The million-degree *corona*, farther out around the Sun, is best seen by the X-rays it emits. The very highest energy radiation given off by the Sun is not due to a hot gas but is actually produced by erupting streams of very-high-speed electrons and protons which strike the ordinary atoms of the Sun's atmosphere with sufficient force to generate X-rays and gamma rays. On Earth we use a very similar process on a vastly smaller scale to generate X-rays for medical examinations.

In addition to the X-rays, ultraviolet, and other forms of light from the Sun, satellite-borne instruments have observed pulses and streams of atomic particles that are emitted from the Sun and travel outward to the Earth and beyond. These particles provide actual samples of solar material. Their composition tells what the Sun is made of and how matter is ejected from its atmosphere. From space we can even detect the solar magnetic field, which stretches out into the far limits of the solar system.

The Sun as a star

We sometimes forget that there is one star that is easily visible in the daytime: our Sun. The Sun is the only star close enough to be studied in detail, but we are confident that all the processes in the Sun must also occur in billions of distant stars throughout the universe. To understand the nature and behavior of other stars, we must first understand our own. At

the same time, observations of other kinds of stars help put the Sun in perspective.

The Sun is a relatively typical star among the approximately 100 billion stars in our Milky Way galaxy. The masses of most other stars that we see range from approximately one-tenth the mass of the Sun to about 30 solar masses. The surface temperatures of most stars range from about 2000°C to $40,000^{\circ}\text{C}$. Although the Sun is somewhat on the cool side at about 6000°C , hot stars are rare, and most normal stars are cooler than the Sun. Compared to some of the explosive stars – novae and supernovae – which sometimes appear in the sky, the Sun is stable and ordinary.

This long-term stability of our Sun probably was crucial for the development of life on Earth. Biologists believe that a relatively stable average temperature had to prevail on Earth during the past 3 billion years, in order for life to evolve to its present state. The relative stability of the Sun is also important to astronomers trying to understand the basic nature of it and other stars. Violent activity in the Sun could mask the more subtle and long-enduring processes which are the basic energy transport mechanisms of our star. Fortunately, they are not hidden, and we have been able to map the trend in solar properties with height above the visible surface. Above the minimum temperature region in the photosphere, we have measured how the gas gets hotter as it thins out with height. The chromosphere and corona, each hotter than the layer below, are warmed by the

transfer of energy from below, by processes that still are not well understood.

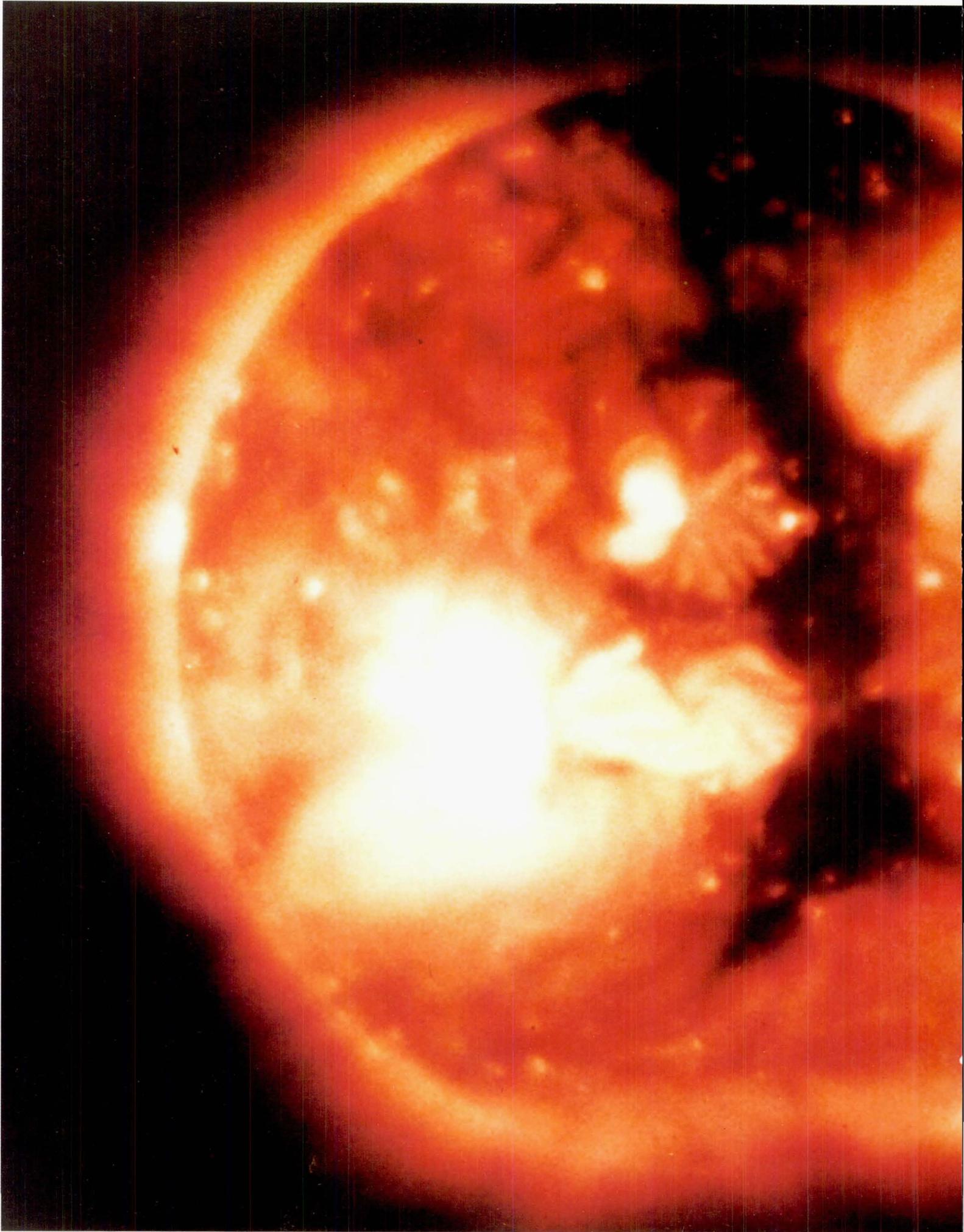
Until space observations became possible we knew nothing about coronae in any other stars, and had only marginal information about the properties of stellar chromospheres. Now, space observations have shown us that a large fraction of the stars in the sky have chromospheres and coronae. On several dozen stars, we have even detected activity which may be connected with sunspot (or "starspot") cycles like those of our own Sun. X-ray telescopes carried on satellites have recorded flares in other stars that are far more powerful than the already impressive flares of the Sun. By observing the strength and frequency of these events on stars with masses, ages, and rotation rates which differ from those of the Sun, we search for answers to such basic questions as: "How does the sunspot cycle period depend on the star's rotation rate?" or "What is the relation between the temperature of a star's corona and the strength of its magnetic field?" By deciphering the general pattern of stellar properties we can better understand what makes things happen on the Sun.

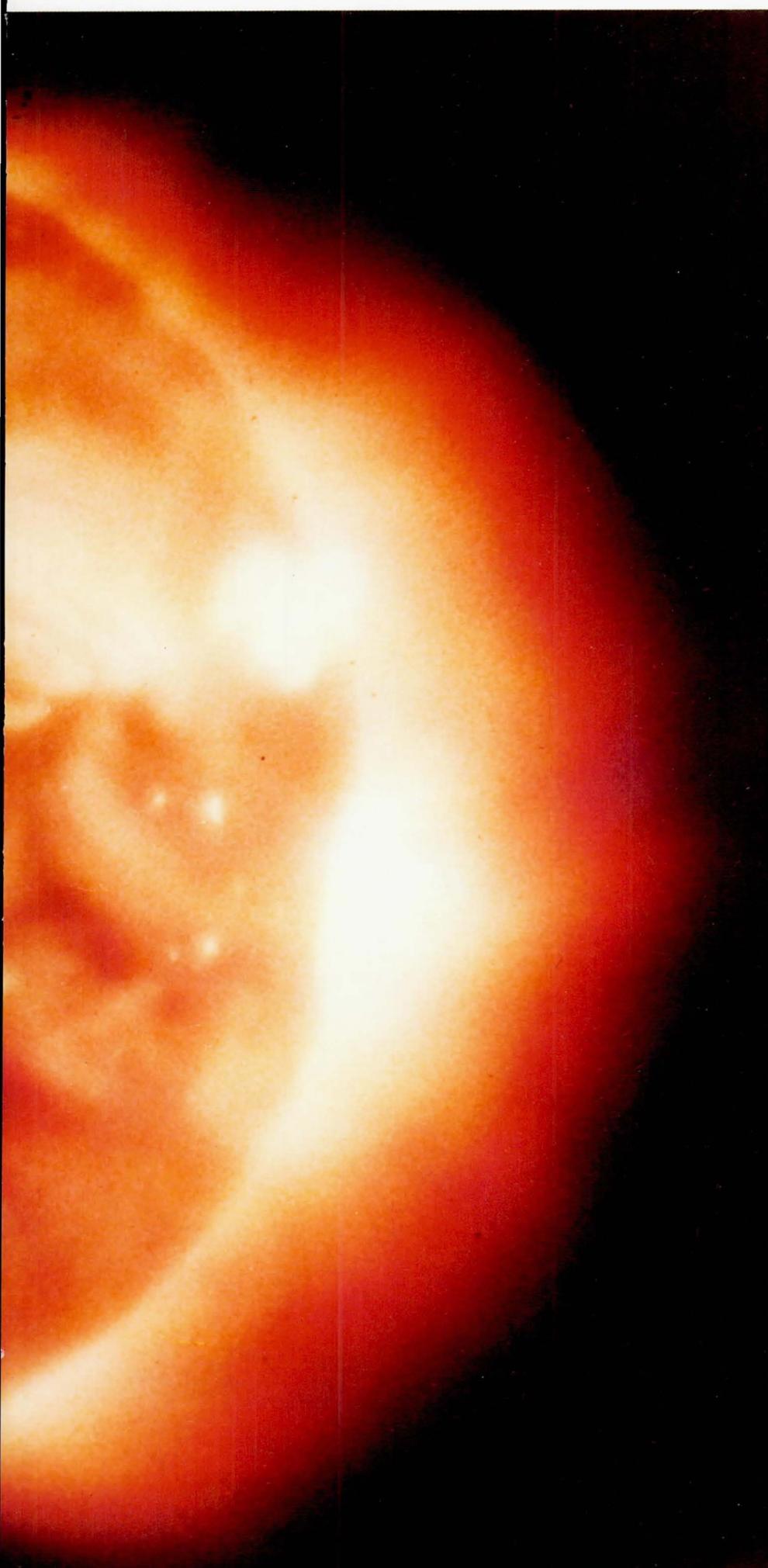
The Sun presents us with a bewildering variety of surface features, atmospheric structures, and active phenomena. Sunspots come and go. The entire Sun shakes and oscillates in several different ways at the same time. Great eruptions called *prominences* hang high above the Sun's surface for weeks, suspended by magnetic force, and then sometimes shoot

abruptly into space from the corona. The explosions called *solar flares* emit vast amounts of radiation and atomic particles in short periods of time, often with little or no warning.

Space observations have discovered many new aspects of solar events that were hidden from ground-based observatories. The hottest spots on the Sun shine primarily in ultraviolet and X-rays, rather than in visible light. Thus, only from space can we map the true structure of high-temperature solar flares and determine their physical conditions. Space observatories have shown us the higher, hotter layers of the Sun's atmosphere that normally are invisible from the ground. Instruments on satellites revealed that in flares and other violent disturbances the Sun acts like an atomic accelerator, driving electrons and protons to velocities approaching the speed of light. At such high speeds, the particles emit the high-energy X-rays and gamma rays measured by our satellites. Sometimes they even induce nuclear reactions on the surface of the Sun.

Two aspects of our improved knowledge of the Sun deserve special attention. One is the role of magnetic fields in determining virtually all aspects of the structure and behavior of the Sun's upper atmosphere. The other is the discovery of the *solar wind*, a stream of atomic particles that constantly evaporate from the Sun's atmosphere and are accelerated to speeds of hundreds of kilometers per second, escaping into space in all directions.





The Sun in Space: Magnetic Fields and the Solar Wind

The Sun as a magnet

We have known since 1912 that there are powerful magnetic fields in sunspots. In fact, the sunspot cycle could just as well be described as a periodic increase and decrease in the amount of solar magnetism. The magnetic fields are generated deep within the Sun by a natural dynamo that reverses itself every eleven years. This dynamo action may result from an interaction between the Sun's 27-day rotation and the rising and falling of huge blobs of gas in a layer just below the solar surface.

When the Sun was photographed from *Skylab*, we learned that the whole atmosphere above the surface of the Sun is structured by the presence of changing magnetic fields. The solar corona often appears smooth when glimpsed from the ground during total eclipses of the Sun. However, *Skylab* X-ray photographs proved that the corona is composed almost entirely of individual loop structures, formed by streams of hot gas channeled along lines of magnetic force. Some loops are small and isolated; others are so large that their two feet may be separated by half the solar surface. The majority of the loops are arranged in long rows or *arcades*, which frequently cover a large fraction of the surface.

Mysterious source of the solar wind. A long, dark coronal hole, here seemingly parting a glowing "Red Sea" of million-degree coronal gas, separates magnetically-shaped coronal arches to expose the Sun's cooler chromosphere layer below. Invisible in ordinary photographs, coronal holes appear prominently in images made, as here, in so-called "soft," or low-energy, X-rays.

In addition to the prominent loops in the corona, many very small magnetic loops appear suddenly at random locations on the solar surface, where they emit intense X-rays for a few minutes, and then fade away in an hour or two. These loops, identified as "X-ray bright points" in *Skylab* photos, are generated when magnetic fields emerge from inside the Sun. For some unknown reason, this type of magnetic activity grows to a *maximum* when sunspots are at a *minimum*. An explanation of this unexpected anticorrelation remains as a challenge to solar researchers.

Perhaps the Sun's most remarkable magnetic features are the *coronal transients*. These objects were discovered by the seventh *Orbiting Solar Observatory* satellite (OSO-7) and later were studied intensively by *Skylab*. A typical transient begins as a gigantic bubble that appears near the solar surface and flies out through the corona at a velocity of hundreds of kilometers per second. These transients usually are caused by solar flares or by the eruption of a type of solar prominence known as a cool loop. The bubbles, consisting of high-temperature plasma, carry along magnetic fields from the lower corona and disrupt the upper corona as they expand outward.

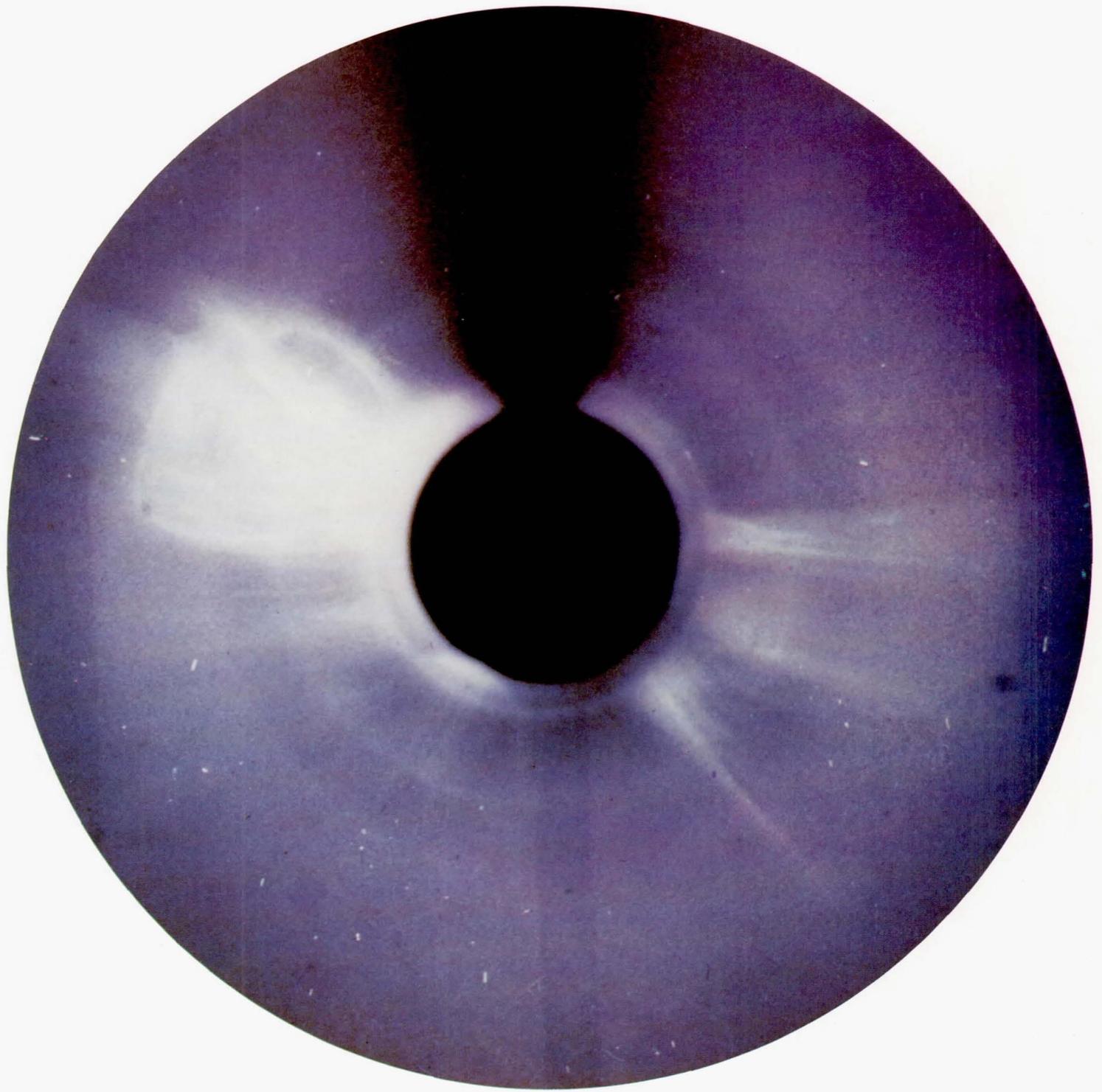
The solar wind blows on the Earth

Before the Space Age, people thought that the material that makes up the Sun stays with it. The solar corona was thought to merge gradually into interplanetary space, a static gas of low density.

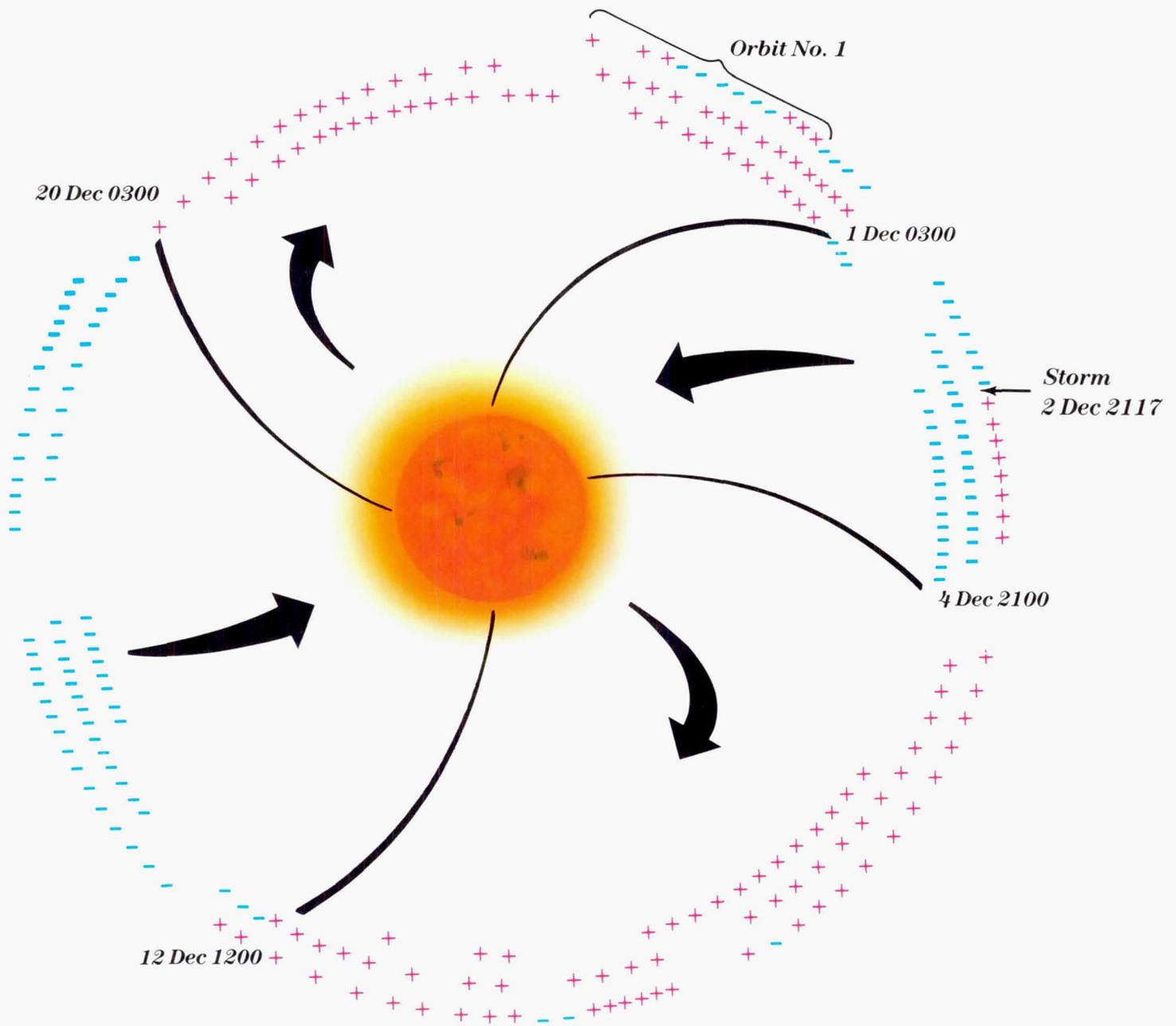
There were some problems with this "quiet sun" concept. It was known that the violent solar flare explosions are often followed by brilliant displays of *aurorae* (the Northern Lights and Southern Lights) in the Earth's atmosphere and by disturbances in the Earth's magnetic field. Some physicists speculated that these effects might be due to streams of atomic particles from the Sun, but even these scientists felt that these events were rare and not part of the day-to-day behavior of the Sun.

Geophysicists who studied the Earth's magnetic field were faced with a mystery. They often found disturbances in the Earth's field that did not coincide with solar flares but which repeated at intervals of 27 days, the period of the Sun's rotation on its axis. Because of the coincidence in timing, the geophysicists thought that some solar influence was at work. The influence was ascribed to so-called "M-regions" ("M" standing for "mystery") on the Sun, but attempts to locate the M-regions as sunspot groups or other specific visible features on the solar surface were unsuccessful.

The first step in solving these puzzles was taken in 1957, when a University of Chicago physicist, Eugene Parker, demonstrated that the solar corona, which has a temperature of two million degrees, cannot be static. The corona is so hot, Parker explained, that its gas is constantly evaporating away from the Sun at supersonic speed. He predicted that there must be a solar wind, with a density of about 10 atoms per cubic centimeter (160 atoms per cubic inch), continuously blowing away from the



Escape from the Sun. More than 1.6 million kilometers (one million miles) in diameter, a glowing white "solar bubble," or coronal transient, races off into space from the solar corona. The Sun itself is eclipsed by the dark disk of a Skylab instrument designed to study these remarkable phenomena that occur unseen from Earth. A series of photographs made on June 10, 1973, showed how the bubble grew as it moved rapidly outward. Other Skylab observations confirmed that the bubble was produced when a prominence erupted into the corona from the solar surface below.



Spiral pattern in interplanetary space. The interplanetary magnetic field makes a spiral pattern as the Sun turns. Pie-shaped "sectors" between the curved black lines are regions where the magnetic field has a consistent direction, its lines of force pointing either away from or toward the Sun (denoted by plus and minus signs, respectively). Illustrated here are measurements made by the IMP-1 (Interplanetary Monitoring Platform 1) spacecraft during three 27-day solar rotation periods beginning in late 1973. Each plus or minus denotes the direction of the field according to three hours of IMP-1 data. Outermost circle of plus and minus signs (with December dates) represents the first 27-day period; the two circles within represent the next two periods in succession. Comparison of data from one circle to the next shows that the sector structure persisted over most of the long interval of observation.

Sun and passing the Earth at the high speed of several hundred kilometers per second. The theory would also account for the behavior of certain comet tails, which acted as though they were blowing in an electrified wind.

Several early interplanetary spaceprobes detected the solar wind around 1959-1961. In 1962, *Mariner 2* made a detailed survey that showed that the properties of the solar wind agreed with Parker's predictions. Instruments carried on *Mariner* and other spacecraft also found that the solar wind actually is guided along an interplanetary magnetic field which originates at the Sun. The magnetic field is stretched outward by the flowing wind and warped by the turning of the Sun, so that it has the spiral shape of a gigantic pinwheel. The field begins to be stretched at a height of about one solar diameter above the surface of the Sun. This stretching explains the elongated and nearly radial appearance of the streamers seen in the outer corona during eclipses of the Sun and which also have been photographed by solar telescopes on *Skylab* and other satellites.

In the plane of the Earth's orbit, the interplanetary magnetic field often is divided into sectors of alternating inwardly (*i.e.*, toward the Sun) and outwardly directed fields. This magnetic pattern will persist for months as the Sun rotates and sometimes lasts for as long as two years.

We have recently discovered that the magnetic fields which originate in the northern hemisphere of the Sun will point in one direction (inward or outward) while fields originating in the southern hemisphere

point in the opposite direction. The boundary between the two magnetic hemispheres consists of a thin *neutral sheet*, in which the magnetic directions are not consistent. The neutral sheet is slightly warped, so that it does not lie quite flat in the plane of the Earth's orbit. As the Sun rotates, the sheet turns too, so that the Earth is alternately on one side of the warped region and the other. As this happens, satellites near the Earth observe the change in the direction of the interplanetary magnetic field as the sector boundaries pass the Earth.

Study of the solar wind revealed the identity of the mysterious M-regions on the Sun, which cause the recurrent disturbances (*geomagnetic storms*) in the Earth's magnetic field. The geomagnetic storms are found to coincide with streams that are much faster than the normal solar wind. By comparing the arrival times of these high-velocity streams with pictures of the Sun's corona taken by *Skylab* X-ray telescopes on known dates, the high-speed streams were traced to parts of the corona which emit *no* X-rays, the so-called *coronal holes*.

The temperatures and densities of coronal holes are much lower than those of other parts of the corona. Investigations show that in the holes, the magnetic field has no loops, but extends directly out into the solar wind. We do not yet know how and why coronal holes form, but we do know that they are a major source of the solar wind. Two apparently permanent coronal holes exist at the north and south poles of the Sun, and it may be that much of the solar wind that leaves the Sun originates in these two polar coronal holes.

The Magnetosphere: Our Shield in Space

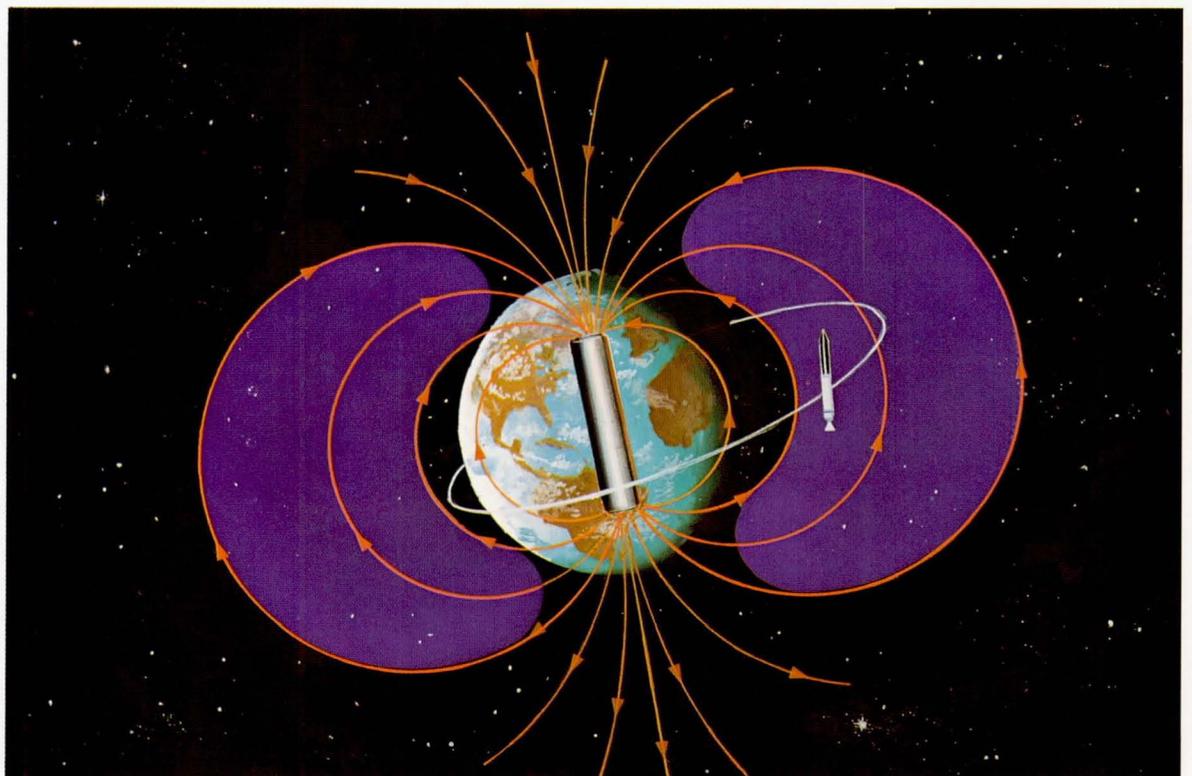
The Earth-Sun battle

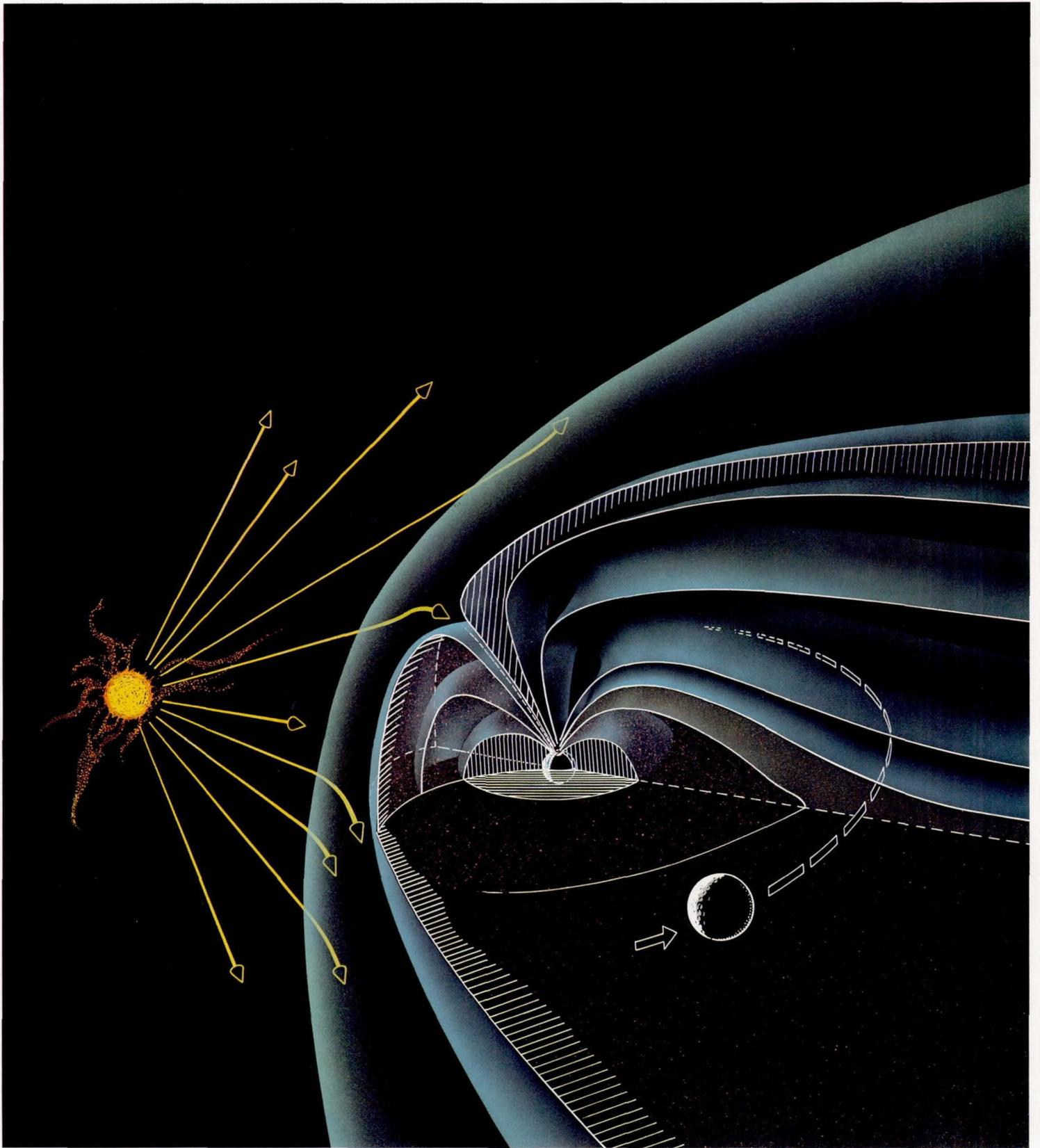
In order for any solar particle to reach the Earth, it must first pass through the Earth's magnetic field. Before the solar wind was discovered, the Earth's field was thought to be symmetrical, resembling that of a huge bar magnet, fading off indefinitely into space. However, we now know that the solar wind shapes the outer regions of the Earth's magnetic field, and that the field is sharply bounded. Outside the boundary, space is dominated by the solar wind and the interplanetary magnetic field. Inside the boundary is the region or *magnetosphere* dominated by the Earth's magnetic field. The measurements from many space missions have been combined to reveal that the Earth's magnetosphere is blown out by the solar wind into a teardrop shape. The head of the drop extends only about 10 Earth radii, or about 65,000 kilometers (40,000 miles) "upwind" toward the Sun. The tail of the drop stretches away in the direction opposite the

Sun, actually reaching beyond the Moon's orbit. This long *magnetotail* extends more than 600,000 kilometers (370,000 miles) from the Earth.

At the boundary of the magnetosphere, there is a constant struggle between the magnetic field of the Earth and the forces of the Sun. Buffeted by fluctuations in the velocity and density of the solar wind, the magnetosphere's size and shape are continuously changing. At the point where the solar wind strikes the magnetosphere, a shock wave forms, analogous to the sonic boom that precedes a supersonic airplane.

Inside the boundary with the solar wind, the magnetosphere remains an active region. It contains two belts of very energetic charged atomic particles that are trapped in the Earth's magnetic field hundreds of miles above the atmosphere. These belts were discovered by Professor James Van Allen of the University of Iowa and his colleagues in 1958, using simple radiation detectors carried by *Explorer 1*, the first U.S. satellite.





Magnetosphere and magnetotail. Studies by several satellites and spaceprobes have now mapped much of the region of magnetic field structures and streams of trapped radiation particles around the Earth, the magnetosphere. The solar wind, streaming out from the Sun, shapes the magnetosphere into a teardrop, with a long magnetotail stretching out opposite the Sun.

Earth's radiation environment. It once was thought that the Earth was surrounded by near-empty space, in which the Earth's magnetic field would trace a pattern resembling that of a bar magnet (orange lines). However, the first American spacecraft, Explorer 1 (shown here), discovered a belt of energetic particles trapped in the field and streaming back and forth above the Earth. It was the first of two such zones, the Van Allen belts, to be found.

The Northern and Southern Lights: gifts from the Sun

The structure of the Earth's magnetosphere also controls the behavior of aurorae, seen in our night skies. Pre-Space Age textbooks stated that aurorae are produced by protons which are emitted from the Sun and reach the Earth's upper atmosphere through gaps that exist in the Earth's magnetic field at the north and south magnetic poles. According to the theory, these protons strike oxygen atoms in the atmosphere, and the collisions cause the glow which we call the Northern Lights.

This view has changed in the Space Age. The data collected by

many spacecraft showed that the situation is more complicated. Particles from both the solar wind and from the Earth's atmosphere apparently are stored in the magnetotail. From there, they periodically are violently ejected into the northern and southern polar regions of the atmosphere along the Earth's magnetic field and are accelerated to high speeds by a process not yet fully explained. The magnetotail is in effect a reservoir of particles that is periodically refilled. When the Sun is active during maximum sunspot years, this process is especially intense and frequent, and the aurorae are brighter and move closer to the equator.



Northern Lights, a gift from the Sun. This brilliant green display of the aurora borealis, photographed from Fairbanks, Alaska, resembles a huge curtain with a circular fold. Aurorae, stimulated by disturbances on the Sun, are atmospheric phenomena which also take the shape of rays, streaked clouds, and a "starburst" or crown form, which corresponds to a curtain viewed from directly below. Colors range from white through green, blue, and red.

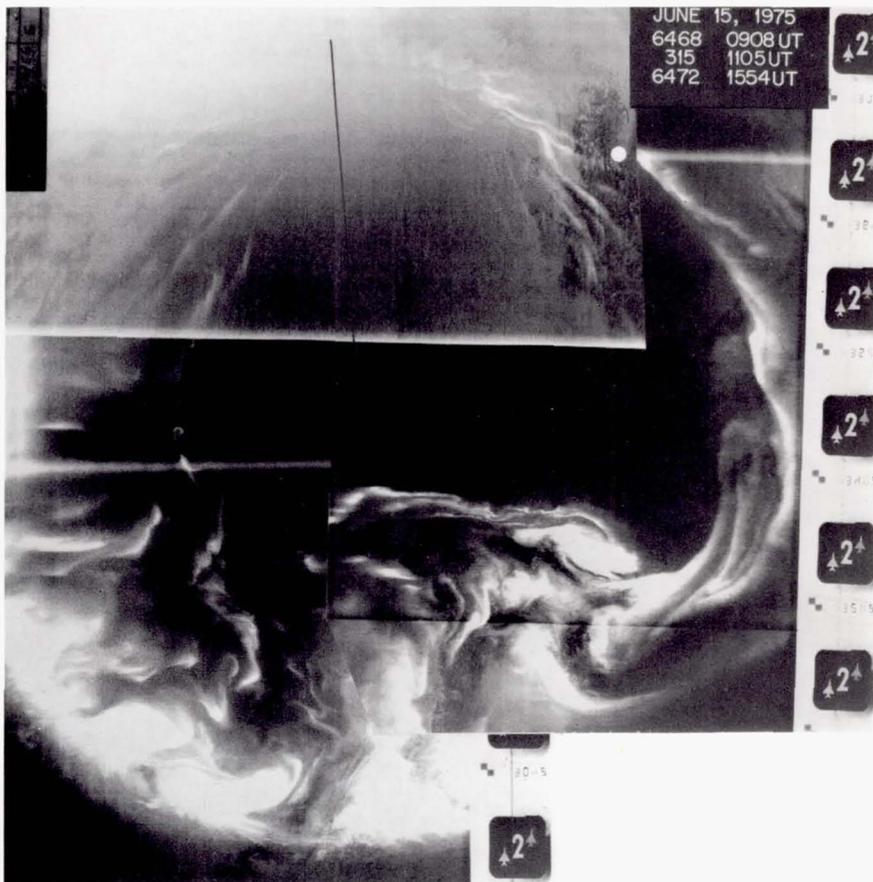
Other planetary magnets

Spaceprobes have discovered that three other planets besides the Earth have magnetic fields strong enough to form magnetospheres around them. The magnetospheres of these planets, tiny Mercury, giant Jupiter, and ringed Saturn, are as different as the planets themselves. Mercury's magnetosphere is much smaller and weaker than the Earth's, while Jupiter's very strong magnetic field has trapped particles in a violently active magnetosphere so large that, if visible from Earth, it would appear as big as the full Moon. Saturn's magnetosphere is intermediate between those of the Earth and Jupiter. Comparative studies of the magnetic fields and magnetospheres of the planets should help us interpret the origin of the Earth's magnetosphere and its associated phenomena, and to under-

stand why some planets apparently do not generate their own magnetic fields.

Just as there is a sharp boundary between the Earth's magnetosphere and the solar wind, there must be a limit to the much larger region filled by the solar wind and the interplanetary magnetic field. This region, called the *heliosphere* since it is dominated by particles and fields that originate in the Sun, has "upstream" and "downstream" directions just as the Earth's magnetosphere does. In the case of the heliosphere, this streaming is caused by the motion of the Sun through interstellar space at a velocity of about 20 kilometers per second (12 miles per second) with respect to the surrounding interstellar gas.

The distance to the edge of the heliosphere is unknown, because no spacecraft has yet gone far enough. However, we do know that the heliosphere extends at least as far out as the orbit of the planet Uranus [almost 3 billion kilometers (1.9 billion miles) away], because the outward bound *Pioneer 10* spacecraft passed Uranus' orbit in September 1979, and has still not found the boundary.



Looking down on the aurorae. The entire oval of aurorae around the south geomagnetic pole of the Earth is seen in this photograph made from space on June 15, 1975. Images of this kind show many types of aurorae simultaneously and are used to study the difference between "dayside" aurorae (near the top of this picture) and "nightside" aurorae (at the bottom).

The Sun-Weather Connection

The Sun and the weather

The energy that the Earth receives from the Sun is the basic cause of our changing weather. Solar heat warms the huge air masses that comprise large and small weather systems. The day-night and summer-winter cycles in the weather have obvious causes and effects. Are there other, more subtle ways in which the Sun affects weather and climate? Will the future climate—even our survival—depend on sunspots, flares, coronal holes, or other forms of solar activity? If so, can future trends be predicted?

The effects of currently observed changes in the Sun—small variations in light output, the occurrence of solar particle streams and magnetic fields—are very small in the Earth's lower atmosphere or *troposphere* where our weather actually occurs. However, at higher altitudes, the atmosphere reacts strongly to changes in solar activity. The *ozone layer*, at an altitude of 25 kilometers (16 miles), and the *ionosphere*, which extends upwards in a series of layers above 60 kilometers (37 miles), are produced by solar ultraviolet light and X-rays which ionize the thin air at these altitudes. Although the visible light of the Sun is stable, large variations in X-ray and ultraviolet radiation accompany solar activity, and these variations on the Sun cause major changes in the ionosphere. Some meteorologists believe that the ionospheric changes in turn influence the weather in the lower atmosphere, but the physical mechanism by which this may occur

has not been definitely identified. There is much research under way on possible relationships between solar activity and the weather.

A study of short-term weather patterns by Walter Orr Roberts of the University Corporation for Atmospheric Research and Roger H. Olson of NOAA suggests that weather may be affected as the spiral-shaped interplanetary magnetic field rotates past the Earth. They found that about a day after the boundary between inward-pointing and outward-pointing sectors sweeps by, there is a decrease in the number of low pressure weather systems forming in the Pacific Ocean off the western United States and Canada. Because these low pressure systems give rise to most of the storm centers that pass over North America, an understanding of this effect may ultimately assist in making weather predictions.

Like most suspected Sun-weather connections, the effect seen by Roberts and Olson is hard to explain. The problem is that the amount of energy present in the weather phenomena themselves far exceeds the energy that apparently is available from the variations in solar activity. In this case, the low pressure storm systems in the Pacific contain far more energy than do the particles and magnetic fields which enter the Earth's magnetosphere from the solar wind. If the Roberts-Olson effect is real, then there must be an amplifier mechanism, whereby the magnetic variations trigger the changes in the weather. But the nature of the ampli-

fier mechanism is currently unknown.

The search for Sun-weather relations is further complicated by the presence of many non-solar influences on both short- and long-term weather patterns. Volcanic eruptions can inject huge amounts of dust and ash into the atmosphere, cutting off some of the Sun's light and heat. Changes in the amount of carbon dioxide in the atmosphere, as a result of volcanic eruptions or the burning of coal and oil, affect the amount of heat absorbed by the atmosphere. Even small variations in the Earth's orbital motion around the Sun from year to year may cause significant changes in the weather. In looking for direct effects of solar activity on the weather we must first disentangle the many non-solar effects that are going on simultaneously. It is a challenging task.

Climate through the ages

Climate is the state of the weather over long periods of time, tens to thousands of years. Long-term effects of the Sun on the Earth's weather are called climate effects.

If the total output of radiant heat and light from the Sun (the *solar constant*) changed with time, rather than just the X-rays, ultraviolet and other fringe effects of solar activity, the variations would affect the lower atmosphere directly and surely would change the Earth's weather and climate. But we still do not know whether the solar constant has changed in the past or even if it is changing today. The necessary meas-

urements are very hard to make with the required accuracy. Because of absorption and scattering of sunlight in the Earth's atmosphere, these measurements are unreliable if made from the ground. Recently, techniques have been developed to measure the solar constant from space vehicles. There are now several instruments in orbit that are measuring the Sun's output with an accuracy that should be sufficient to detect variations capable of changing the climate.

The spacecraft measurements of the solar constant that we are accumulating now will enable us to determine the day-to-day and month-to-month changes in solar output. It should eventually be possible to find out whether the Sun varies, not only during its 11-year sunspot cycle, but perhaps even over longer periods as well.

Our studies with spacecraft are motivated in part by indirect evidence that long-term variations in the Sun's light have actually occurred. Observational records show an almost complete absence of sunspots between the years 1650 and 1715. During this period, named the *Maunder Minimum* for the English astronomer who first pointed it out, the sunspot cycle apparently ceased to exist. Historical sources attest to the fact that the weather in Europe was particularly cold during these years, a fact which would follow logically if the light from the Sun decreased significantly during years when the sunspot count was low.

Where Do We Go from Here?

We have made much progress in using observations from space to discover basic properties of the Sun, its magnetic field, and the Earth's magnetosphere. But we have only just begun to see the Sun as it really is, and many very important questions remain. For instance, we still have no adequate theory to explain why the period of the sunspot cycle is 11 years rather than, say, 2 years or 50 years. And we are far from being able to predict when (or even if) another long interval with few if any sunspots will occur. To answer such questions, we will need a program of systematic new space observations and much intensive theoretical work in the years to come.

New techniques of observation will enable us to probe the convective, oscillatory, and rotational motions that take place deep inside the Sun. These studies will be crucial for understanding how the solar magnetic field is generated. Telescopes, mounted on spacecraft, will give us detailed pictures of the fine structure of the Sun's surface. Currently anticipated instrumentation can reveal details a fifth as large as can be perceived (due to blurring by the Earth's atmosphere) from the ground. Spacecraft could be launched into trajectories that would carry them far out of the plane of the planetary orbits, so that they could look down over the poles of the Sun. Moving along these paths, the spacecraft could pass directly through the streams of solar wind that originate at the Sun's north and south poles. We would thus obtain our first information on the full three-dimensional structure of the solar

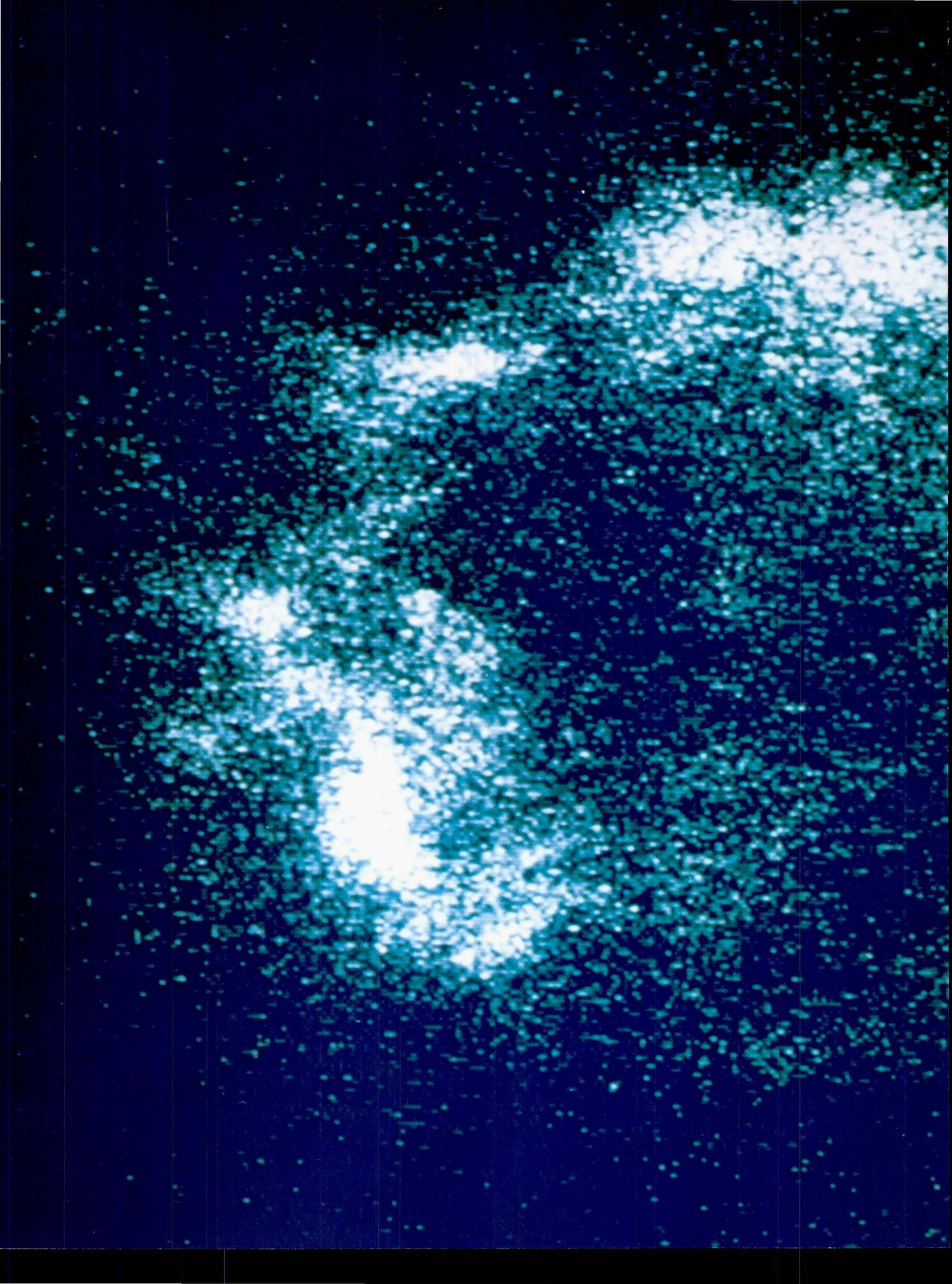
wind and the Sun's magnetic field.

To better study the Earth's magnetosphere and ionosphere, the next major advances will require measurements made simultaneously by perhaps five different spacecraft located around the magnetosphere and in the solar wind just upstream from the Earth. With coordinated measurements like these we can accurately trace the changing motions of the magnetosphere and follow disturbances in the streams of solar particles as they travel through space around the Earth.

A basic new type of investigation will be possible with future large orbital laboratories such as *Spacelab*, which will be launched on the *Space Shuttle*. These laboratories will allow us to make *active* experiments in space, in contrast to the earlier passive measurements. By injecting known amounts of radio waves or atomic particles into space and observing how they travel away from the spacecraft, we can answer questions about space around the Earth in much the same way that Earthbound physicists determine physical conditions in laboratory vessels. The future missions will be logical extrapolations from previous space- and ground-based studies of the Sun and the Earth's environment. We now know enough to frame the questions that we believe they will answer. These explorations will bring closer the day when our understanding of the phenomena around us is complete enough to tell how the entire Sun-Earth system works and how we can anticipate its future behavior.

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BEYOND THE SOLAR SYSTEM

David Gilman

Blast from an unseen explosion. Here photographed in X-rays by the HEAO-2 satellite, supernova remnant Cassiopeia A is the expanding blast from a star that exploded in the late seventeenth century. Historical records suggest that astronomers of the time missed the event, although one observer may have seen a faint star at the location of the explosion. Cassiopeia A is one of the most conspicuous objects found with X-ray telescopes, although only very dim nondescript wisps of gas are seen on visible-light photographs.

New Windows in the Sky

Astronomy has undergone a tremendous burst of discovery thanks to our new ability to study the universe through “windows” available to telescopes flown above the Earth’s atmosphere. We are observing radiation that never reaches the ground: X-rays, gamma rays, ultraviolet, and infrared light. Each new telescope in space brings the universe into clearer focus and reveals objects and phenomena not even imagined when the telescopes were planned. We are seeing further than before, with greater sensitivity, and at wavelengths of light that are utterly invisible to observatories on the ground.

Observing this heretofore unseen radiation, we are exploring what amounts almost to a new universe. X-rays and gamma rays from matter heated to millions of degrees tell us of violent explosions both in our own galactic neighborhood and as far away as the edge of the known universe. At the other extreme, infrared telescopes discern clouds of dust in interstellar space whose temperatures are scarcely 50 degrees above absolute zero (-273°C). We have found places in our own galaxy where enough matter to make a planet apparently disappears into a black hole each day, and there are far-off galaxies where more ravenous black holes may consume whole suns every day. At the very edge of the observable universe is a wall of frozen fire, the remnant of the Big Bang of creation, which appears to us as a whisper of radiation just a few degrees above absolute zero. No light from behind that wall can ever reach us, but the wrinkles in the wall remain to tell us the very details of creation itself, if we are clever enough to understand them.

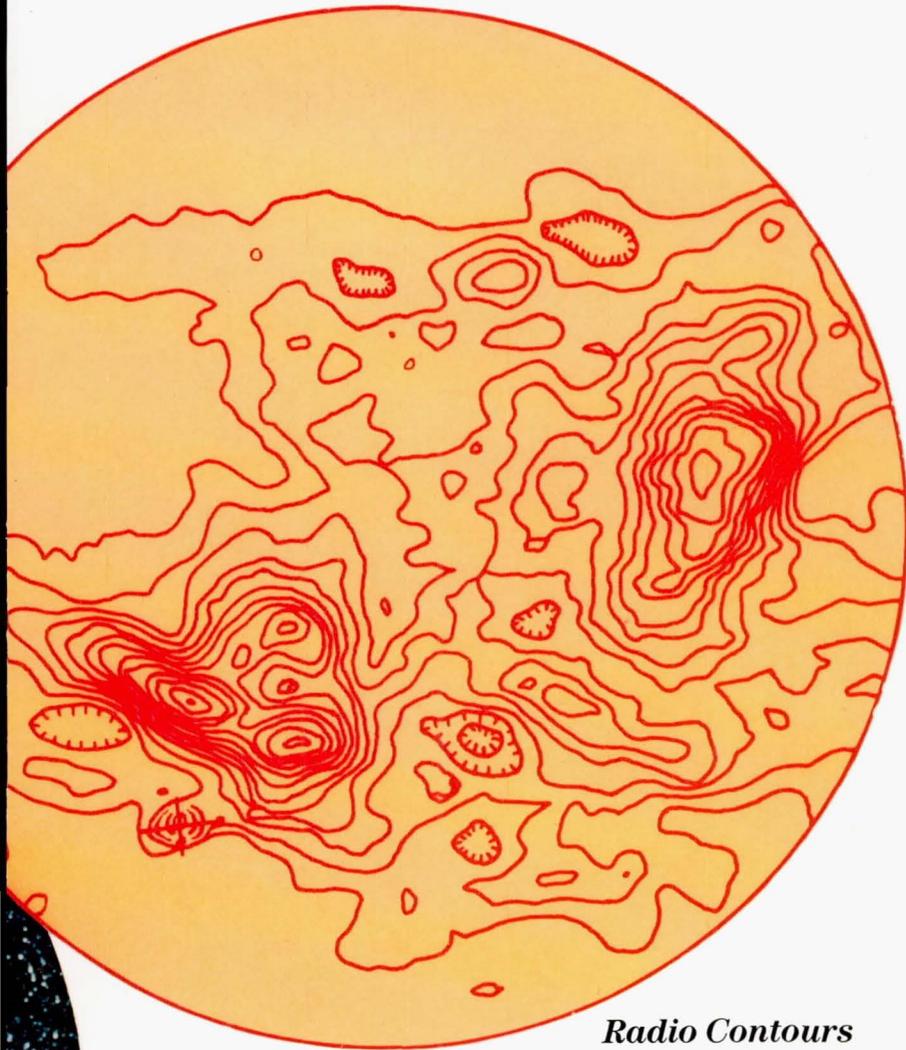


The Scale of the Universe

To discuss the universe, we must abandon our ordinary frames of reference and think along almost unimaginable scales of distance and energy, and we must consider unusual, even fantastic, states of matter. True, our own horizons have expanded through space exploration. Humans have gone higher and faster than ever before. But our experience is still drastically limited by comparison to the immensities of structures in the universe.

Speed and distance

The scale for speed in the universe is set not by space flight but by light waves, which travel at 299,800 kilometers per second (186,000 miles per second). This velocity is a fundamental constant of the universe, and it provides a standard for judging our progress into space. At the beginning of the Twentieth Century, the speed of light was more than 5 million times faster than any human had ever traveled. Now it is only 25,000 times faster than astronauts have flown on their



Radio Contours

Three ways to see a nebula. Observed in visible light (bottom), X-rays (top, left) and radio waves (top right), the eta Carinae region reveals wholly different aspects. Each is studied so that the physical processes at work in the nebula can be understood. The visible-light photo shows glowing, electrically excited gas, heated by radiation from adjacent hot stars, themselves not clearly distinguished. Dark lanes are clouds of interstellar dust that hide the bright nebula beyond. X-ray image from the HEAO-2 satellite reveals exact locations of the stars; X-rays come from their thin, hot outer atmospheres or coronae, while visible light comes from deeper layers. Faint blue glow around the stars in the X-ray picture (color supplied by a computer) reveals the presence of million-degree gas in a localized region of the nebula. Contours mapped by a radio telescope show that radio emission regions are highly structured (courtesy of D. S. Retallack, Kapteyn Institute). Infrared measurements (not shown) revealed that at some wavelengths, eta Carinae is the brightest object beyond the solar system, as seen from Earth.

way to the Moon. As space travel develops, it is no longer inconceivable that humans may someday travel at such high speeds that trips to the stars may become possible.

Dimensions in space are most conveniently expressed not in miles or kilometers, but in terms of the time it takes light to travel the distances involved. The distance from the Earth to the Moon (385,000 kilometers or 240,000 miles) is 1.3 *light seconds*. The distance from the Earth to the Sun is 8 *light minutes*, or 150,000,000 kilometers (93,000,000 miles). The spacecraft *Pioneer 10*, launched in 1973 and now past the orbit of the planet Uranus, has gone more than 3 *light hours* from the Earth. Even the nearest stars are *light years* away. It takes 4.3 years for light from the nearest star beyond the Sun, Proxima Centauri, to reach the Earth, traveling 41 million *million* kilometers (25 trillion miles) in the process.

Galaxies, which are irregular, ellipsoidal, disk- or spiral-shaped systems of billions of stars, are aptly termed "island universes." Our own galaxy, the Milky Way, is a flat spiral that is 100,000 light years across and almost 1,000 light years thick, with a large central bulge. The distances between galaxies are greater still, often measured in millions of light years. And the universe itself extends at least 10 to 20 billion light years in every direction from the Earth.

Energy

The amounts of energy involved in celestial processes are equally difficult to appreciate from our own exper-

ience. A typical unit of human energy is the joule, about the amount of energy needed to lift a glass of water from the dinner table to your mouth. On earth, energy releases can reach a quadrillion (a thousand million million) joules, about equal to a megaton, the energy produced by the detonation of a million tons of TNT. This is also roughly the amount of energy contained in a tornado or in a small earthquake. A very different scale is needed for astronomical power. A useful unit is the energy released by one star—our Sun—which emits the equivalent of 100 billion megatons in the form of light every second. Even this immense quantity is tiny by cosmic standards. An average galaxy may contain 100 billion stars, many comparable to the Sun. The strange, distant objects called quasars are even more powerful, some individually releasing as much energy as a million galaxies.

Energy has many different forms in space. Energy is present in light, in the motions of particles, in magnetic fields, and in gravitational attraction. The temperature of atoms and molecules moving randomly in space is proportional to the energy contained in each particle. As each particle moves, it radiates energy. By detecting and measuring this energy, we can measure the particle temperatures at distances of thousands of light years.

The scale of temperatures found by space astronomy runs from a few degrees above absolute zero, with particles moving at a slow 30 kilometers per hour (19 miles per hour), to almost 10 billion° C, where electrons move at close to the speed of light. Most of

The New Astronomy

the universe is made of hydrogen, and for this reason the temperature of $10,000^{\circ}\text{C}$ is a critical threshold. At this temperature, the energy of a moving particle is enough to knock the electron from a hydrogen atom when they collide. If energy is added to interstellar hydrogen, the gas will heat up until it reaches $10,000^{\circ}\text{C}$ and then will stay at $10,000^{\circ}\text{C}$, even though energy is continuously added, until the hydrogen is completely ionized.

Density

The density of matter in space is very different from conditions on the Earth. The best vacuums are found in space, especially between the stars, where there often is only one atom in more than a thousand cubic centimeters (60 cubic inches). An average star, with about a trillion trillion atoms in each cubic centimeter, is about as dense as water. At the extreme of astronomical density, however, are the *neutron stars* that form in supernova explosions. Their matter is so compressed that the individual atoms collapse into neutrons. A single cubic centimeter of a neutron star contains enough material to make a cubic kilometer of a normal star and may weigh as much as several billion tons.

One cannot perform laboratory experiments on stars and galaxies. For this reason, astronomy has always been a science of careful observation. Our two main sources of information about the universe are *electromagnetic radiation* (light, radio waves, infrared, X-rays, gamma rays, etc.) and *cosmic rays*, which are atomic particles that have been accelerated to high velocities and carry great amounts of energy. Each kind of electromagnetic radiation moves at the speed of light, while cosmic rays are slightly slower. Electromagnetic radiation is electrically neutral, but cosmic rays carry an electric charge. As a result, light can travel through space in essentially straight lines, but cosmic rays spiral along the weak lines of magnetic force that permeate space. We can see where a beam of light or of X-rays has come from, but because of their spiraling, cosmic rays cannot be traced to their points of origin.

Before the Space Age, all astronomy was performed on the ground, limited by the Earth's atmosphere. Cosmic rays could not be observed directly, but it was possible to study the showers of energetic charged particles that they produce when they strike the atmosphere. The atmosphere absorbs almost all of the radiation that reaches the Earth from space, so stars and galaxies could only be seen at the limited wavelengths to which the atmosphere is transparent, primarily visible light and radio waves. Large telescopes were built to "see" at these wavelengths. Diameters of optical telescopes are measured in meters, while some radio telescopes are hundreds of meters across. Ground-based

observations discovered star clusters, galaxies, cosmic radio sources, and the expansion of the universe. Optical and radio telescopes also discovered quasars and pulsars, two types of energetic objects that have gained in interest through studies from space.

Perhaps the most significant discovery of ground-based astronomy was that the universe is expanding, a result which led directly to the *Big Bang* theory of creation. As fragments fly apart from any explosion, the faster-moving pieces leave the slower-moving pieces behind. A simple law applies to the various exploded parts: the further apart they are the faster they are moving apart. From the ground, we could see that galaxies as far away as 40 million light years were receding from us in accordance with just such a law. This law—that the velocity at which a galaxy recedes from us is 20 to 40 kilometers per second for each million light years of distance away from us—lets us determine the size and age of the universe. At great distances, everything is moving away; nothing is approaching us. About 10 to 20 billion light years away, the receding matter would have the speed of light, and observation to greater distances is impossible.

There are several alternative versions of the Big Bang theory and also some competing theories about the nature of the universe. We hope to learn whether the universe is “open,” meaning that the expansion will continue forever, or if it is “closed,” in which case the expansion will some day come to an end. In that event, the end of the expansion will be followed

by a collapse phase, in which all the galaxies in space approach each other and eventually coalesce in a fiery end to the universe as we know it. To discriminate among these alternatives, we need to see further and make measurements of distant phenomena at appropriate wavelengths and with higher precision than heretofore. Hopefully, we can then resolve the uncertainties we face in applying the laws of physics at the very largest scales of energy and distance.

Astronomy will advance greatly in the future when we launch large optical and radio telescopes above the interfering atmosphere, but the main achievement of space astronomy so far has not been in these traditional areas. The Space Age has made it possible to see the universe in new kinds of light, not just the visible light and radio waves that reach the ground. The most dramatic discoveries have come from the telescopes that observe ultraviolet radiation, X-rays, and gamma rays. Small telescopes to study cosmic rays have also been flown, and the first large cosmic ray telescopes were launched on the third *High Energy Astronomy Observatory* (HEAO-3) in September, 1979. From these telescopes in space has come a burst of discovery that rivals the revolution produced by the invention of the telescope itself in the early 1600's. We are reaching toward a new understanding of the components of the universe: the stars, the galaxies, the strange pulsars and stranger quasars, even the almost-empty space that lies between the stars.

Life-Styles of the Stars

Normal stars

Before the Space Age, most astronomy concerned stars and systems of stars. The reason for this is that stars emit much of their energy as visible light, and this light can penetrate our atmosphere and be detected easily from the ground. Even though scientists were limited to studying this kind of starlight, much was learned. Stars were counted, analyzed, measured, weighed, and sorted into groups. Their nuclear energy sources were deduced. Their life histories, from birth to death, gradually were deciphered.

The so-called "normal" stars, such as our Sun, shine steadily. They have a variety of colors: red, orange, yellow, white, and blue. Most are smaller than the Sun, many resemble it, and a few are much larger. In addition, there are several types of "abnormal" stars: giants, dwarfs, and a variety of variable stars.

The Sun is about 1.4 million kilometers (865,000 miles) in diameter—about 109 times the diameter of the Earth—and has a surface temperature of about 6000° C. It is a natural hydrogen-fueled nuclear power plant. Deep inside, the hydrogen that makes up 90 percent of the Sun is fused into helium atoms, releasing an intense flood of energy that finds its way to the surface and so out into space. Today the Sun is in a state of balance between two forces: gravity, which pulls it inward, and the pressure of the hot gas and outward streaming radiation from the central nuclear furnace.

The diameters of most normal stars range from one tenth to ten times as much as the solar diameter. The larger, more massive ones are blue or white, and notably hotter than the Sun. Sirius, in the constellation

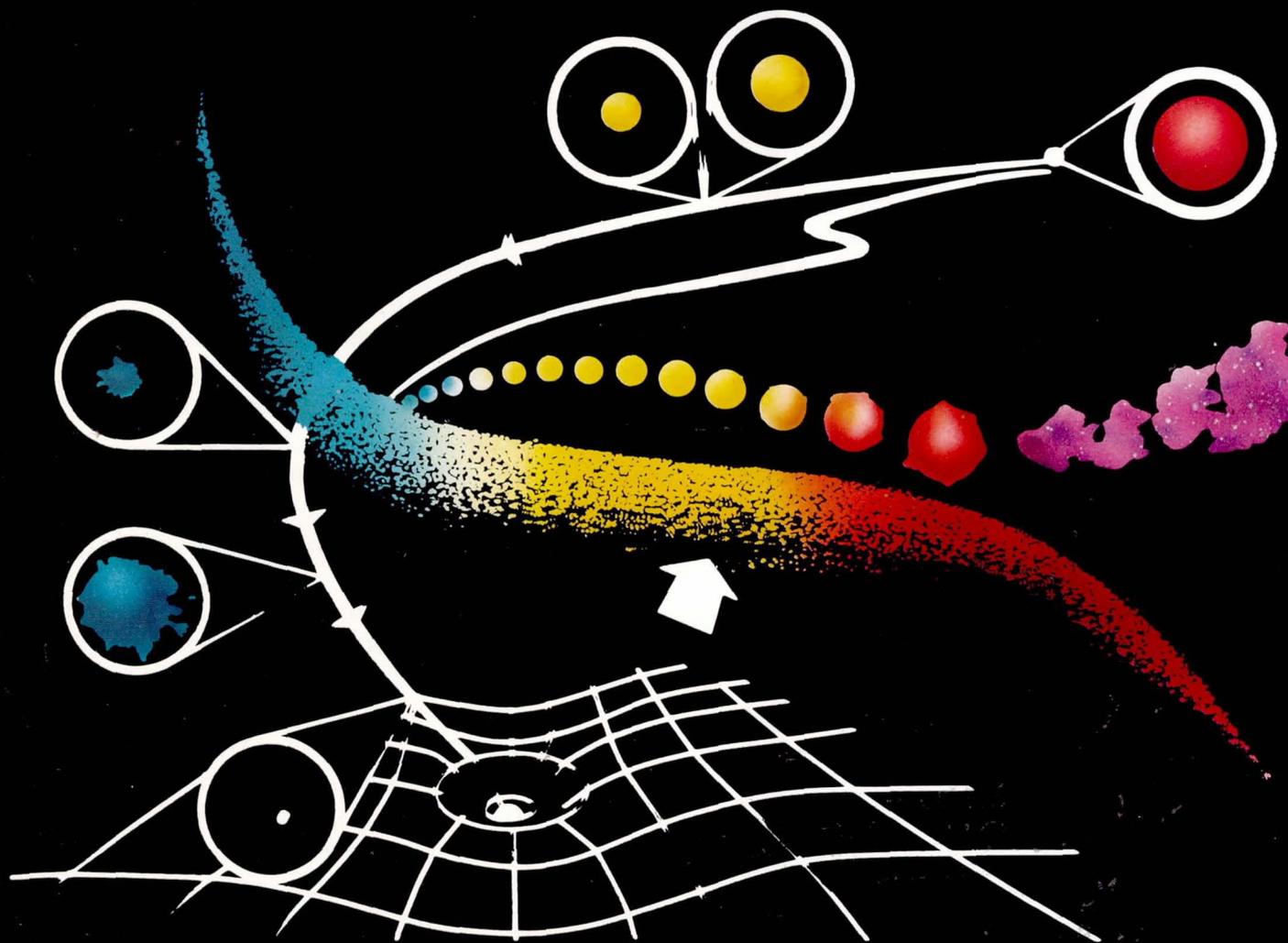
Canis Major, and Vega, in Lyra, are examples of hot, massive normal stars that are fairly close to the Sun (8.6 light years and about 26 light years away, respectively). They are white, several times more massive than the Sun, and have surface temperatures about 10,000° C. Other, more distant normal stars have temperatures up to about 40,000° C. There are many normal red stars near the Sun, with temperatures of a few thousand degrees and masses much less than that of the Sun. None, however, is bright enough to be seen without a telescope. All of the bright red stars in the night sky are red giants and supergiants, counted among those we term abnormal stars. Examples are the supergiants Betelgeuse in Orion and Antares in Scorpius (each about 520 light years from Earth) and giant Aldebaran (68 light years) in Taurus. The Sun is slightly unusual in one respect: It has no companion star. Most stars seem to have companions, with which they orbit in binary, triple, or larger systems, and some stars are members of clusters, with from a few dozen to a few million members.

In the first half of the Twentieth Century, astrophysicists worked out the life cycle of the stars. Stars are born out of giant clouds of gas and dust called *nebulae*. We can see the young stars in such clouds as the Great Nebula in Orion. (This nebula is visible to the eye, and even with small binoculars one can see that it is a diffuse object and not a star.)

The large blue supergiant stars have up to 100 times the mass of the Sun, while small, red dwarf stars have less than one-tenth the mass of the Sun. (For comparison, the planet Jupiter has slightly less than one thousandth the mass of the Sun.) The biggest stars burn hotly and rapidly,

Stellar Evolution

Absolute Magnitude



Color/Temperature



consuming all their nuclear fuel quickly, sometimes in less than a million years. Stars like the Sun, on the other hand, burn slowly and steadily; their hydrogen fuel may last for 10 billion years or more. The red dwarf stars burn up so slowly that trillions of years would have to elapse before their hydrogen is exhausted. When a star *has* used up its hydrogen fuel, it leaves the “normal” state. This occurs when the core of the star has been converted from hydrogen to helium by the nuclear reactions. Now the burning process moves outward to higher and higher layers. The atmosphere of the star expands greatly and it becomes a red giant. “Giant” is an apt name; if a red giant were placed where the Sun is now, the innermost planet, Mercury, might fall inside it, and a larger red “supergiant” might extend out past the orbit of the planet Mars. As nuclear evolution continues, the star may become a variable, pulsating in size and brightness over periods of several months to a year. The visual brightness of such a star may vary by a factor of 100, while its total output of energy changes by only a factor of two or three.

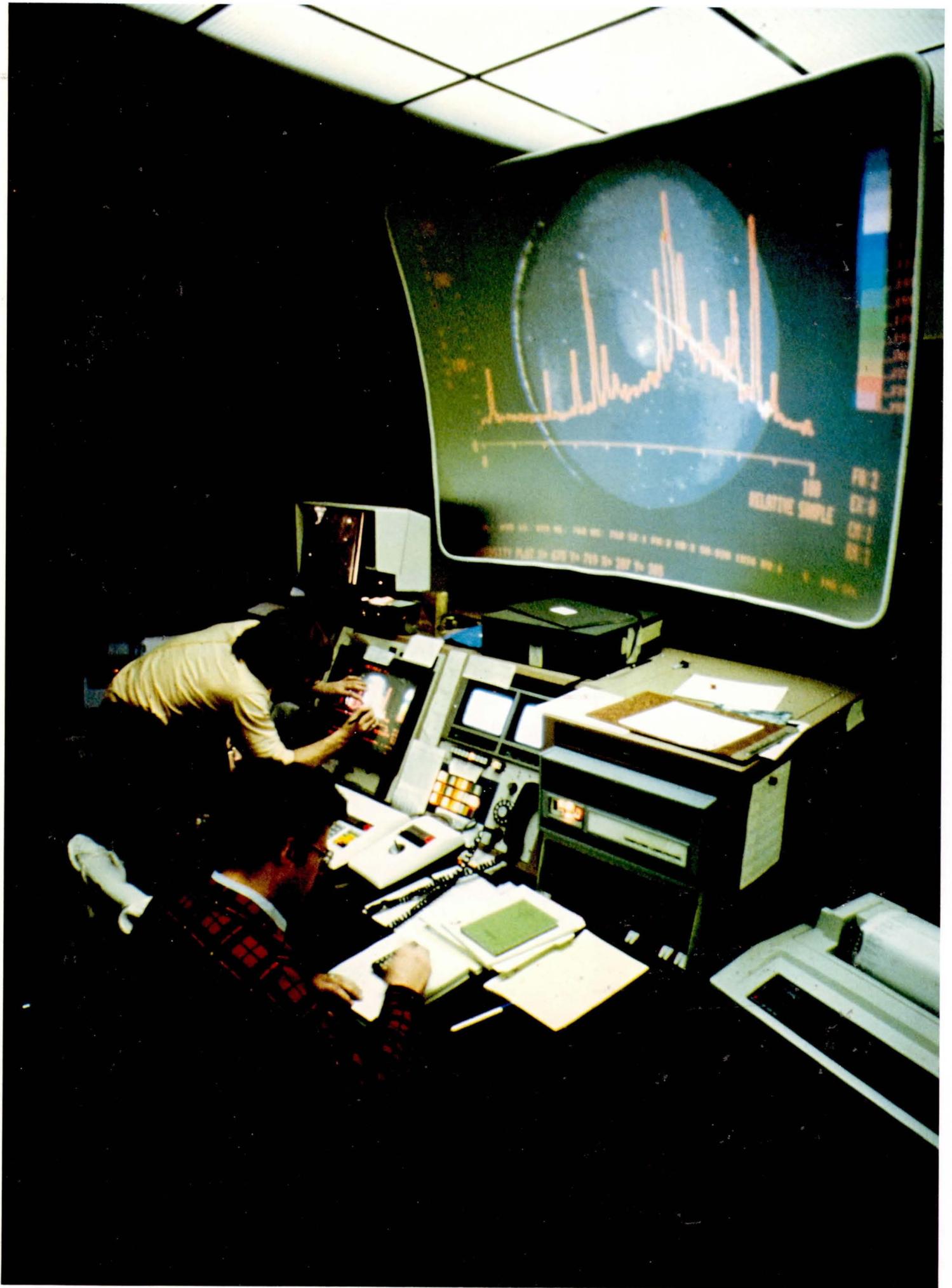
Stars in a New Light

Space astronomy has allowed us to understand some of the really hot stars in the universe. When a star shines with a temperature of about 6000° C, like the Sun, most of the energy is emitted as visible light. A 10,000° C star produces much ultraviolet radiation. Unusual, very small stars, with temperatures around one million degrees, generate X-rays. But we can never see these extremely hot stars from the ground. The X-rays are absorbed by our atmosphere. In fact, they were discovered with instruments flown in space.

Ultraviolet telescopes in orbit have observed hot blue supergiants, such as Rigel in Orion (about 900 light years away), that are much more massive than the Sun. To our surprise, these massive stars turned out to have intense *stellar winds*, streams of atoms that boil off the top of the star’s atmosphere and race into space.

Although the winds from the hot supergiant stars are invisible to telescopes on the ground, they are hundreds of millions of times more powerful than the wind from our own Sun.

Evolution of a massive star. *Bluer colors and higher temperatures are to the left; redder colors and cooler temperatures are to the right in this schematic diagram, while stellar luminosities are plotted so that the brighter values are higher, the dimmer ones lower. Seen, according to theory, is the collapse of an interstellar dust and gas cloud to form a massive blue star, which spends most of its life at a position to the left of center on the thick colored band at the center of the diagram. The arrow shows the position of the Sun on this band, known as the main sequence. Although the massive star may shed some matter in a stellar wind, it will remain on the main sequence until its central store of nuclear fuel is nearly exhausted. Then, it begins to expand. The visible “surface” of the star gets larger but cooler; its radius may become as great as that of the Earth’s orbit, hence the term “red giant.” After further mass shedding and nuclear burning, the star begins to pulsate, rhythmically growing larger and smaller. Finally, when nuclear burning no longer releases enough radiant energy to support the giant star, it collapses, its dense central core becoming either a compact white dwarf or a tiny neutron star. The collapse also triggers an explosion of the star’s outer layers, which manifests itself as a supernova. In exceptional, very massive cases, the core or perhaps even the entire star may shrink into a black hole (symbolized by warped grid lines).*



These winds sweep away the interstellar gas and dust around their stars, sometimes producing an "interstellar bubble" over 10 light years in diameter. The wind "blows" at thousands of kilometers per second and carries away enough of the star's mass to make a whole Sun every million years. In the lifetime of a blue supergiant, which may be 10 million years, a substantial fraction of the original mass of the star may be expelled into space.

Studying the X-rays from stars has given us more surprises. With the X-ray telescope on the second *High Energy Astronomy Observatory* (HEAO-2), stars of all kinds have been observed through the X-rays they produce. Contrary to what scientists expected, massive stars were found to have coronae: thin, hot gaseous envelopes surrounding their lower atmospheres. These coronae, with temperatures up to several million degrees, generate the X-rays. Normal yellow stars like the Sun seem to make much fewer X-rays. Even some cool stars make more X-rays than the Sun. New theories are being developed to account for this discovery. The space observations indicate that the speed of a star's rotation may play a more important role than its temperature

in determining its X-ray luminosity, and indeed the Sun is a slowly rotating star. Faster-turning stars seem to outshine slower ones of the same type in X-rays.

The interplay between space telescopes and ground-based astronomy has not only given us a new look at familiar objects, it has also turned up a number of very strange and unfamiliar ones. One example is the remarkable, still somewhat mysterious object known as SS 433. The light from SS 433 was observed to have spectral lines that did not correspond to the spectra of any known stars. More detailed observations revealed that these lines moved very quickly from one wavelength to another, indicating a surprising change in the velocity of the gas emitting the light. Over several months, the range in velocity amounted to nearly one-third of the speed of light. This was sufficient to shift some infrared and ultraviolet wavelengths alternately into the range of visible light. No wonder the spectral lines were hard to identify! The high-speed movement is characteristic of gas at a temperature of close to a billion degrees. The width of the lines, however, showed that the gas is cool, with a temperature of only about 10,000° C. How the gas in SS 433 can move so very fast and still remain cool is one of the outstanding mysteries of the 1980's in astrophysics. X-ray observations from satellites first called our attention to this star, stimulating the spectral studies that revealed the enormous velocities.

Underground observers of distant space.

In a basement room at the NASA-Goddard Space Flight Center, astronomers work with an orbiting telescope far above. The telescope is aboard the International Ultraviolet Explorer, a spacecraft suspended over the south Atlantic, in Earth-synchronous orbit. In continuous touch with the IUE telescope, the astronomers can view star fields through it or examine the ultraviolet spectrum of a star (as shown here on large screen at top of photograph) or nebula shortly after a time-exposure observation is completed. (Photograph courtesy of Fred Espenak.)

The End of Stars: Death and Transfiguration

White dwarfs

Perhaps the greatest surprise of the Space Age has been the realization that "dead" stars that have used all their nuclear fuel can sometimes produce more energy than they did when "alive." We have discovered that there are three possible ends for a burnt-out star. If the star has about the mass of the Sun, it will collapse under its own gravity until the collective resistance of the electrons within it finally halts the process. The star has become a *white dwarf* and may be comparable in size to the Earth. A star with a mass of about 1.5 to 2 or 3 times that of our Sun will collapse even further, ending up as a *neutron star*, perhaps 20 kilometers in diameter. In neutron stars, the force of gravity has overwhelmed the resistance of electrons to compression and has forced them to combine with protons to form neutrons. Even the nuclei of atoms are obliterated in this process, and finally the collective resistance of neutrons to compression halts the collapse. At this point, the star's matter is so dense that each cubic centimeter weighs several

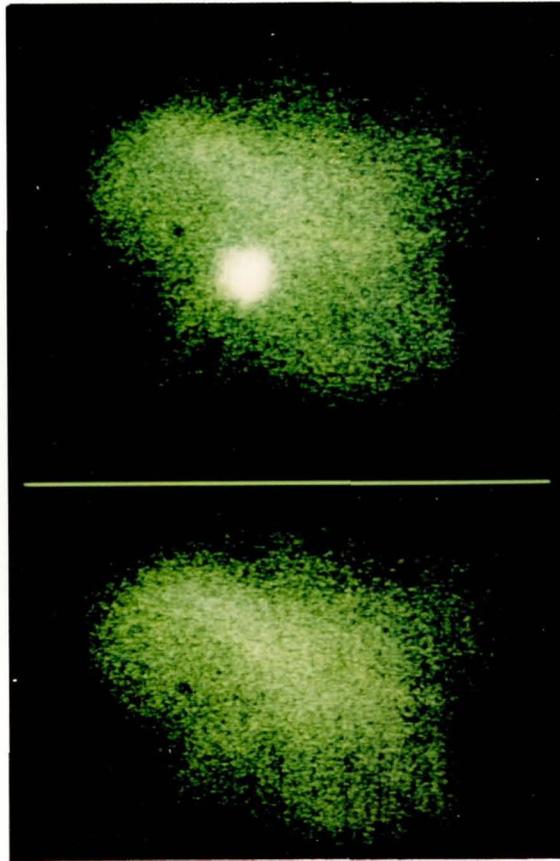
billion tons. For stars that end their life weighing more than a few times the mass of the Sun, even the resistance of neutrons is not enough to stop the inexorable gravitational collapse. The star ultimately becomes a *black hole*, a region in space so massive that no light or matter can ever escape from it.

The existence of white dwarfs has been known for some time, and many have been detected with ground-based telescopes. However, neutron stars and black holes existed only in much-disputed theory until the Space Age.

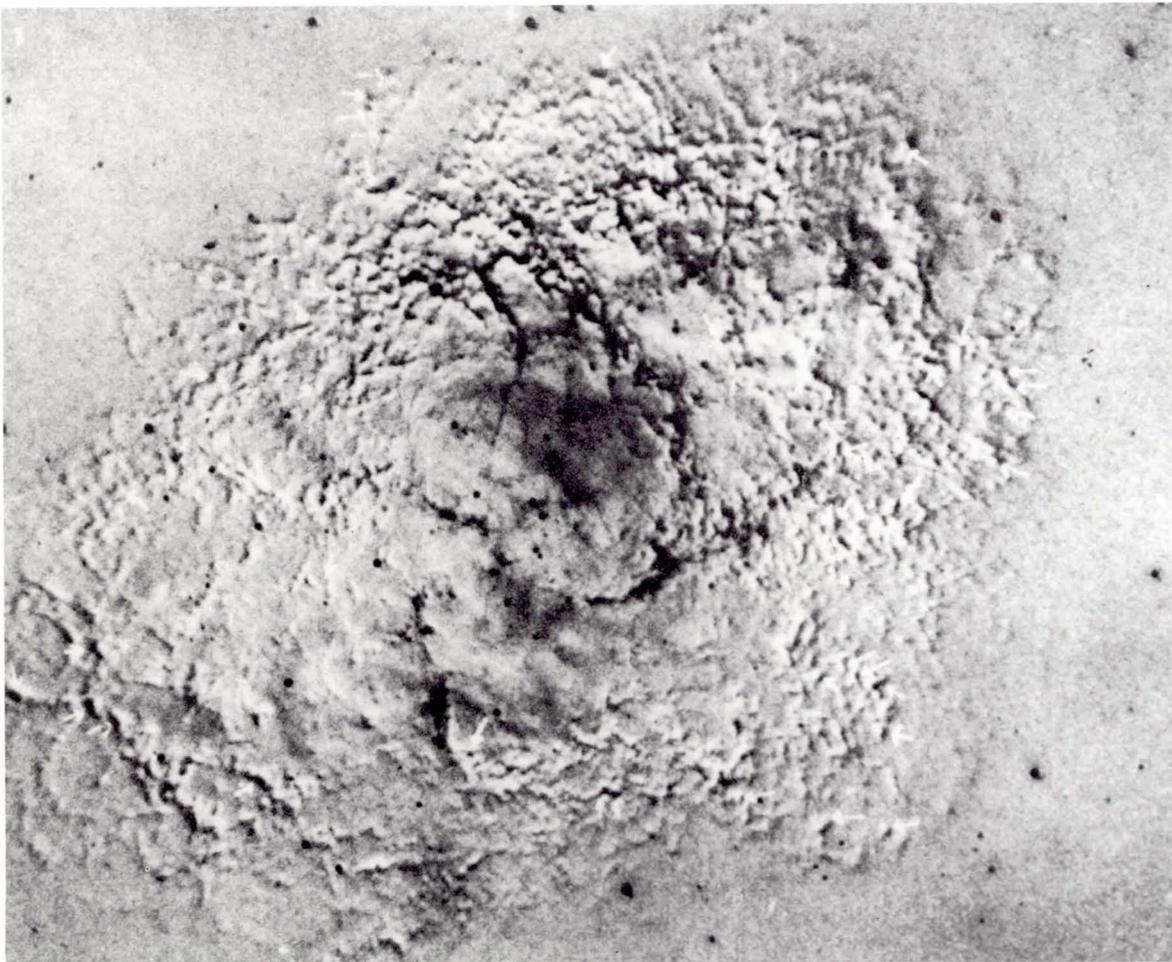
Neutron stars and supernovae

The discovery and understanding of neutron stars involve studies of two poorly understood types of space objects, supernovae and pulsars. Supernovae are extremely violent explosions, in which a star suddenly detonates, pouring out so much energy that for a few days it may outshine all the other stars in its galaxy put together. Pulsars, first detected by radio astronomers in 1967, are

Strange remains of a shattered star. Result of a supernova explosion seen in the year 1054 A.D., the Crab Nebula is now about 10 light years in diameter. The Crab is shown in visible light at upper left; filamentary structures are shreds of the disrupted star, while the smooth white glow is radiation from high-speed electrons streaming through a magnetic field in the nebula. At upper right, two X-ray images from HEAO-2 show the pulsar at the heart of the nebula as it seems to blink on and off. Actually, the pulsar is a neutron star (the surviving core of the exploded star), rotating 30 times per second, each of its twin "searchlight" beams sweeping past the Earth at like intervals. Each sweep corresponds to an observed pulse of X-rays, gamma rays, visible light, and radio waves. The spinning core is gradually slowing as it supplies energy to the fast electrons that make the smooth part of the nebula shine. At the bottom, two black-and-white photographs from the 5-meter (200-inch) Hale reflector on Mt. Palomar are combined to reveal the motion of the filaments thrown out in the 1054 A.D. explosion. A photo made in 1950 is printed as a positive (bright regions are white), while one made in 1964 is printed as a negative (bright regions are dark). Note that each small white structure has a black rim on the outer side, indicating that expansion from the center persists.



Images of the Crab Nebula



sources of very accurately spaced bursts of radio waves. These bursts were so regular, in fact, that the scientists who detected them wondered briefly if they had found artificially generated signals from an interstellar civilization.

The discovery of a pulsar in the Crab Nebula supernova remnant led to a great synthesis in our understanding of pulsars and supernovae. Supernovae occur at the end of a massive star's life, when it is a red supergiant, with its nuclear fuel almost spent. When the central core becomes so dense that electrons and protons begin to form neutrons, it collapses catastrophically to form a neutron star. In the process, more energy is released than the star ever generated from its nuclear fuel, producing an explosion in which every atom in the outer parts of the star is heated to well over a million degrees. The star is literally destroyed in an instant, but the debris from the explosion shines briefly with the energy of a billion suns.

Besides splattering stellar debris into space, supernova explosions leave behind a "cinder" — the dense, collapsed core, made of neutrons — where there once was a star. The weak magnetic field of the original star is greatly enhanced in the collapse, and the remnant core — the neutron star — may have a magnetic field trillions of times stronger than the magnetic field of the Earth. The rotation of the star also increases dramatically during collapse, and the resulting neutron star spins many times a second. Beams of radio waves, X-rays, and other radiation, perhaps focused by the powerful magnetic field, sweep through

space like the revolving beam of a lighthouse. The neutron star has become a pulsar.

Pulsars were discovered accidentally during a study of "twinkling" radio sources in the sky. This twinkling is not due to our atmosphere, as is the twinkling of stars. Instead it is caused by the highly rarefied interstellar gas, which affects the passage of radio waves. As the study went on, the scientists at Cambridge University noticed that in some sources the twinkling was periodic, the signals came at regular intervals of 1 or 2 seconds or less.

Gradually, more pulsars were discovered. The fastest one known so far, which rotates at 30 times a second, is in the Crab Nebula, the remnant of a supernova explosion that was observed in 1054 A.D. When this rapid pulsar was found, it was quickly realized that it must be a neutron star. Only a neutron star could remain intact under such rapid rotation without breaking up. (A rotating black hole would remain intact, but it would not produce a regular signal.)

Now that we can see the universe by the light of X-rays and gamma rays, further unexpected properties of pulsars have been found. The theories that were rather successful in explaining the Crab Nebula pulsar failed to predict or account for phenomena found in the brightest gamma ray pulsar, located in the constellation Vela. New theories are needed to explain how pulsars can create intense radio waves, visible light, X-rays, and gamma rays, all at the same time.

Many neutron stars of another kind have been found with orbiting X-ray telescopes. We usually cannot

detect the heat left over from their collapse, but instead we detect X-rays from matter that is heated intensely as it falls rapidly towards the surface of the star. The realization that neutron stars suck up surrounding matter came from the discovery in 1971 of an X-ray pulsar, Hercules X-1. Detailed study of this X-ray source revealed very small variations in the 1.2-second period of pulsation. More study proved that these small variations were caused by motion of the neutron star in orbit around another star.

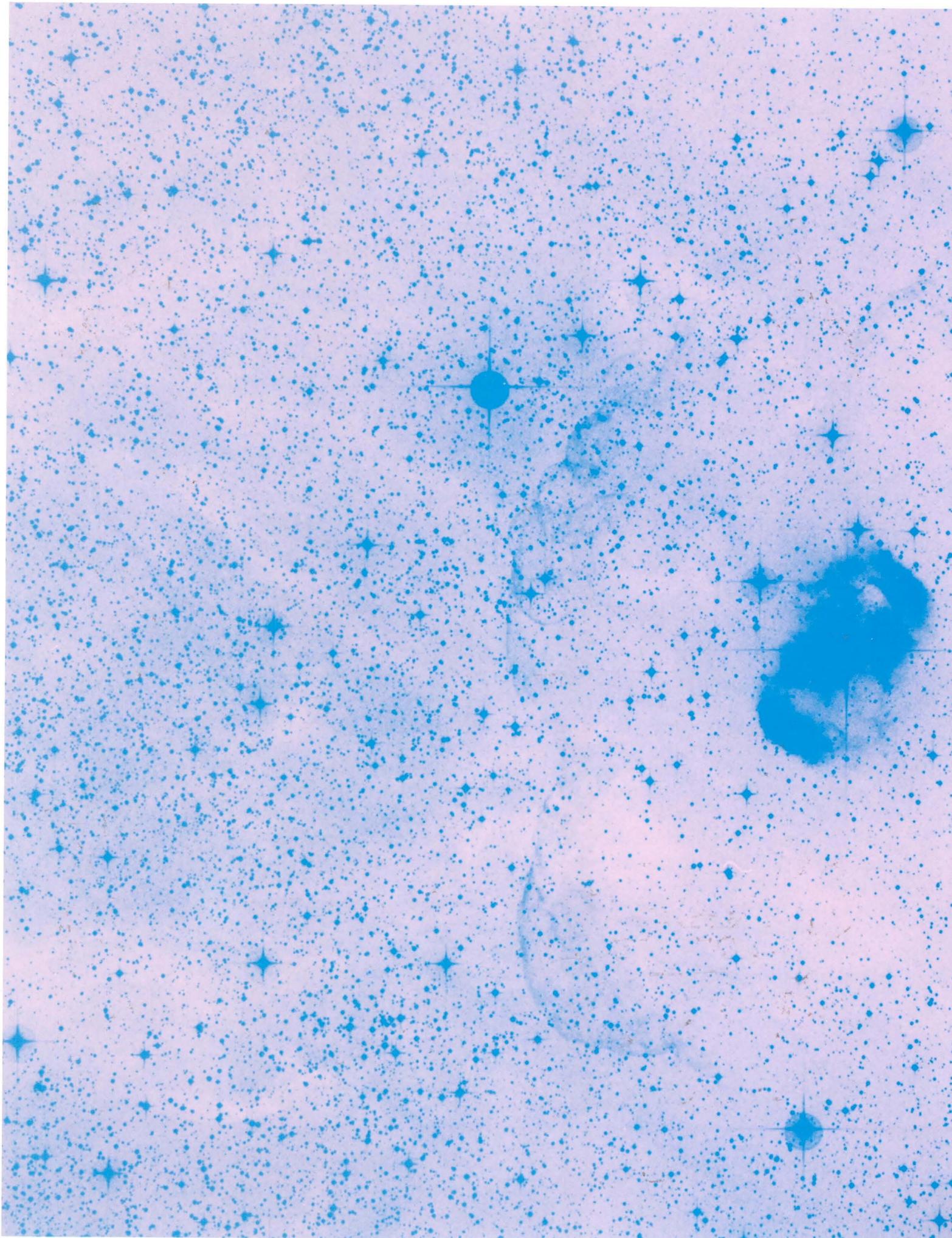
We have now learned that most X-ray emitting neutron stars are in orbit around other, otherwise normal stars. In some cases the stars are so close that the intense gravity of the neutron star actually pulls gas away from the atmosphere of its companion. Even when the stars are farther apart, the neutron stars may collect material from the stellar winds of the companions. As the gas is pulled from the normal star down to the surface of the neutron star, the gravitational energy of the neutron star heats the gas to millions of degrees. The hot gas gives off X-rays that mark for us the location of the otherwise invisible neutron star. X-ray pulsars derive their energy from the accretion of matter; the pulsars discovered by the radio astronomers are mostly single stars that are using up their energy of rotation and thus are gradually slowing down.

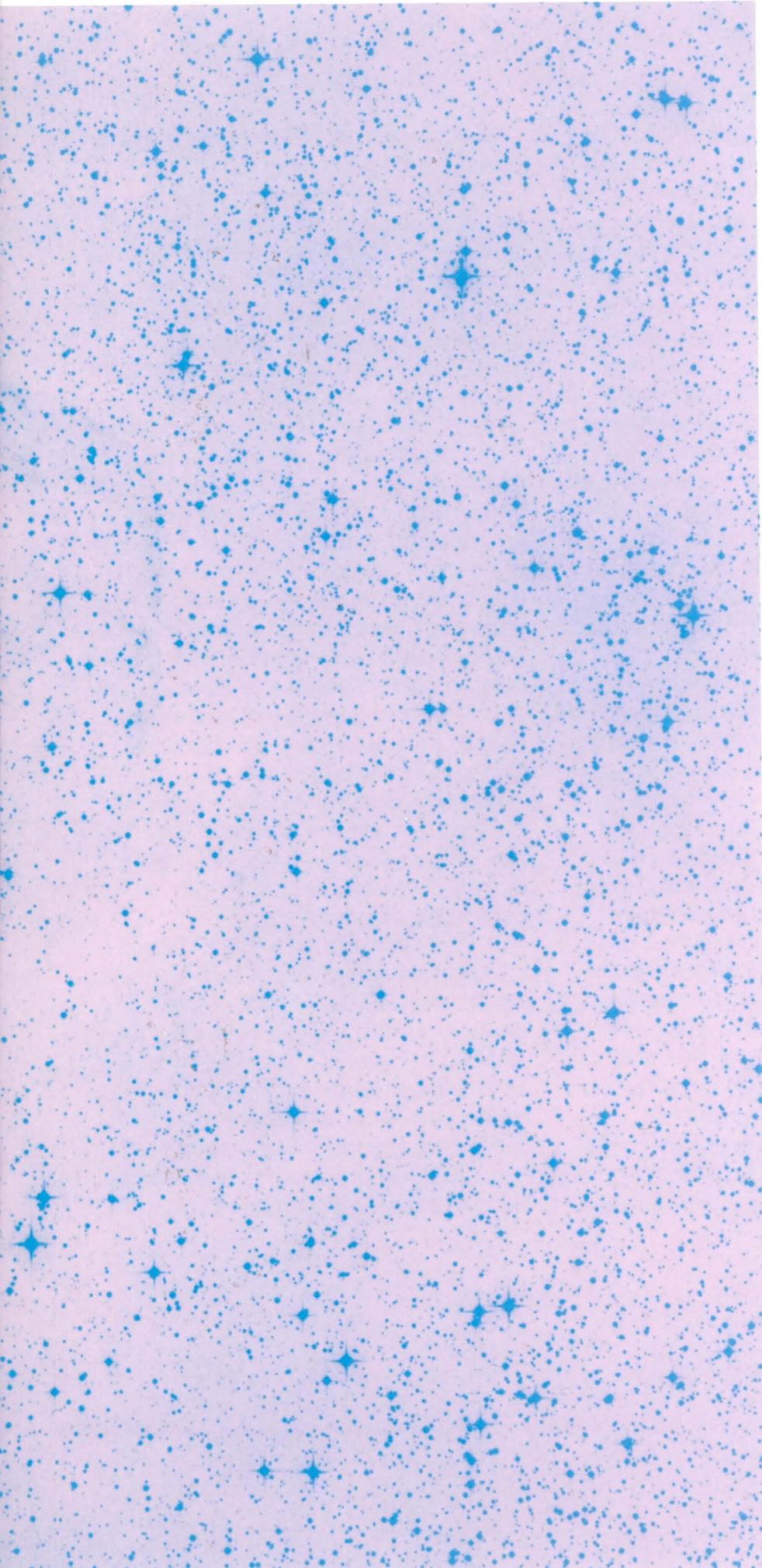
Black holes: the end point

When the gravity of a collapsing star is too strong for even neutrons to resist, a black hole may be formed. A black hole is a point mass in space, surrounded by a literally black region

in which the gravity is so strong that no matter, nor even light, can escape it. But, just as in the case of a neutron star, matter that falls toward the black hole is intensely heated, producing copious X-rays that can be detected with telescopes flown above the atmosphere.

A few of the brightest X-ray sources in our galaxy are probably black holes orbiting closely with relatively ordinary stars. The X-ray source called Cygnus X-1 is a famous example. In 1971, astronomers learned that Cygnus X-1 was associated with a visible star that also is a radio source. This discovery is an important example of how ground-based optical and radio telescopes work in consort with orbiting X-ray telescopes to solve the problems of Space Age astronomy. The identity of the stellar companion was confirmed when both the radio source and the X-ray source were observed to change dramatically and simultaneously in intensity. Observations of the spectrum of the visible star and its changes in velocity as it and its X-ray source companion followed their orbits led to an estimate of the mass of the X-ray source. This unseen star that does produce X-rays appears to have at least six times the mass of our Sun, much more than can possibly be supported by the resistance of neutrons. Comparing the deduced mass with the theoretical limits on the masses of neutron stars, we conclude that the unseen X-ray source in the Cygnus X-1 binary star system must be a black hole. However, the proof necessarily is limited—you can't see a black hole—and further studies of this and other cosmic X-ray sources are needed.



A photograph of a star field with a prominent blue bubble structure. The background is a dense field of small, faint blue stars. Several larger, brighter blue stars are scattered throughout. In the center-right, there is a distinct, irregularly shaped region of brighter blue stars, which is the bubble mentioned in the text. The overall color palette is various shades of blue, from light to dark.

“Empty” Space: The Birthplace of Stars

Our first exploration of the deep space beyond the solar system is approaching. Our spacecraft—*Voyagers 1 and 2*, *Pioneers 10 and 11*, and still others to come—are moving out toward the space between the stars. Thanks to Space Age astronomy, and especially to observations made in ultraviolet wavelengths from satellites, we already know something about what to expect there.

Our view of the interstellar space that they are approaching has changed completely since the *Pioneers* and *Voyagers* were launched for solar system studies several years ago. For one thing, we now know that “empty” space isn’t empty and quiet. True, you can count on your fingers the number of atoms in a cubic inch of interstellar space, but these atoms are subjected to violent processes. Some are heated to more than a million degrees, while others may cool to within fifty degrees of absolute zero. Within this thin gas, winds blow and bubbles are formed, expanding and sometimes popping out of our galaxy altogether.

A bubble in space. Massive, rapid winds pouring out over several million years from three bright blue stars formed a large, hot gas bubble in interstellar space, its periphery seen as a series of irregular arcs around the much smaller “planetary” nebulae expelled by two of the stars, now shrunk into hot, blue stars called subdwarfs. On one side of the bubble the boundary arcs (which represent the interface between the bubble gas and the cooler interstellar material) are not seen, perhaps due to overlying dust clouds or because the bubble has merged there with a larger one not readily discerned in the photograph. (Photograph by the U.K. Schmidt Telescope Unit, copyright 1978, Royal Observatory, Edinburgh; used by permission.)

As the spacecraft move out, they will first enter a region of warm gas that surrounds the solar system to at least 10 light years in all directions from the Sun and which contains our nearest neighbor stars such as alpha Centauri and Sirius. We have been able to measure the temperature of the cloud (about 12,000° C) and its density, about 100,000 atoms per cubic meter (1.6 atoms per cubic inch). Since the Sun is moving through the cloud, we observe the gas streaming through the solar system. It will take *Voyager 1* more than 200,000 years to leave this cloud, but when it does it will enter a region of much higher temperature and much lower density, a bubble of very fine vacuum in space. The bubble extends at least 100 light years in all directions around the smaller "warm" cloud. It will be millions of years until *Voyager* leaves the bubble and enters another zone of denser interstellar gas. The high temperatures in the bubble – more than 10,000° C – pose no threat to the spacecraft (which will have ceased operating several hundred thousand years earlier) because the gas is an almost-perfect vacuum. There are less than 10 atoms per cubic meter (1 atom in 6100 cubic inches) in the bubble. Even if the temperature of the gas is a million degrees, the energy the gas conveys to the spacecraft will be quickly radiated into space. The greatest danger

to the spacecraft in interstellar space will be that of getting too cold.

The recent discovery of large bubbles of hot, very thin gas has produced a radically new view of what's going on in the space between the stars. In the old view, gas in interstellar space was either warm or cold. Now, with X-rays and ultraviolet light, we find that most of the space between the stars is much hotter than we had suspected. In the old view, pressures of thin, warm gas were balanced against those of denser cold gas, and the situation was stable. Our telescopes in space now tell us that this is not true; pressures are out of balance. There is a great deal of interstellar pushing and shoving going on. Matter gathers and cools in some places because matter elsewhere is heated and dispersed. Besides discovering the very hot gas, the orbiting telescopes discovered two sources of the gas: the intense stellar winds that boil off hot stars, and the rarer but more violent blasts of matter from exploding supernovae.

The hot bubbles of very thin gas pile up colder matter at their boundaries as they spread out into space, much as a soap bubble collects a film of dust from the air. All over the galaxy, these bubbles have piled up matter and swept it into clouds. Some of these cold clouds are enormous and contain enough matter to make millions of suns. Our own solar system

formed out of just such a cloud. We have even found evidence in meteorites telling us that the solar system itself formed only a few million years after the very first stars had formed in the cloud that was to be our Sun's nursery.

Although infrared astronomy research satellites have not yet been launched, infrared astronomy conducted from balloons, airplanes, and mountaintop observatories has given us important new information about the cool interstellar clouds. It has been discovered that the tiny interstellar grains contain silicon compounds similar to clay minerals. These particles can survive temperatures up to 1500°C and may possibly come from the atmospheres of red giant stars. The origin of the interstellar grains is one of the great questions of astrophysics that we can investigate by space astronomy. Very recently, ultraviolet telescopes in orbit found evidence for a covering of graphite (a form of carbon) on the silicate grains. Our best picture of interstellar space is that half its matter (other than the predominant hydrogen gas) is in the form of sooty sand grains the size of tiny smoke particles. It is possible that comets are made of accreted interstellar material, and so we hope that someday grains like this will be brought back from a comet sample-return mission.

The Galaxies: Islands of Stars

Beyond the Milky Way

Stars are not scattered uniformly across the seas of space. They are collected into huge disks, spirals, and globular forms that may contain billions of stars. These may be more than 100,000 light years across, but they are often millions of light years apart. Hence, they have occasionally been called "island universes."

Astronomy before the Space Age was mostly concerned with stars and star clusters. It was not until 1924 that the existence of galaxies beyond our own Milky Way was firmly established by the then-new 100-inch telescope at Mount Wilson. Once scientists were convinced that those dim, fuzzy patches in the sky actually contained hundreds of billions of stars, a new astronomy was started.

It was quickly realized that galaxies come in different shapes and sizes. The most numerous ones are *dwarf galaxies* like the Magellanic Clouds, two satellites of our own galaxy. Dwarf galaxies are small and often irregular, but even they can contain a million to a billion stars. At the other end of the scale, some of the very biggest galaxies are elliptical in shape, ranging from almost spherical to very elongated like a football. Many people, scientists and nonscientists alike, feel that the most beautiful galaxies are the spirals, such as the famous Andromeda galaxy, whose mass amounts to half a trillion suns. Our own galaxy, the Milky Way, is a comparable spiral, although the details of its structure are hard to determine from within. Besides the normal spiral galaxies such as Andromeda, there

are spiral galaxies with a bar across the middle, the spiral arms trailing like pennants at the end of the bar.

As ground-based investigations of galaxies proceeded, it was soon learned that far-off galaxies are receding, and that the more distant the galaxy, the faster it is moving away from us. This discovery was a major achievement of the 100-inch telescope at Mount Wilson, and it provided the impetus for the Big Bang theory of formation of the universe. Studies of the detailed appearance of galaxies also revealed several new types. Among these are the Seyfert galaxies (named for the American astronomer Carl Seyfert), which have very bright central nuclei. The spectra of these nuclei reveal the presence of hot gases in rapid motion.

Other remarkable aspects of galaxies were found when radio telescopes were developed. After some galaxies were found to emit intense radio waves, more detailed observations of these radio galaxies showed a characteristic double-lobe structure of the radio-emitting regions. These lobes typically are located far beyond the visible structure of the galaxy. The amount of energy required to produce the lobes is immense, sometimes equal to the output of a galaxy over its entire life. Later it was found that at the centers of some radio galaxies there are very intense radio-emitting cores which could not be spatially resolved even with the biggest radio telescopes. The character of the radio waves showed that these sources must be very small—in some cases as small as the solar system—and yet somehow they produce enor-

mous amounts of energy. This has been further corroborated by infrared measurements.

Another unusual galaxy, known as Centaurus A, has been the subject of some exciting space observations. Centaurus A has a typical double-lobe radio source, but in addition there is an inner pair of lobes, spaced along the same axis as the outer lobes. Within these inner lobes there is yet another, unresolved source of radio emission. In addition, Centaurus A produces a tremendous amount of high-energy radiation. The gamma ray telescope on HEAO-1 revealed that Centaurus A emits gamma rays with energies up to 1 million electron volts. Another experiment detected gamma rays from Centaurus A with even higher energies of *100 billion* electron volts. The latter, very high-energy gamma rays produce showers of electrons in the Earth's atmosphere.

X-rays are also emitted from the inner radio lobes of Centaurus A. In addition, there is a jet, visible to X-ray telescopes, that extends from the innermost core to the northern inner lobe. The existence of the jet indicates that the lobes are constantly being resupplied with energy from the active, but still mysterious nucleus of the galaxy.

Normal galaxies

The nearest neighbors to our own Milky Way galaxy are the Magellanic Clouds, about 150,000 and 190,000 light years away. To observers in the southern hemisphere they resemble luminous clouds several times the

size of the full Moon, but the Magellanic Clouds were not well explored until recently, when large telescopes were built in the Southern Hemisphere and airborne telescopes conducted far-infrared observations. In the Magellanic Clouds, our satellite observatories are finding the kinds of X-ray sources that we earlier discovered in our own galaxy: binary stars, supernova remnants, and others. In addition, the most intense gamma ray burst yet observed, the event of March 5, 1979, apparently came from the Large Magellanic Cloud.

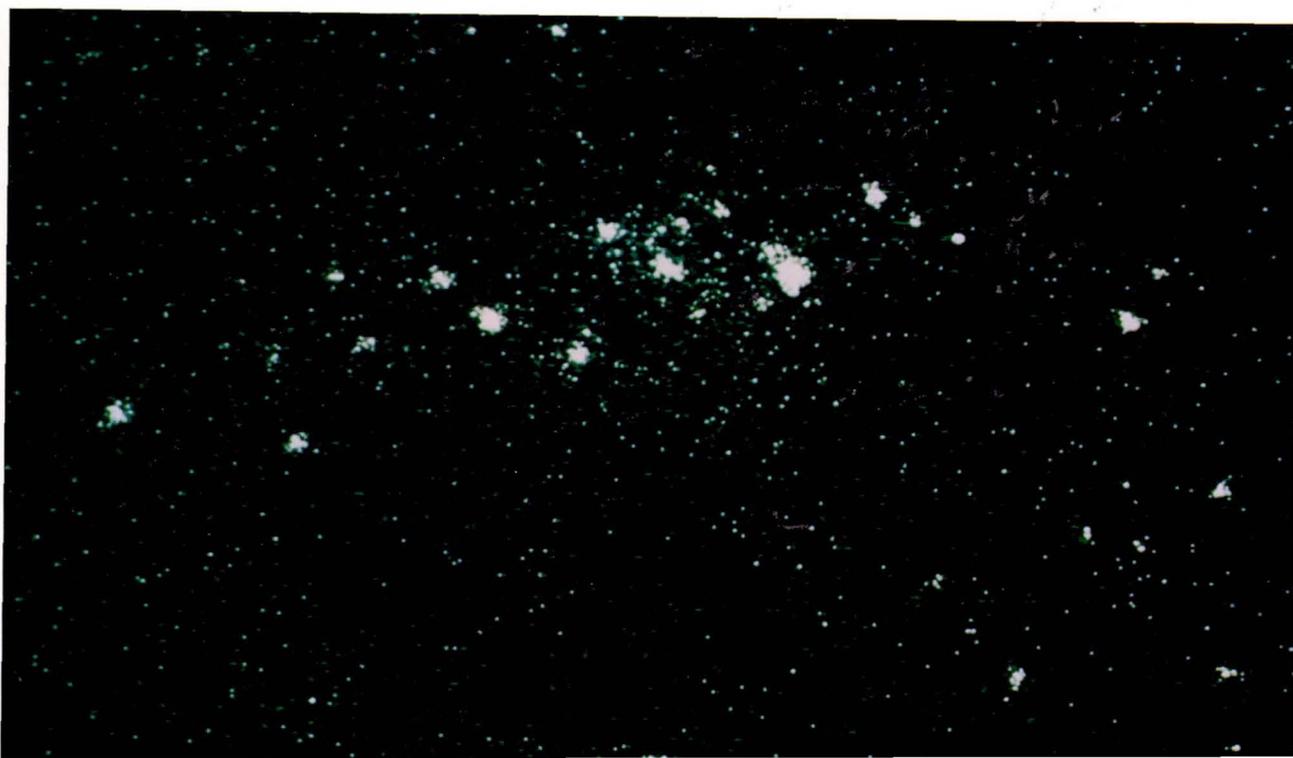
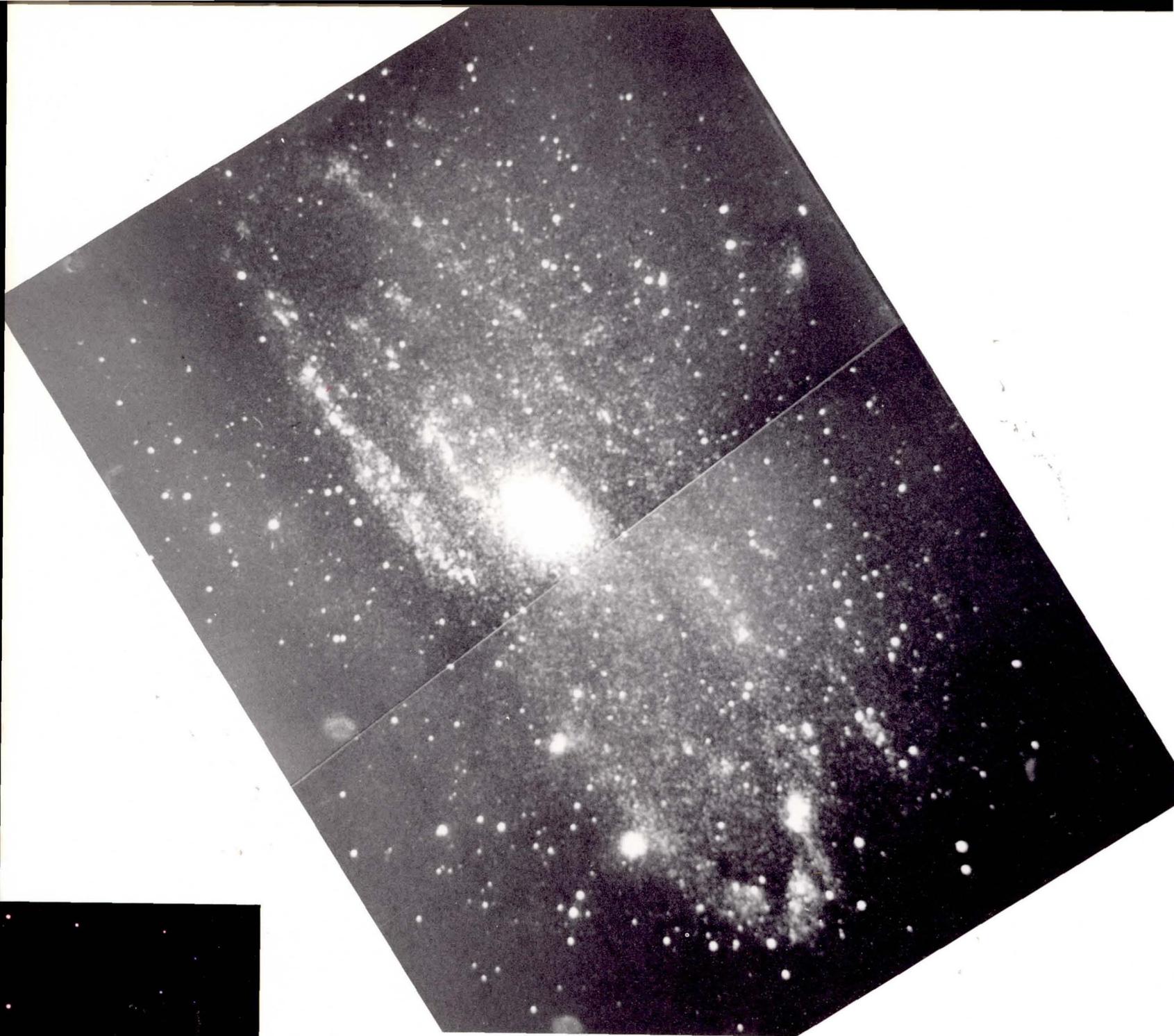
Gamma ray bursts are a relatively new discovery from orbiting satellites. Many objects in the universe emit gamma rays fairly steadily, but these sudden eruptions of gamma rays from a single point typically last a few seconds to tens of seconds, during which they outshine the rest of the universe in gamma rays. We think that the sources of typical gamma ray bursts are somewhere in our own galaxy, perhaps as close as 20 to 50 light years from Earth. But if the intense burst on March 5, 1979 came from as far away as the Large Magellanic Cloud, the release of energy must have been truly enormous for the event to seem so bright at a distance of 150,000 light years. The direction of the source of this burst has been determined with great precision by combining measurements from nine different spacecraft, and it lies near the heart of a supernova remnant in the Large Magellanic Cloud. Perhaps an unusual neutron star left behind by the supernova explosion was the actual source of the gamma rays.

Our next neighbor galaxy is the Great Spiral Galaxy in Andromeda, the most distant object visible to the naked eye. It is as large as or larger than our galaxy and is about 2 million light years distant, yet emits only about one-tenth as much energy in the form of infrared radiation as our galaxy. X-ray images taken with a telescope on the HEAO-2 satellite revealed more than 70 X-ray sources, which appear to be binary stars and super nova remnants in this neighbor galaxy.



Deep in the heart of Andromeda. X-ray emission marks the locations of powerful energy sources in the Andromeda galaxy. Top left: Photographed in visible light, M31, the Great Spiral Galaxy in Andromeda, resembles our own Milky Way as it might appear to a distant observer. Two small elliptical galaxies are satellites of M31. (Copyright, California Institute of Technology and Carnegie Institution of Washington.) Top right: Composite of two photographs made in ultraviolet light from an Astrobe rocket in August, 1980 emphasizes regions where hot stars are present, notably in spiral arms. Central bulge of the galaxy, largely consisting of cooler stars, is less prominent than in photo at left. (Courtesy of R. C. Bohlin and T. P. Stecher, Goddard Space Flight Center.) Lower left: Short exposure on bright central region of M31 reveals faint dust lanes threading an aggregation of innumerable stars, one seemingly indistinguishable from the other. (Official U.S. Naval Observatory photograph.) Bottom right: Seen in a new way, M31 central region was imaged in its own X-rays by an instrument on the HEAO-2 satellite. Strong sources of X-rays (bright spots) are few enough to count, but more common near Andromeda galaxy's center than in the nuclear region of our own Milky Way. Observations made at intervals show that the intensities of many X-ray sources are changing.





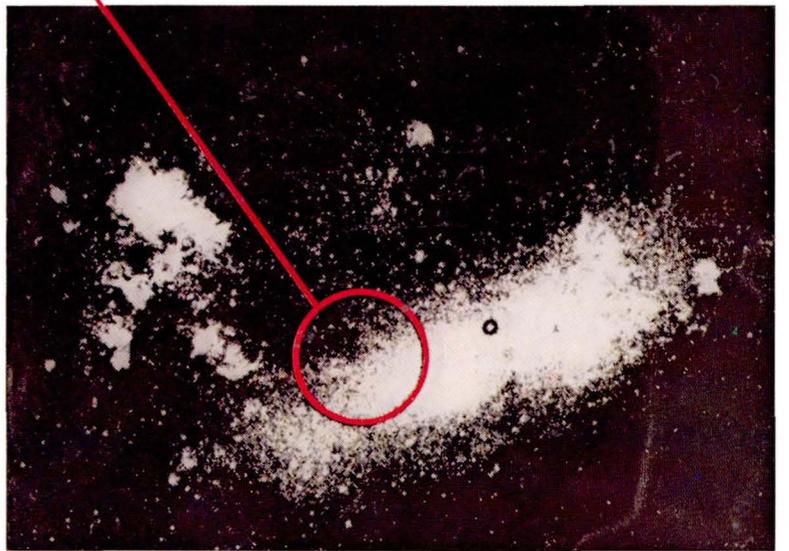
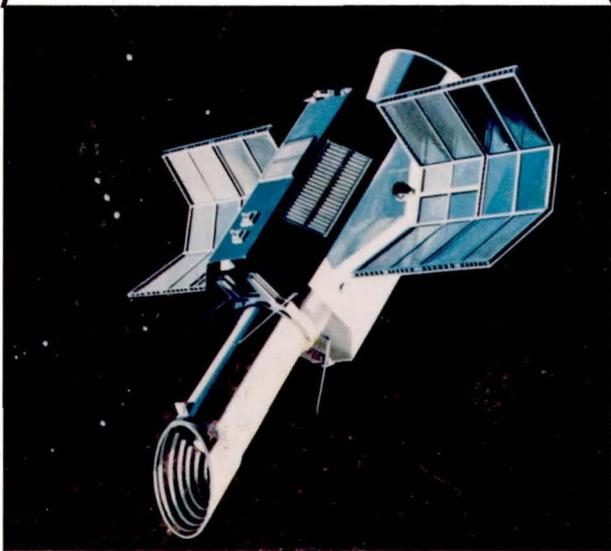
*Discoveries From IUE:
A Halo Surrounding The Milky Way*



Sun

The Milky Way

*Observed
Extent of 10^5 K Galactic Halo*



Magellanic Clouds

We have just discovered that our own Milky Way is surrounded by a corona, a very thin atmosphere of hot gas. The sources of the corona probably are the bubbles of hot, thin gas that pervade the interstellar space in our galaxy. Some of the bubbles probably expand to such enormous sizes (thousands of light years in diameter) that they must actually break out of the disk of the galaxy altogether, injecting hot gas into intergalactic space. Much of the hot gas remains bound to the galaxy by gravitation and thus forms the invisible corona at a temperature of about $100,000^{\circ}\text{C}$. Because the galactic corona produces no visible light, it could not be seen until the launch of the *International Ultraviolet Explorer* (IUE) satellite in January, 1978. IUE found evidence of the corona in the form of ultraviolet absorption lines in the spectra of bright blue stars in the Magellanic Clouds. The measured Doppler shifts of the lines proved that they are produced by foreground gas around the Milky Way, rather than in the Clouds.

Some coronal gas is not gravitationally bound to our galaxy and must expand into the space between the galaxies. The scales of distance here are immense. Galaxies are tens to hundreds of thousands of light years across, but the distance *between* gal-

axies is typically a few million light years, a million times the average distance between stars in our galaxy. Even if *Voyager*, with its great speed, could escape our galaxy, it would take 30 billion years for it to reach the Andromeda galaxy, much longer than the present age of the universe!

In places where galaxies cluster together to form a group millions of light years across, the escaping hot gas between the galaxies is revealed by its X-ray emission. With the X-ray telescopes of HEAO-2, we obtained images of the gas in such clusters of galaxies. We have even found clues to the age of the gas. For example, in clusters where the gas has only recently emerged from its parent galaxies, it is still clumped around them, as revealed by the patchy appearance of the X-ray images. In more evolved clusters, the images are smooth, showing a diffuse, centrally-peaked distribution of hot gas. These differences in the X-ray images of clusters of galaxies are correlated with differences in the types of galaxies involved. Spirals seem to be associated with the patchy X-ray emission. Thus, X-ray observations are providing basic clues to the evolution of giant systems of galaxies. We have only a few tantalizing clues just now, but the picture should become clearer after the launch of the planned *Advanced X-ray Astrophysics Facility* in the late 1980s.

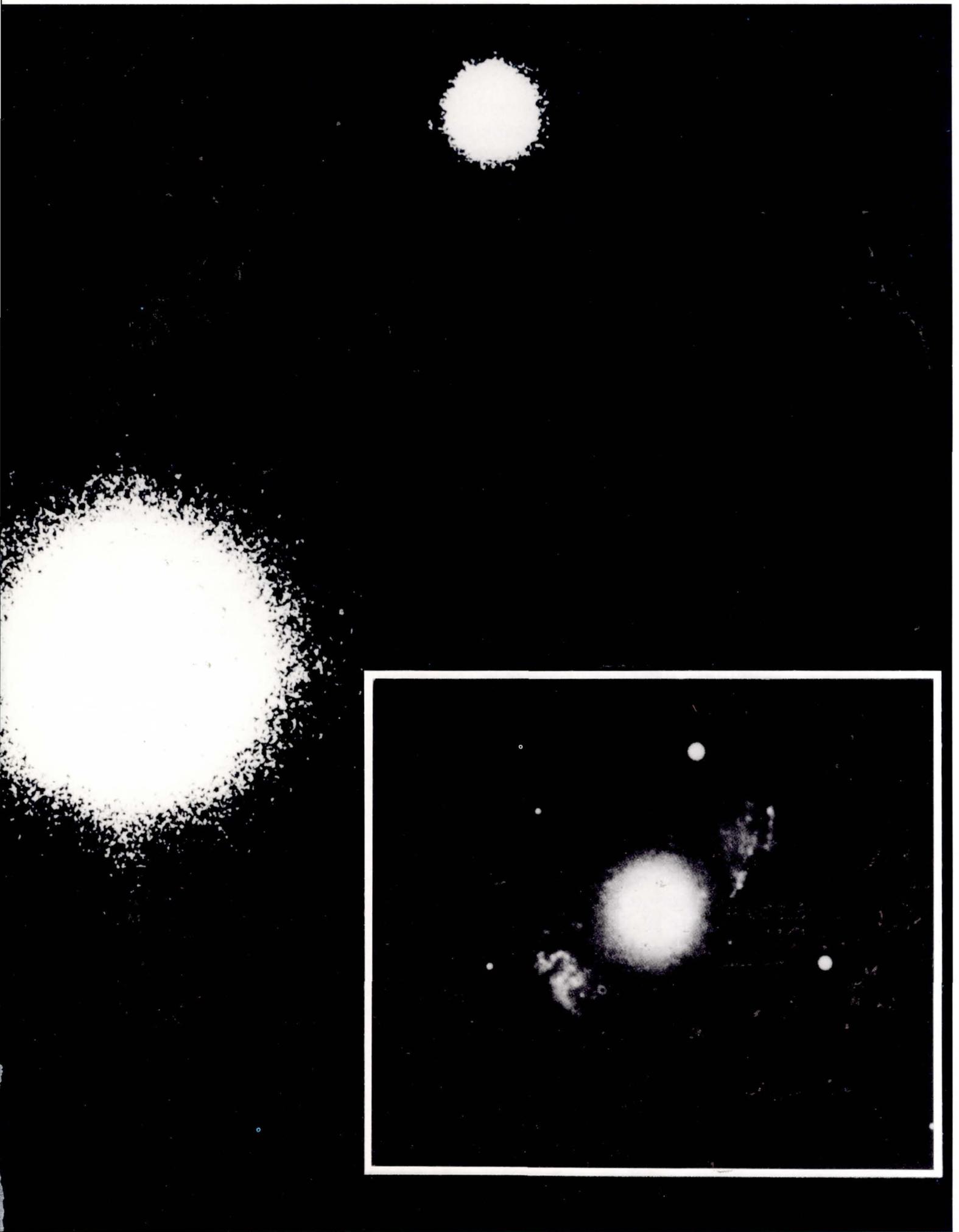
The galactic corona. Our Milky Way galaxy is surrounded by a galactic corona of thin hot gas. The corona was found when the International Ultraviolet Explorer (lower left) recorded the spectra of hot, bright stars in the Large and Small Magellanic Clouds, two neighbor galaxies of the Milky Way. The spectra showed dark lines identified as absorptions by gas in the corona. The gas rotates along with the Milky Way, so it is not simply a medium in which the galaxy is embedded. Similar observations now reveal coronae around each of the Magellanic Clouds and at least one other, more distant galaxy.

Quasars and the X-Ray Background

As NASA launched successively more powerful X-ray observatories, more and more cosmic X-ray sources were found. In addition we investigated a background of cosmic X-rays that seem to come from all directions in space. As it became quite clear that these background X-rays were very uniformly distributed, astronomers wondered whether they were produced by a vast collection of point sources at great distances, so numerous that individual ones could not be seen, or whether the emission source is genuinely spread out over all of intergalactic space. To answer this question, the X-ray astronomers took very long exposures of portions of the sky. With one type of instrument they confirmed that the background radiation is remarkably uniform; with another they found a surprisingly large number of quasars that emit X-rays. Quasars, first discovered in the early 1960s, appear almost like stars, although vastly more distant than any individual star that we can see. They were called "quasi-stellar radio sources" (shortened to "quasars") when they were detected with radio telescopes. They emit tremendous amounts of energy from very small volumes. The most distant quasars seen are so distant that they are receding at more than 90 percent of the



Beacons of distant space. Two of the most powerful known energy sources, a quasar and a Seyfert galaxy (inset) are shown here as photographed in visible light. 3C273, the first quasar found, has a noticeable jet, extending toward the lower left. Most of the radiation from a Seyfert galaxy comes from the central nucleus. Thus, at a sufficiently great distance, a Seyfert galaxy might resemble a point-like quasar. Both 3C273 and NGC 4151 (the Seyfert galaxy) are strong sources of infrared waves, X-rays, and gamma rays. Although the two objects are about equally bright in visible light as seen from Earth, the quasar is perhaps 80 times as far away, and hence about 6400 times more luminous.



speed of light. As bright, concentrated radiation sources, they resemble the nuclei of Seyfert galaxies, but are far more luminous.

Remarkably, the visual brightness of some quasars can change by a factor of two in about a week, and noticeable changes can occur even in one day. Since a source of light cannot change brightness significantly in a time shorter than it takes light to cross it, these quasars cannot be much bigger than one light day across, only twice the size of our solar system. The problem, then, is to explain how a quasar can produce vastly more energy than a galaxy in such a small region.

The brightest quasar as seen from Earth, 1.5 to 3 billion light years away, is called 3C273, from its number in a catalogue of radio sources. It is speeding away from us at nearly 16 percent of the speed of light. It has been detected as a source of radio, infrared, visible light, ultraviolet, X-ray, and even gamma ray emission. Some of the new quasars found by the HEAO-2 satellite are much further away, with recession velocities of two-thirds the speed of light.

Another distinctive type of X-ray source is closely related to the quasars and may even be an unusual type of quasar. They are called "BL Lac" objects after the first known member of the class, BL Lacertae, which for years was listed as an ordinary variable star of the Milky Way in astronomers' catalogues. More recently, we learned that it is in fact a distant object in extragalactic space, which resembles a star until studied in detail. The visible light of BL Lac objects is dominated by radiation from high-ve-

locity electrons spiraling in magnetic fields. By contrast, in ordinary quasars there are prominent visual emissions from hot gas. However, in their compact dimensions, rapid intensity variations, and emissions of X-rays, gamma rays, infrared and radio waves, the BL Lac objects resemble quasars and constitute yet another mystery of distant space that we are only beginning to explore.

Quasars, galaxies, and the X-ray background seem to be linked together. By making some reasonable guesses about how quasars and galaxies evolve—that is, how they change their X-ray brightness as they grow older—it is possible to account for all of the observed background radiation. But this idea is not easy to confirm. The imaging X-ray telescopes launched thus far are sensitive only to relatively "soft" X-rays, with energies of about one kilovolt, in physicists' terms. At higher energies there is a "bump" of enhanced intensity in the X-ray spectrum of the X-ray background near 40 kilovolts, but none of the quasars observed so far have such bumps in their spectra. If this bump is not from quasars, what is it from? One suggestion is that very young galaxies formed shortly after the creation of the universe would have a great many pulsars and neutron stars in them to supply the necessary X-rays. This is one of several possible descriptions of the very early universe to be tested by the *Cosmic Background Explorer* mission planned for mid-1980s. There is also a diffuse background of gamma rays, with a bump at the energy of 1000 kilovolts. Is it due to the quasars once again or to something even more exotic?

The Edge of the Universe

There is no place in the universe that is truly empty, but the space between clusters of galaxies comes close. These regions contain less than one atom in every 10 cubic meters (350 cubic feet), or only three atoms in a space about the size of a small room. Although galaxies continually supply new material to intergalactic space, the continuous expansion of the universe makes the net effect nil. Intergalactic space is very empty, and it is getting emptier as the universe expands.

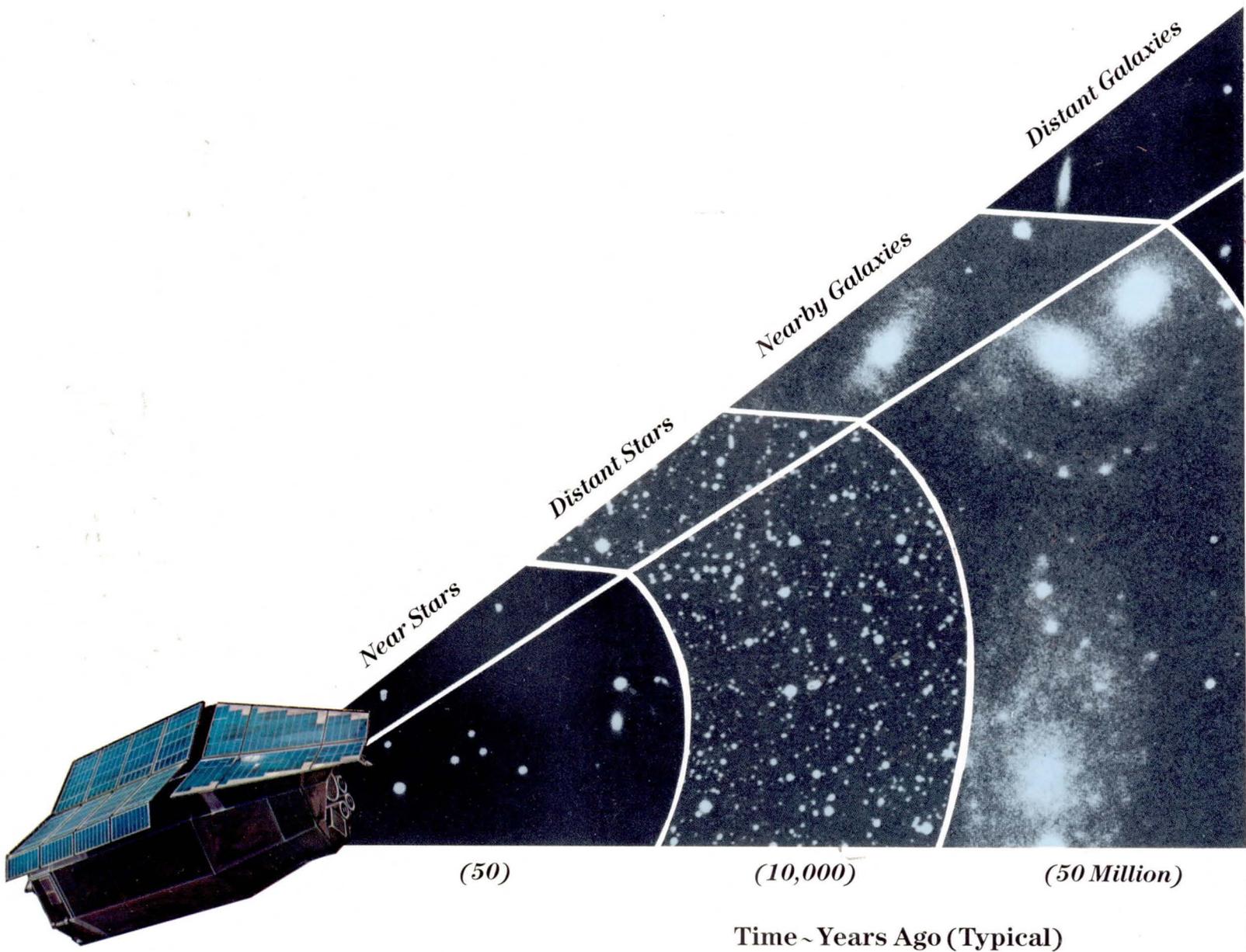
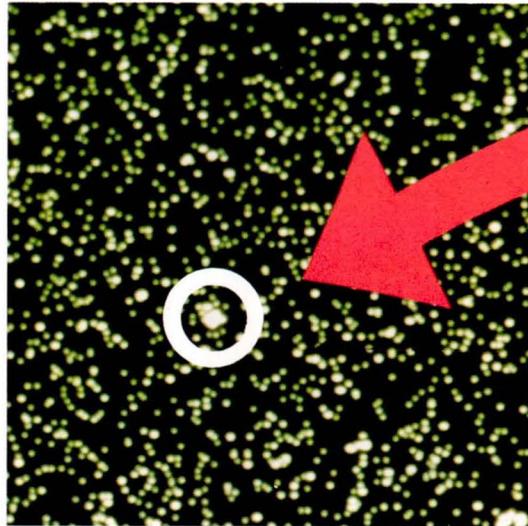
The more we learn about it, the more complicated the expansion of the universe seems to be. In the region near our galaxy, the expansion seems less rapid than for the universe as a whole. In fact, it appears that the combined gravitational pull of a very large cluster of galaxies in the constellation Virgo is actually retarding the local rate of expansion to half the rate for the universe as a whole. We're finding evidence of how gravity attracts even over distances of hundreds of millions of light years.

Although there must be many very distant galaxies and quasars that we are not yet able to detect, astronomers have observed radiation from an even more remote source, literally at the edge of the observable universe. As we look far out in space, we are looking back in time, since light waves take time to cross space from their source to the observer. Hence, we view distant regions of the universe as they were long ago. According to the Big Bang theory, the universe originated in a great explosion and has been expanding ever since. At a very early epoch, before galaxies and stars formed, the universe was

filled with hot glowing gas, and it was opaque. At some point during the first million or so years after the Big Bang occurred, the expanding and cooling gas became transparent. Hence, we can see out into space and back in time only until we come to the distant region that we observe as it was in the era when the universe cleared. Beyond that point, space is opaque so light waves cannot reach us. We see the glow from the hot gas that cooled to about 10,000° C and then cleared, but we cannot see further. This glow was emitted as ultraviolet light, but has been shifted to longer wavelengths by the expansion of the universe, so that we observe it today as a diffuse background of microwave (short-wavelength radio) and infrared radiation. This microwave background is thus the radiation that comes to us from the limits of the observable universe. We can never see beyond it to more distant regions or earlier times. Due to the redshift, the background radiation resembles the emission from a dense gas at only 2.7° C above absolute zero.

You can think of the source of the microwave background as a distant, spherical wall that surrounds us and delimits the observable universe. If an observer is moving with respect to the wall, then the spectrum of the radiation coming from the region of the wall that he is approaching will be shifted toward shorter wavelengths, while radiation from the opposite direction will be shifted toward longer wavelengths. Thus, the existence of the microwave background allows us to determine whether the solar system is moving with respect to a basic frame of reference in the universe.

*X-Ray Quasars
(~13,000 Million Years Ago)*





According to the results from recent measurements with telescopes on high-altitude aircraft, balloons, and sounding rockets, we appear to be moving at about 300 kilometers per second (190 miles per second) toward the constellation Leo. When we launch infrared and microwave telescopes on orbiting satellites, it will be possible to make more sensitive measurements and to search for structure in the spatial distribution of the microwave background that may reveal fundamental aspects of the nature of the universe.

(500 Million)

(5,000 Million)

Out in space and back in time. Light waves from distant space show how objects there looked when the waves left. Light from the nearest star outside the solar system takes over three years to reach the Earth, while photographs and X-ray images of very distant quasars show them as they were billions of years ago. Expansion of the universe shifts light waves to lower frequencies, but they carry information to us on the early history of the cosmos.

What's Coming

The next major development in Space Age astronomy will be the launching of the *Space Telescope* in the mid-1980s. We will finally have an optical telescope above the disturbing influence of the atmosphere, thus increasing the sharpness of images and allowing us to see more distant galaxies than can be photographed, even with larger telescopes, from the ground. The *Space Telescope* will be able to tell a spiral galaxy from a barred spiral galaxy at a distance of 5 billion light years, or take photographs of Mercury from Earth orbit that show as much detail as those made from *Mariner 10*, when it flew past the planet.

After *Space Telescope*, the next major astronomy mission planned is the *Gamma Ray Observatory* (GRO). This satellite will carry instruments designed to detect gamma rays over the entire range of energies from a few hundred to several hundred million kilovolts. The GRO will be a powerful tool for investigating the most baffling and puzzling objects in space: pulsars, quasars, and active galaxies.

To learn more about dust in the universe and about the whisper from the Big Bang, we are developing orbiting infrared telescopes. There are still some technical problems. For example, infrared detectors have to be kept very cold, which is surprisingly difficult on an Earth-orbiting spacecraft. The first planned NASA mission is called IRAS (for *Infrared Astronomy Satellite*); it will carry a small telescope in a low-temperature chamber. Later, a *Spacelab Infrared Telescope Facility* (SIRTF) will be de-

ployed on the *Space Shuttle*. With these instruments, we can study for the first time the coolest matter in our galaxy: the clouds of interstellar molecules and the dense condensing masses of dust and gas from which stars are born. The *Cosmic Background Explorer* (COBE) will concentrate on the study of the microwave background and other sources of widely distributed infrared and microwave radiation. Planning now calls for a launch in the late 1980s for a mission that will last about one year.

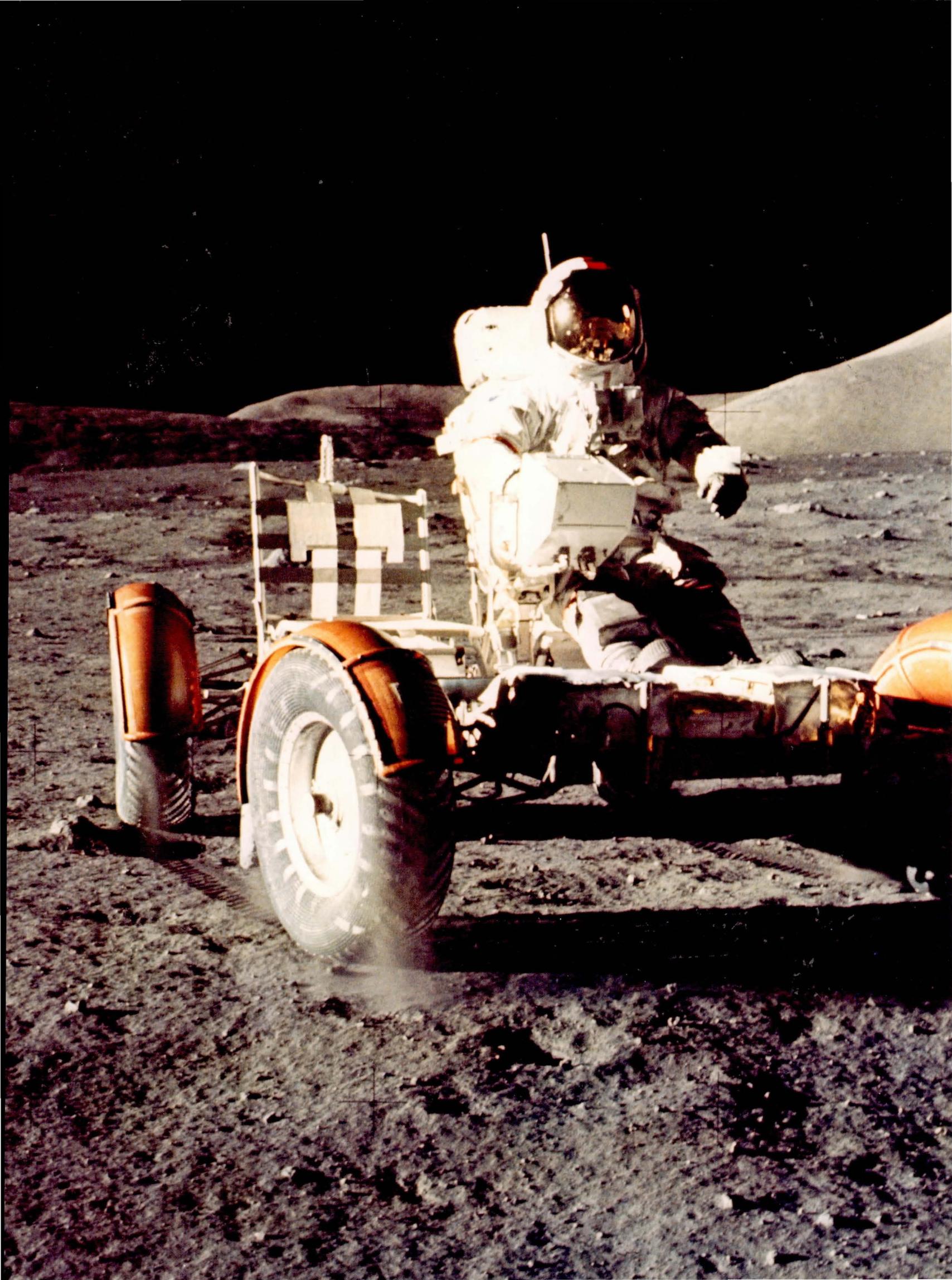
The advance of Space Age astronomy is being supported by new instruments on the ground, notably the Very Large Array (VLA) of radio telescopes in New Mexico. The VLA consists of 27 radio dish antennae that simulate a single radio telescope 31 kilometers in diameter. This same principle, that a set of small radio telescopes can be designed to act like a very large telescope, may eventually be exploited in space. Operating a radio telescope in orbit in conjunction with radio telescopes on the ground would produce a system that acts in some respects like a radio telescope larger than Earth! At the same time, new techniques in photography and in electronically recorded optical images are greatly improving the speed and sensitivity of astronomical observations made on the ground. Space Age astronomy is a joint effort of all astronomers to elucidate the nature of the universe. In spite of all that we have learned in the last few years, we have only just begun to see.

Table 1 Typical dimensions of the stars

Star	Mass (Mass of Sun = 1)	Diameter (km)	Diameter (miles)
<i>Normal Stars:</i>			
Red dwarf	0.1	180,000	112,000
Sun	1	1,390,000	864,000
Sirius	3	3,200,000	2,000,000
Young blue star	18	10,000,000	6,200,000
<i>Evolved Giants:</i>			
Red Giant	6	35,000,000	22,000,000
Red Supergiant	20	1,000,000,000	620,000,000
<i>Dying Stars:</i>			
Black hole	4	24	15
Neutron star	1.5	20	12
White dwarf	1	20,000	12,000
<i>Planetary Comparisons:</i>			
Earth:	0.000003	12,760	7,930
Jupiter:	0.001	143,000	89,000
Earth's orbit:	—	299,000,000	186,000,000

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THE HUMAN ELEMENT

Paul C. Rambaut

Motorist on the Moon. Astronaut Gene Cernan checks out the Lunar Roving Vehicle early in the first extravehicular activity of the Apollo 17 mission. The location is close by the Taurus-Littrow landing site on the Moon.



Our New Domain

Scarcely twenty years have passed since Russian cosmonaut Yuri Gagarin became the first person to orbit the Earth. In less than a single generation, human beings have extended their domain from the upper fringes of the Earth's atmosphere to the mountains of the Moon. If this human progress continues, we can expect that some of those already born since Gagarin's 1961 flight will walk on Mars and that some of their grandchildren will be born, live, and die in colonies beyond the Earth. There has always been a human drive to expand and explore. The last twenty years have shown that space travel is feasible. Now a more profound question faces us: Will our own biology permit us to become full-time residents of outer space?

Spaceflight produces many severe stresses on the body and mind. The astronaut is subject to high accelerations (*G-forces*) on launch and reentry; in between these are long periods of weightlessness. In space, there is radiation more intense, dangerous, and sometimes quite unlike anything encountered on Earth. Inside a spacecraft, high noise levels are produced by the powerful rocket motors and by the continuous operation of life support machinery. Spaceflight involves long periods of isolation, nagging vibrations, and disturbances in normal day-night cycles.

Beyond these specific problems is the ever present element of physical danger. Only the thin wall of the spacecraft separates the occupants from an environment more hostile than any on Earth. Above the atmosphere, the unfettered energy of the

Sun scorches anything that it strikes, and the temperature of shaded objects approaches absolute zero. In the almost perfect vacuum of space, an unprotected human would survive less than a minute before his blood would boil.

We are already quite familiar with many effects involved in space flight. Exposure to highly accelerative forces has become commonplace to the pilots of experimental jet and rocket aircraft. The same forces are produced on rocket-propelled sleds and in centrifuges, where their biological effects can be studied in great detail. The dawning of the Atomic Age, combining the threat of nuclear devastation with the promise of unlimited useful energy, has given great emphasis to studies of the effects of ionizing atomic radiation on living things. Incessant noise, vibration, and jet lag are common accompaniments to modern civilization, and despite all the teeming billions of humanity we need only to recall that people live and work in isolation on the polar ice-caps, under the oceans, and on the windswept slopes of the Himalayas to be reassured of our capacity to adapt to the most lonely environments.

The unique aspects of spaceflight, so far as the human body is concerned, are weightlessness and the heavy, energetic atomic particles (known as *HZE radiation*) that are sprayed out of the Sun and other stars and that fill the space around us. The key to understanding the effects of spaceflight on humans comes from the reactions of astronauts to weightlessness and HZE radiation, and the evaluation of how much of each they can tolerate.





Extravehicular affair. Astronaut Ed White outside his Gemini 4 spacecraft in 1965, in America's first "space walk."

Weightlessness

Fossils in the geological record reveal that humans have existed on Earth for over three million years. Further, we know that vertebrates roamed the Earth for hundreds of millions of years before the emergence of Man. Throughout these eons, all evolution and human development have been influenced by the Earth's gravitational field. In countless subtle ways, humans have responded to this ubiquitous force and have learned to cope with it. Not only are we molded and constrained by gravity, but Earth's whole blanket of life, the *biosphere*, with all its component species, is in some respects a product of the effects of gravity.

So intimate is the relationship between gravity and life that, before the advent of spaceflight, no one could predict precisely how or even whether any particular biological process would function in the absence of gravity. Weightlessness cannot be experimentally produced within the Earth's atmosphere for more than a few seconds at a time in aircraft. We had to wait until spacecraft could be launched into orbit around the Earth before the effects of prolonged weightlessness could be investigated.

Before the Space Age, scientists

predicted many dire consequences if a human being were suddenly thrust into weightless flight. Often, the predictions contradicted each other. Various specialists said that the heart would race or that it would stop, that a person could not sleep or would sleep constantly, and that an astronaut would become euphoric or profoundly depressed. It was said that the bones would soften, that eating would be impossible, and that the ability to think would be impaired.

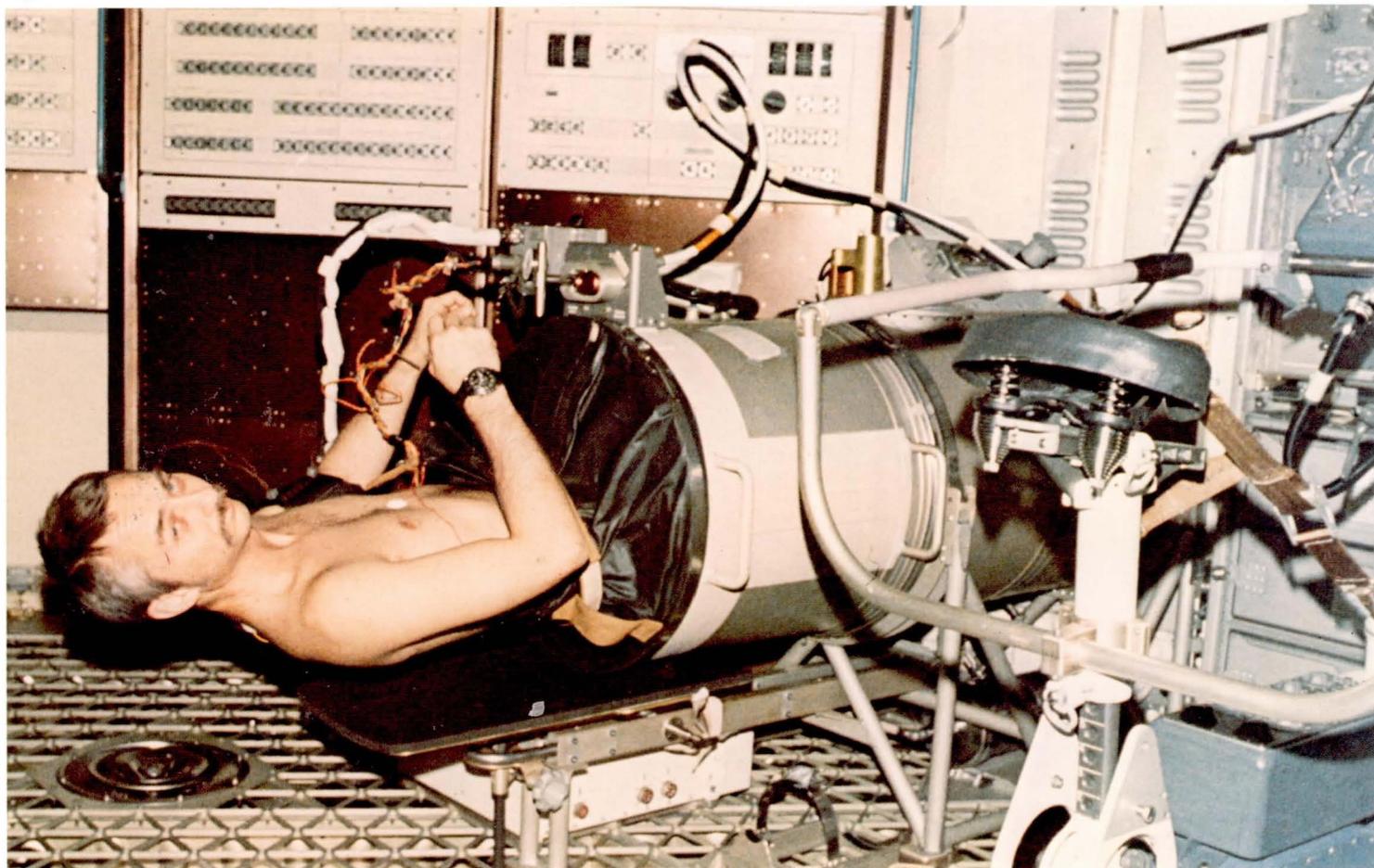
So acute was the concern for the unknown medical effects of weightlessness that numerous animals were flown, first in ballistic suborbital trajectories and finally in complete Earth orbits, before either Yuri Gagarin or Alan Shepard first flew their *Vostok* and *Mercury* spacecraft. Happily, most of the predicted dangers did not occur. Weightlessness in general turned out to be surprisingly benign and tolerable. However, some significant changes in the human body were noted, even in the earliest flights. How long these changes last, and how serious they are in the long run, continue to be the subjects of intense investigation by space medicine specialists in both the United States and the Soviet Union.



Before Man flew. The chimpanzee "Ham" was the live test subject for the Mercury-Redstone 2 flight on January 31, 1961. Here the 17-kg (37-pound) primate is fitted into a special "biopack" couch prior to flight. The 680-kilometer (420 statute miles) suborbital mission was a significant accomplishment in the American route to manned space flight.



Traveler's reward. Ham reaches for an apple following his brief ride in space.



Biomedical research in space. Owen Garriott lies in the Lower Body Negative Pressure Device aboard the Earth-orbiting Skylab. The instrument was used to monitor the time course of cardiovascular adaptation to space flight and to predict the degree of difficulty to be encountered during and after return to Earth.

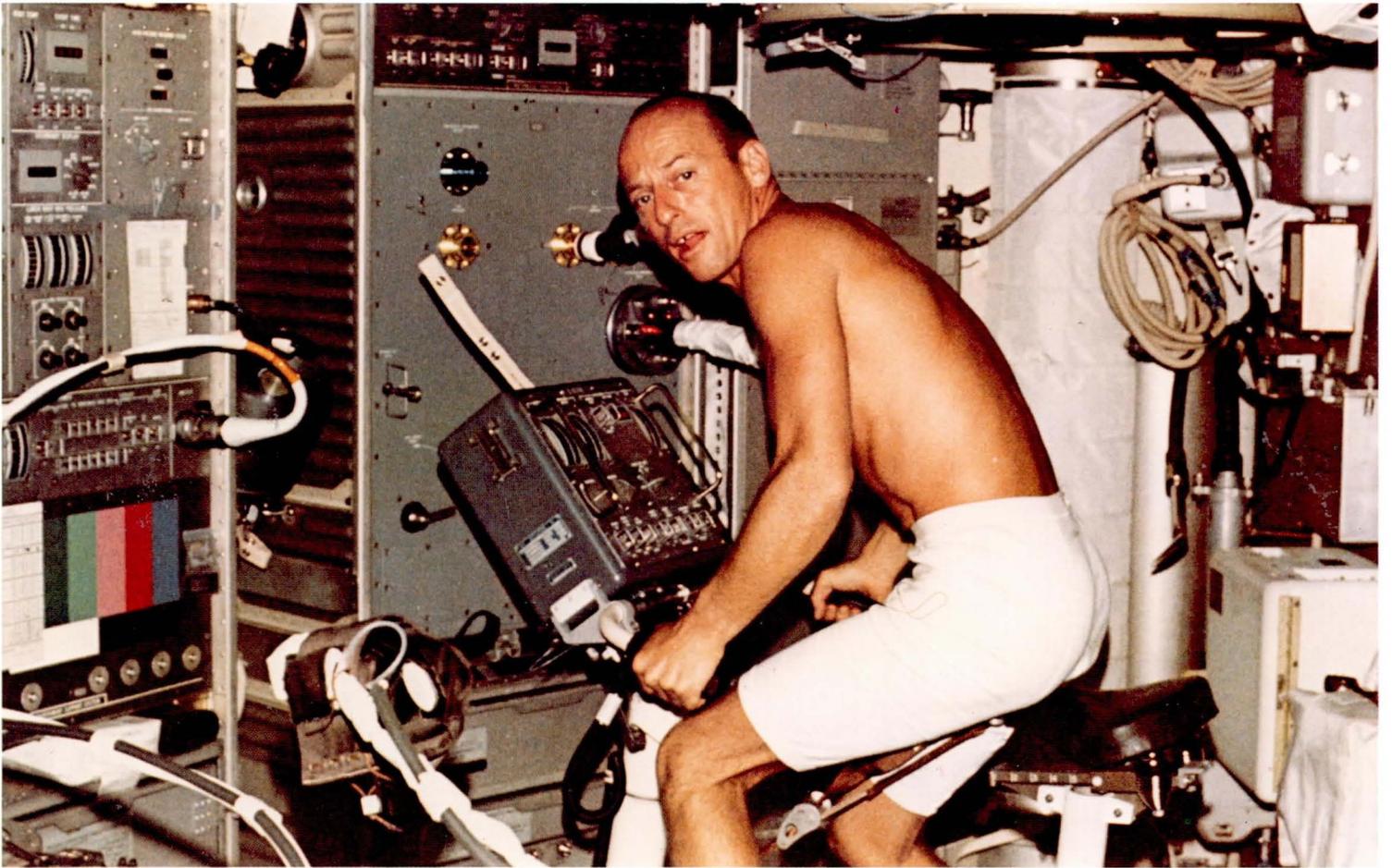
Circulatory changes

The first impairments observed in astronauts that were definitely caused by space flight were the changes in heart rate and blood pressure exhibited by Walter Schirra following his 9-hour flight in October, 1962 and by Gordon Cooper after a subsequent 34-hour flight, each in a *Mercury* spacecraft. Immediately after returning to Earth the astronauts tended to become dizzy on standing, and each showed a decrease in the total volume of blood. These effects were confirmed by medical studies of other astronauts during the later *Gemini* and *Apollo* flights, and they were investigated in much greater detail over a period of months during the long-duration *Skylab* flights in 1973-1974.

The *Skylab* studies showed that

the circulatory changes which occur level off after four to six weeks of flight. After that, no further changes occur, nor do the changes impair crew health or performance aloft. Exercise tolerance during the space flight itself is unaffected, but the ability to perform vigorous exercise is temporarily diminished after return to Earth.

Scientists and doctors are beginning to understand these changes. When a human is suddenly thrust into weightlessness, apparently blood shifts from the legs and lower parts of the body, where it is normally held by gravity, upward toward the head. Sensitive receptors, located in the upper part of the body, mistakenly interpret this sudden and sustained shift of blood as an increase in total blood volume. The body then tries to reduce the blood volume to its "normal" value by eliminating fluid and



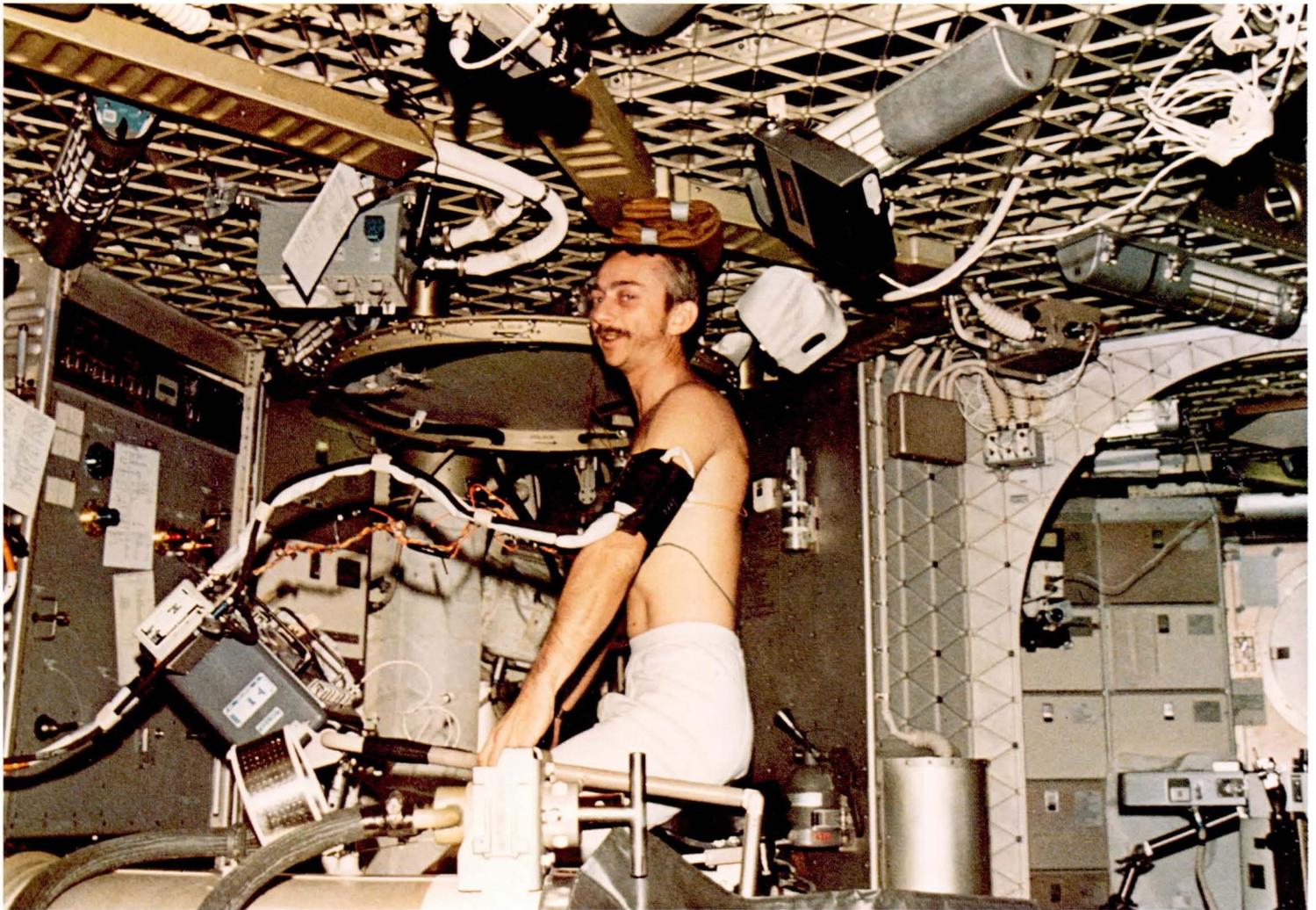
Only way to jog. Pete Conrad exercises on the astronauts' bicycle ergometer inside the Skylab Workshop.

some electrolytes, either by increasing urine flow or by cutting water intake (reducing the feeling of thirst). These changes lower the blood volume to a level that is perfectly compatible with weightless life in space but that is too low to support vigorous activity back on Earth. Just after return, the astronaut is like someone who has just given a blood transfusion and cannot immediately engage in heavy exercise. This diminished performance after return from space continues for a few days until the missing blood volume is restored; there seem to be no long-term effects.

If the circulatory changes, technically called "cardiovascular deconditioning," are caused entirely by lowered blood volume, simple precautionary measures can be used to correct the problem during critical reentry maneuvers and immediately after

return to Earth. However, because it is possible that other, more serious circulatory changes may occur in space, scientists monitor the cardiovascular system of an astronaut in flight as well as the red and white cells and other components of the blood.

The opportunities to study humans in space are still somewhat limited and can involve only a few subjects, so methods have been devised for simulating some of the physiological effects of spaceflight here on Earth. By immersing humans and animals in water baths for extended periods or by confining them to bed or in plaster casts in a slightly head-down position, many of the same cardiovascular changes that occur in space can be produced on the ground and studied in detail.

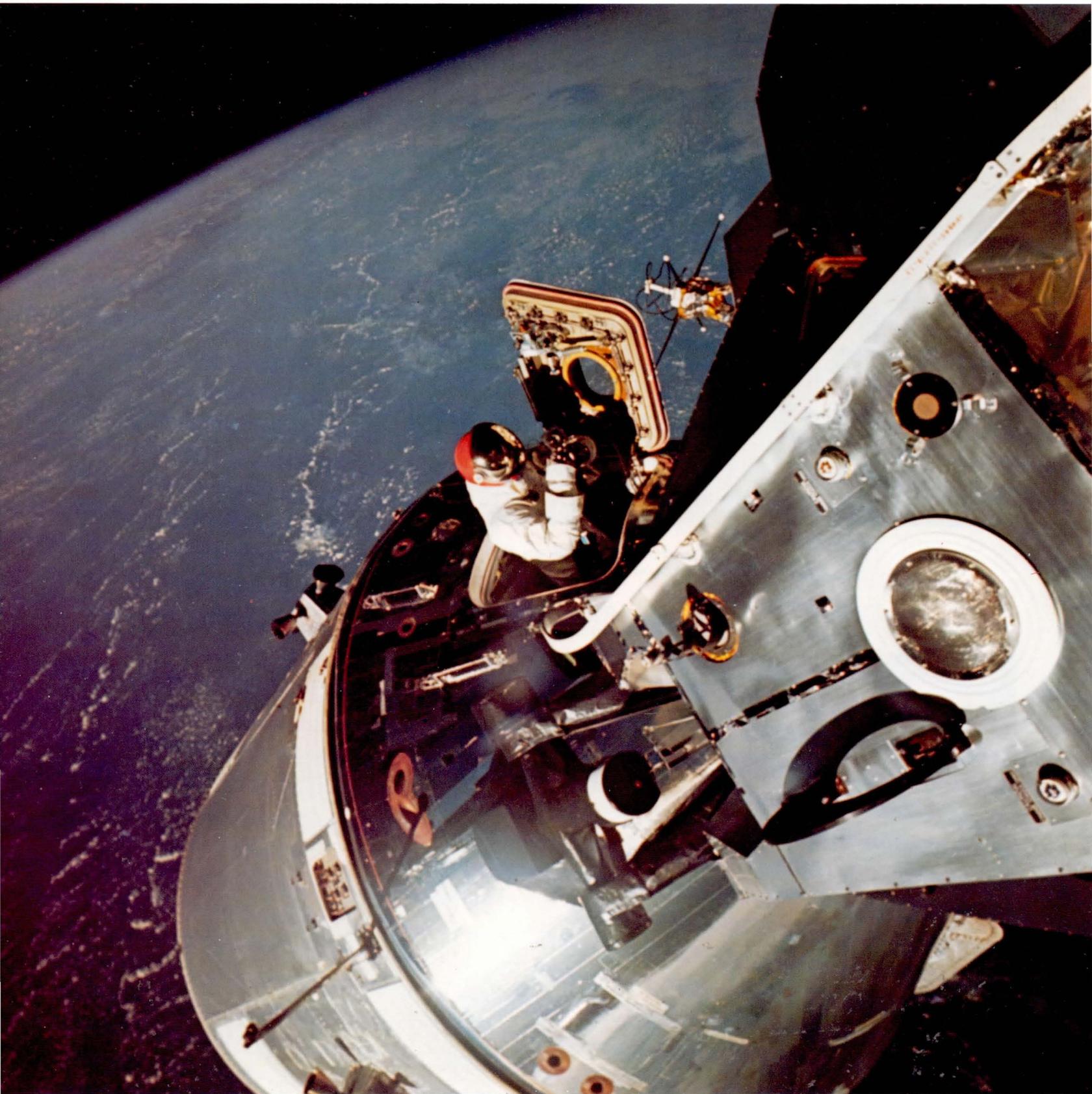


Using his head. Weightless in Skylab, Owen Garriott supports himself on the bicycle ergometer by pressing against the compartment "above" him.

Bone and muscle loss

When they are not used to work against the gravity field of Earth, bones tend to deteriorate and muscles tend to atrophy, that is, to shrink or waste away. Similar problems occur in space. The limited mobility within the small earlier spacecraft and the lack of appropriate stress, even in the larger *Skylab* and *Salyut* space stations, produced a continuous loss of bone and muscle tissue in the astronauts. The loss appears slow enough

to enable space missions of from six to twelve months to be undertaken without instituting any preventive or remedial measures. On longer flights however, steps must be taken to prevent these losses. In-flight exercise was tried on the *Skylab* and is being used by the cosmonauts aboard *Salyut* missions, but so far the correct combination of measures to be applied to prevent bone and muscle loss has not been found. The search is continuing in the *Space Shuttle* missions as well as in laboratories on the ground.

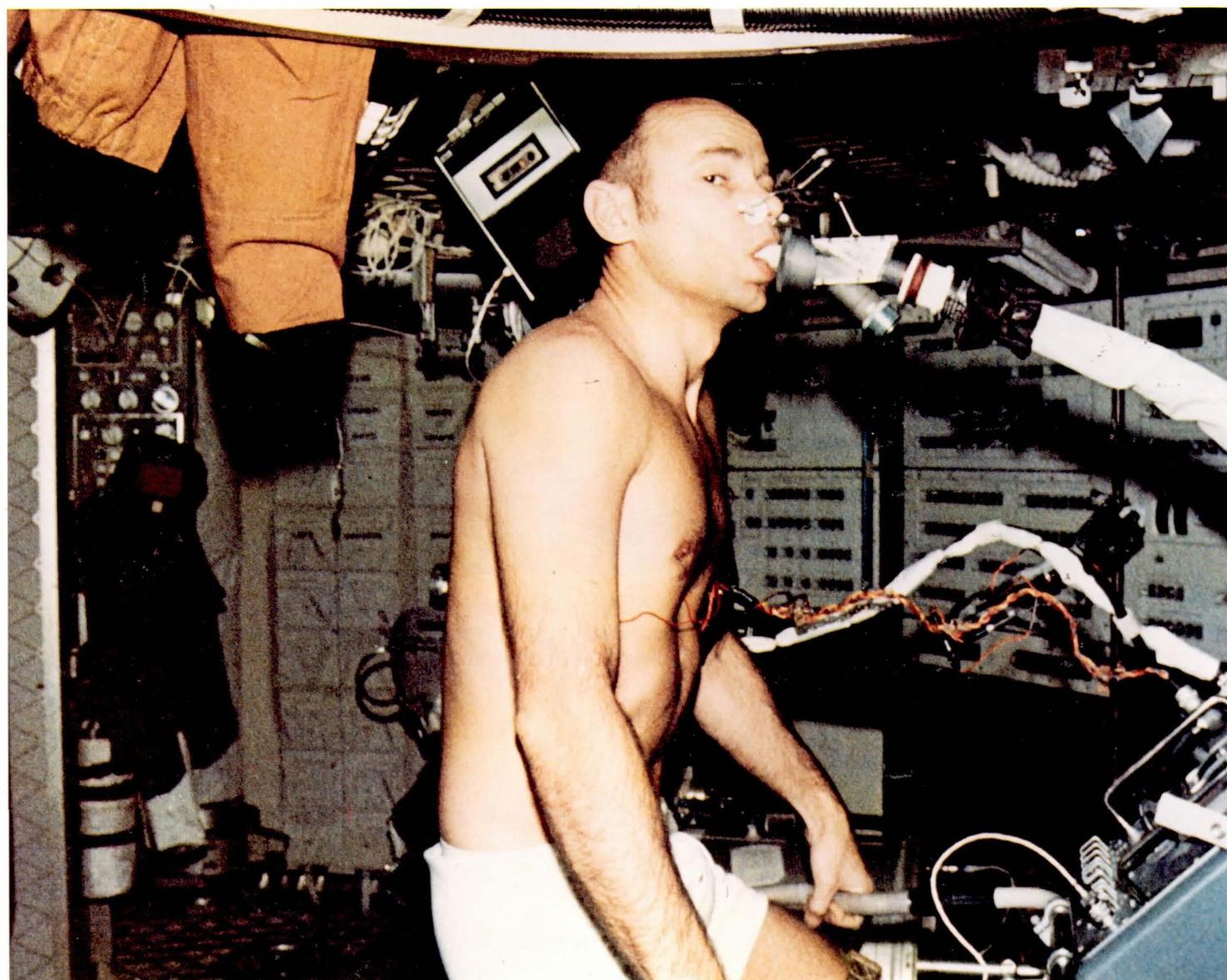


The hatch is open. David Scott's extravehicular activity on the fourth day of the Apollo 9 Earth orbital mission takes place with the Mississippi River valley in the center background.



Behind straps and bars. Alan Bean "weighs" himself on a mass-measuring device aboard Skylab.

Life and breath in space. Measurements of gas exchange and heart activity are made as astronaut Bean pedals the bicycle ergometer.



Motion sickness

Starting in 1968, eleven missions involving astronauts were undertaken during the five-year span of the *Apollo* program. These missions added motion sickness (the "space sickness" of generations of science fiction writers) to the significant biomedical problems produced by space flight. Although nausea had been noted earlier by Soviet cosmonaut Gherman Titov during his one-day *Vostok 2* flight on August 6, 1961, as well as by some crew members of subsequent Soviet flights, no American astronauts had yet experienced the symptoms. (In retrospect, however, the lack of appetite observed on certain *Gemini* flights may have been an early sign of this illness.) The crewmen of *Apollo 8* and *9* were especially plagued with stomach uneasiness, nausea, and vomiting. In *Apollo 9*, an Earth orbit mission, astronaut Rusty Schweickart was sick for a considerable time and had to postpone the first test of the Lunar Module in space.

Throughout the remainder of the *Apollo* program, during subsequent *Skylab* missions, and during Soviet missions, symptoms of motion sickness continued to manifest themselves. It is a serious problem; almost half of the astronauts sent into space have been affected. The illness appears to last for only the first two or three days in space and in almost all cases disappears within a week. The occurrence of motion sickness during the first few days of space flight is of great operational concern during the

forthcoming *Space Shuttle* flights, many of which last only a few days.

Unfortunately, at the present time, the factors responsible for motion sickness are unknown. Scientists believe that the vestibular apparatus, or machinery of the inner ear which controls our sense of balance, is profoundly influenced by weightlessness. Humans are not the only creatures affected. Experiments carried out on the *Skylab* spacecraft produced pictures of disoriented fish swimming in loops in their containers. Furious nervous activity was recorded from the brain of a frog that was suddenly rocketed into weightlessness. In humans, the disorientation arises when sensations from the eyes and from other parts of the body conflict with those from the vestibular (inner ear) apparatus and with information stored in our brains as a result of experience at "1 G." This condition apparently can be overcome. After a few days in space, a re-patterning of the central memory network occurs so that unfamiliar sensations from eyes and ears start to be correctly interpreted and the person adjusts to his new environment. More effective means whereby adaptation can be accelerated and motion sickness symptoms suppressed are being sought in many laboratories. Hopes are high that this search will be successful and that, unlike so many hapless sailors, aviators, and other travelers, future astronauts will be freed of space motion sickness as an occupational nuisance.

Food and diet

It is almost always true that an astronaut or cosmonaut who returns from space to Earth weighs from one to ten pounds less than upon launch. Spring-loaded mass measuring devices, carried aboard the American *Skylab* and Russian *Salyut* spacecraft, were used to "weigh" the astronauts in the absence of gravity. These records showed that about half of the weight loss occurs within the first few days of flight while the remaining loss takes place much more slowly. Scientists believe that, just as in any person who starts to lose weight, the early losses consist mainly of water, while muscle, fat, and bone comprise the later losses.

Weight loss can be reduced by combining appropriate exercise with a complete and balanced diet. However, most of the early astronauts paid little attention to the dietary advice they received prior to flight and could not be convinced that life in weightless flight required just as much food

energy as it did on Earth. The commander of one lunar flight insisted that he wanted nothing but a few candies on the way to the Moon. Some *Gemini* astronauts traded their individually planned metabolic rations with each other, much to the consternation of the dietitians. In later long-term flights such as *Skylab*, food was taken more seriously. Daily intakes were calculated by computer, and supplements were automatically prescribed to each astronaut to make up deficits incurred the previous day.

Insuring that the space food tastes good is one way to promote eating enough. This always has been difficult because of the need to process the food to save as much space and weight as possible, but the individual meals on *Skylab* were a major advance over the primitive edibles available to the *Mercury* astronauts. Food preparation and use will provide increasingly complex challenges in the future, when "closed ecology" food systems will generate food from the waste products of human metabolism.



Mess call. Owen Garriott reconstitutes a container of freeze-dried food at the crew quarters wardroom table in Skylab.



No flies here. The spider "Arabella" spins a web on Skylab.

Ionizing Radiation

Beyond the protective blanket of the Earth's atmosphere, space is filled with radiation of all kinds: the light and heat from the Sun, radio waves from Jupiter, X-rays and gamma rays from the Sun and from energetic, poorly-understood objects beyond our solar system. This radiation not only spans the electromagnetic spectrum, but also includes atomic and subatomic particles of all dimensions and energies. Much of the radiation is similar to that which can be produced on Earth, using radar, cyclotrons, or radioactive materials. The biological effects of these radiations can be studied in great detail. Other space radiations, such as the highly energetic HZE atomic particles, or cosmic rays, are unique to space and can be duplicated only imprecisely and with the greatest difficulty on Earth.

Cosmic rays have been studied in

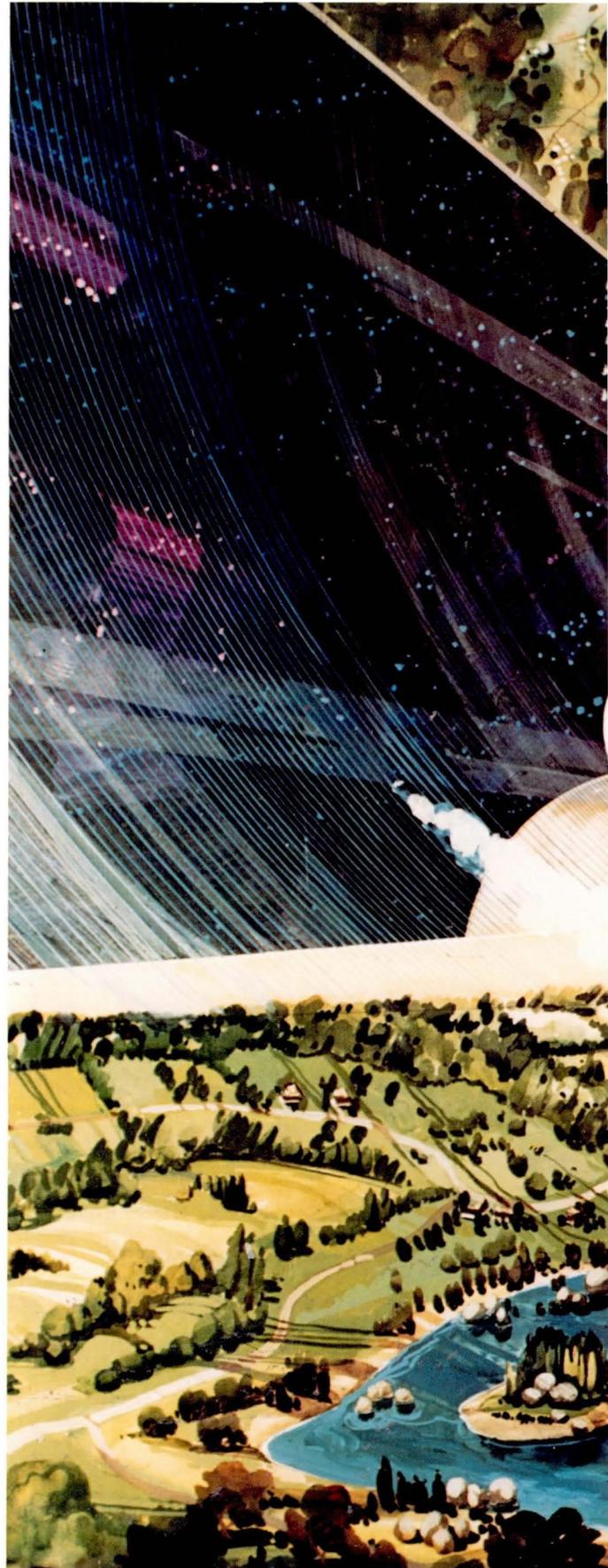
great detail, using a variety of detectors carried into space. One very sensitive detector turned out to be the human eye. Cosmic rays apparently are the cause of the "light flashes," bright streaks seen by the astronauts when their eyes were closed. Some of the displays were striking. On one lunar trip, brilliant green flashes were seen, causing the astronauts to report, "It looks like St. Patrick's Day."

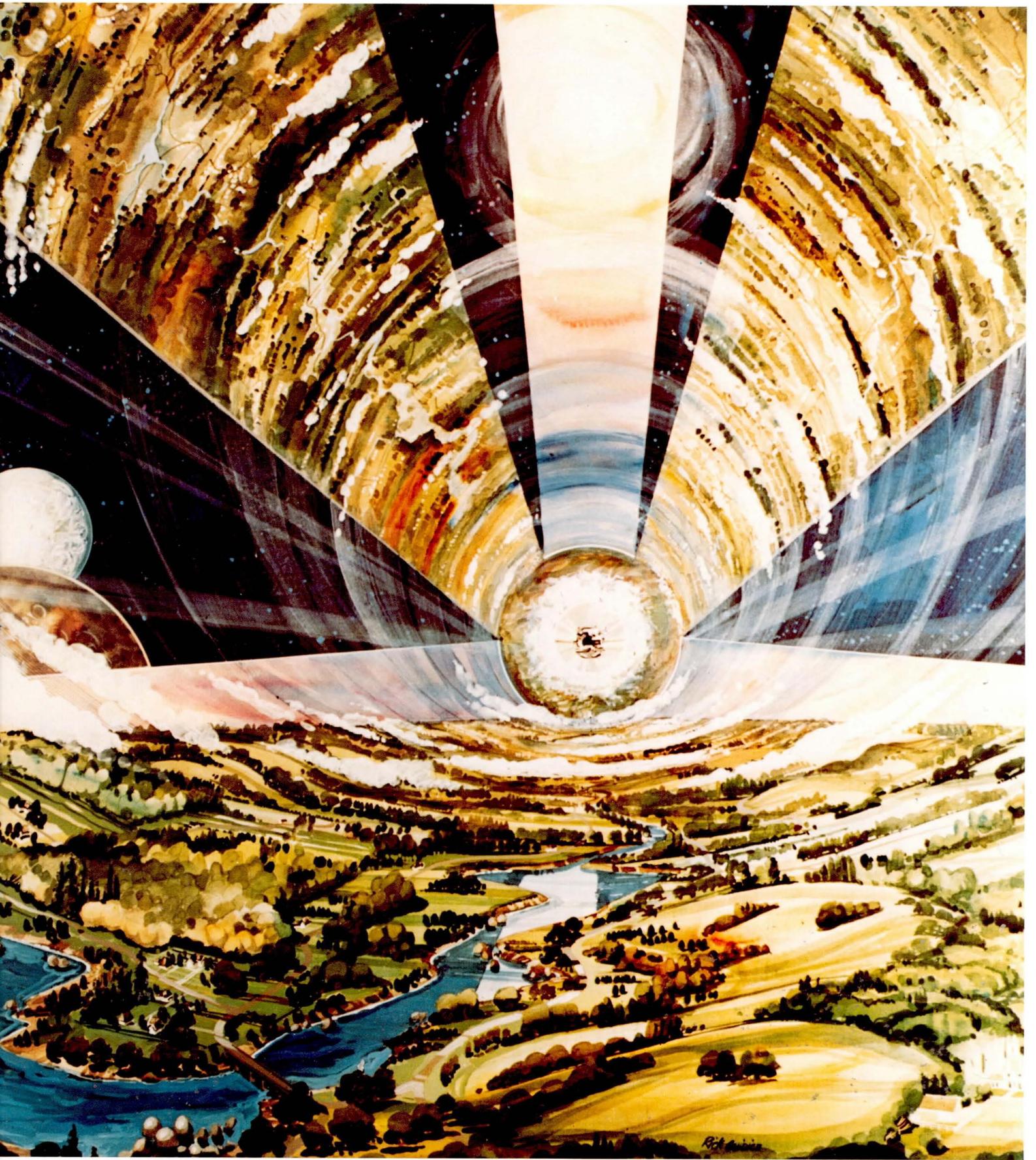
There is no doubt that such penetrating radiation can produce biological damage. It is not yet clear that this radiation is any barrier to our progress into space, but we will need to be protected against it. How the radiation causes damage, what the dangerous exposure times are, and what the possible protective measures may be are all subjects of intense scrutiny.

Conclusion: We Can Go On

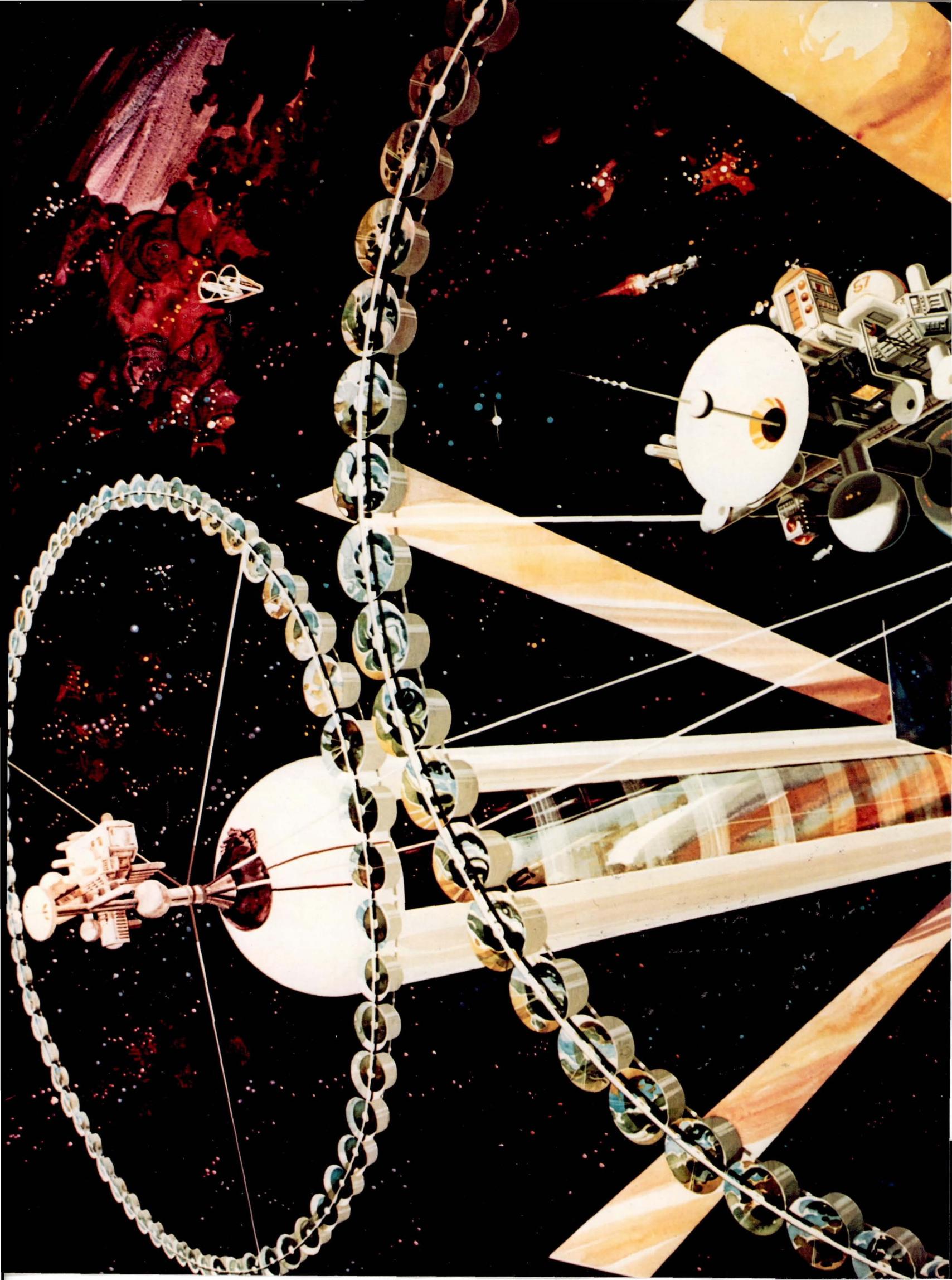
There no longer is any doubt that humans can both survive in space and work hard and productively in this exotic environment for periods of many months. A sizable number of biological responses to weightlessness do take place fairly promptly but are reversible when the space traveler resumes his or her accustomed place on the surface of the Earth. Yet it is equally clear that some of the adjustments are slow and do not reach equilibrium even after many months of weightlessness. There also is concern that a few of these processes, if allowed to go on long enough, may produce irreversible changes. This could be particularly worrisome when older individuals or persons in different physical condition from the astronauts travel into space. Many scientists are seeking to detect, to understand, and ultimately to prevent these changes, so that long voyages into space will be both safe and feasible.

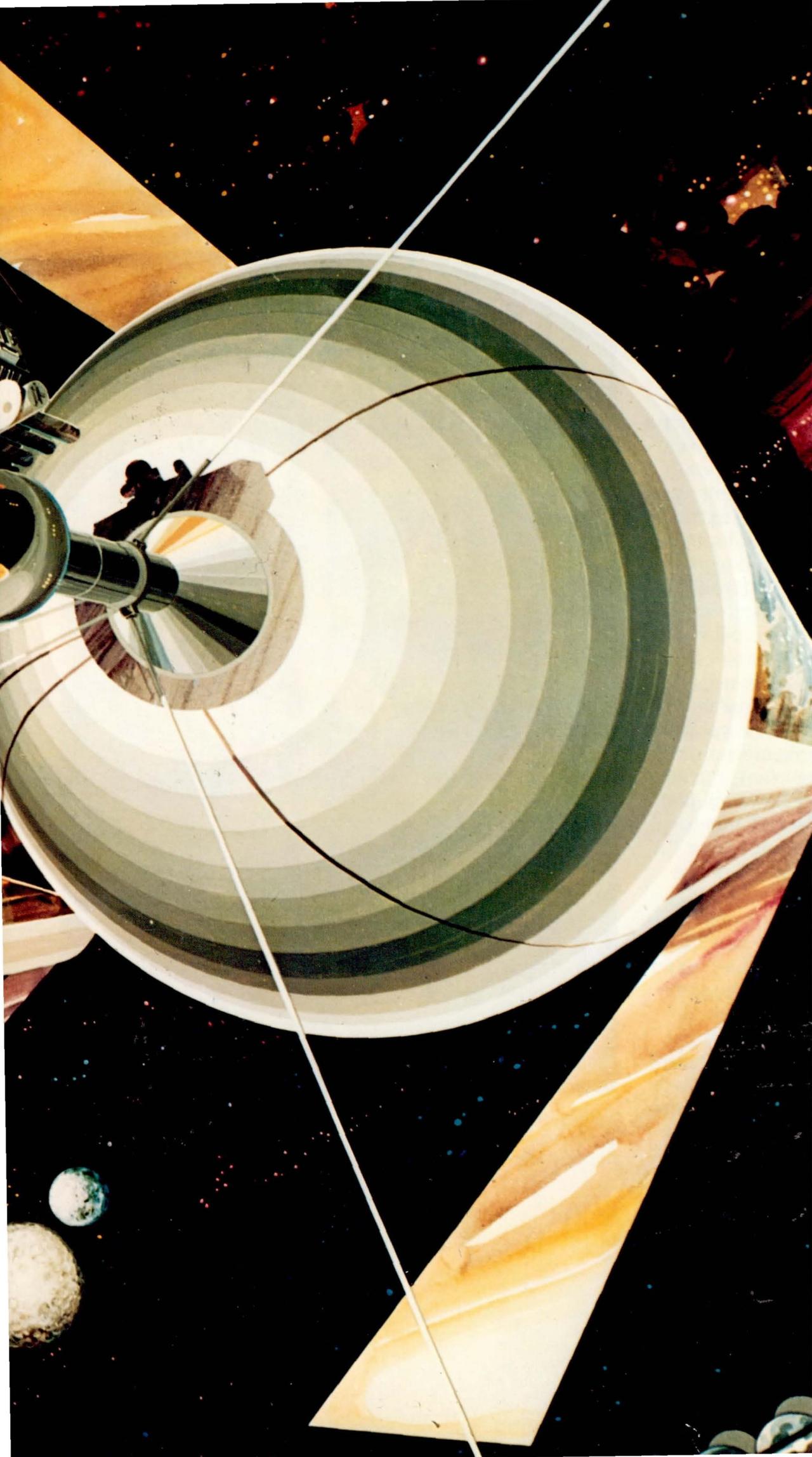
We still do not know whether weightlessness or reduced-gravity environments are suitable for indefinite lengths of time for any terrestrial species. All plants and animals not only are endowed with specialized gravity sensing devices, but also possess many cellular and subcellular structures whose orientation and perhaps even function will be influenced by the withdrawal of gravity. Actual spaceflight data are sparse, but so far gross anomalies in basic living processes have not been detected in the space environment. Much work, of course, remains to be done before the role of gravity in living processes is completely understood and before humanity can erect cities in the sky with the same impunity with which the spiders Arabella and Anita spun webs in *Skylab*.





Habitat of the future? Part of a torus-shaped space colony proposed for the future by members of a study group. Farms would raise food for 100,000 inhabitants, while rotation at 1 rpm would provide artificial gravity.





Station in space.
*An artist's depiction
of a future space
colony somewhere
between the Earth
and the Moon.*

The physiological and psychological barriers to space flight are being methodically and successfully challenged. A major dividend of these space medicine studies is that much of what is learned is directly applicable to ordinary people who may never leave the Earth. The technology that permits the flight surgeon to monitor the heart rate of an astronaut walking on the Moon can be used to keep a careful and continuous watch on cardiac patients going about their daily work. The space suits that cooled and protected astronauts during extravehicular activity have been adapted to treat the cancer patient and to guard the immune-deficient child from the germs against which it has no natural defense. Even an astronaut's adverse reactions to weightlessness are in many ways similar to diseases on Earth. Such diseases are thus seen in a different light from the viewpoint of space. Their underlying mechanisms may become more apparent, and effective treatment may be developed.

Much must be learned, much must be done before humans can spend indefinite periods of time beyond the confines of the Earth. It is still conceivable that prolonged or repetitive exposure to space may ultimately present an impassable barrier to our survival in that environment. Today, however, from the vantage point of twenty years of space flight operations, many thousands of hours of flight experience, more than one hundred astronauts and cosmonauts, and many other living creatures, no such barrier is in view.



Life-saving suit. A child born with severe combined immune deficiency, a rare hereditary disease, is protected from potentially harmful microorganisms by a miniature space suit.

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LIFE IN THE UNIVERSE

Donald L. DeVincenzi

Violent beginnings. Heat, moisture, and gases from volcanic eruptions on the early Earth could have provided the environmental conditions required for initiating chemical evolution reactions which led to life. (Photograph courtesy of Richard S. Fiske, National Museum of Natural History, Smithsonian Institution.)



A Universe of Life

Planets seem to be reasonable places for life. They are neither as hot and deadly as the surfaces of stars, nor as cold and empty as the space between them. The only life we know of in the universe has developed on a planet, the Earth. Thus, other planets have always been the major focus of our search for other forms of life. If planets are abundant in the universe, life may be common. If planets are rare, we and our fellow Earthlings may be unique.

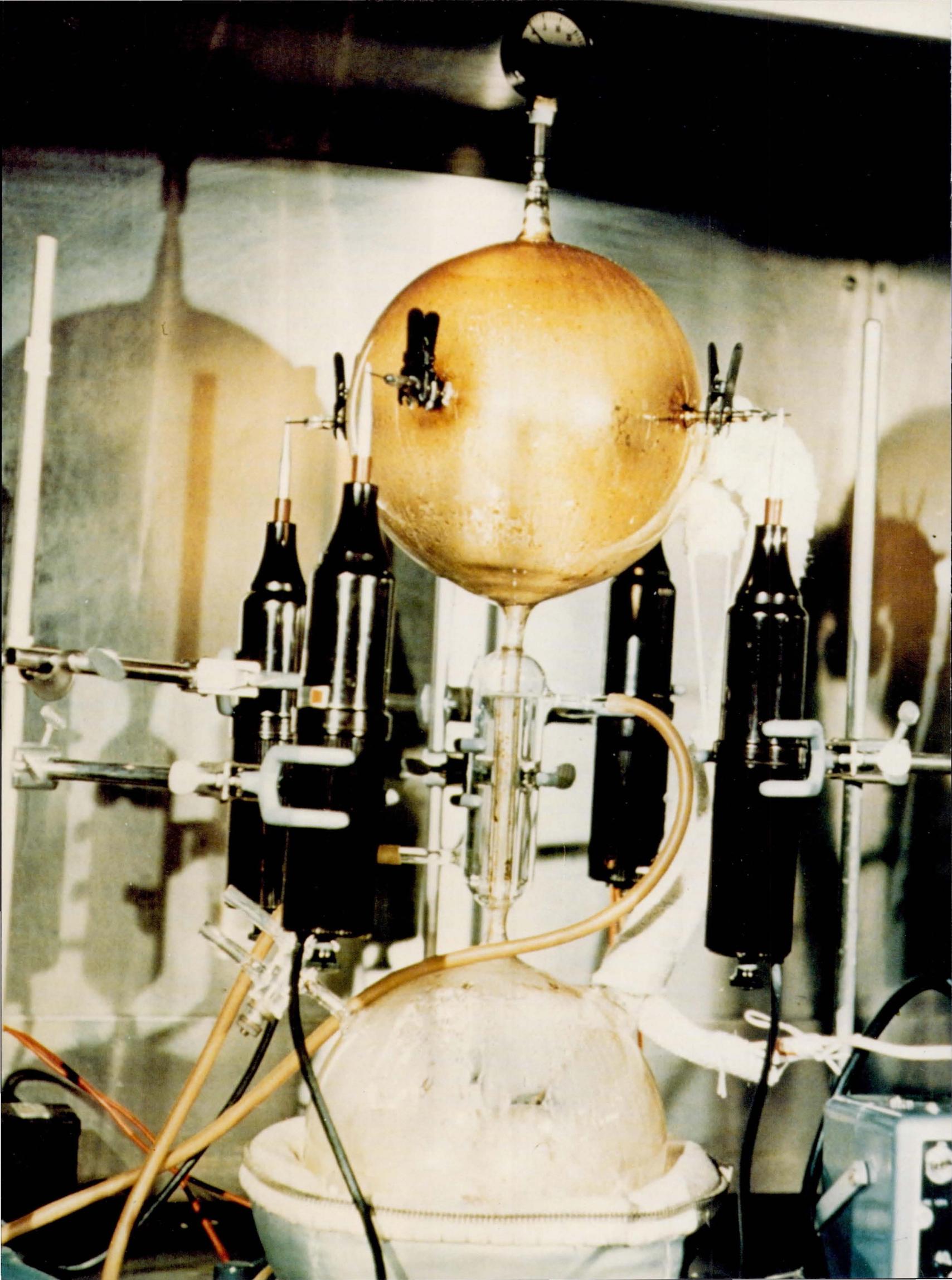
Only thirty years ago, most astronomers believed that planetary systems were extremely rare. It was even thought that the solar system and the habitat that Earth provides might well be unique in the entire galaxy. At the same time almost nothing was known about the chemical basis for the origin of life. Since then, our view has changed drastically. Numerous studies have eroded the reasons why planetary systems and the development of life on suitable planets should be unlikely. Today, the leading theories for star formation suggest that planets may be the rule rather than the exception and that the formation of planets is expected to accompany the formation of stars. At the same time, new discoveries have shown that the chemicals necessary for life are abundant beyond the Earth. Inter-

stellar gas clouds have been found to contain biologically important organic molecules made of carbon, hydrogen, and other elements. Similar molecules have been detected in comets and meteorites. Therefore, today's theories suggest that life could be widespread in the universe. Growing numbers of scientists are now convinced that extraterrestrial life must exist, and more and more people feel that contact with other civilizations is no longer something beyond our dreams but will be a natural event in the history of mankind.

The existence of extraterrestrial life and the origin of life are two questions that are intimately related. The major problem is the origin of life. This topic is intrinsically fascinating. It is surrounded by mystery, philosophy, and religion, and it has been the subject of contemplation and speculation since the beginning of human history. Only in the last century has the question become recognized as a subject suitable for direct scientific inquiry. Individual researchers and groups of scientists have considered the problem for years, but NASA was the first organization to provide a cohesive, interdisciplinary approach, combining the various scientific programs that had investigated the question since the early 1960s.

This integrated attack includes disciplines as diverse as astronomy, biology, chemistry, geology, and engineering. Ground-based laboratory research, astronomical observations, and space missions have all been brought to bear on the questions of the uniqueness of life on Earth, the origin of life in the universe, and the place of life in the general cosmology. We have come to the point that scientists can now devise experiments to answer such fundamental questions as: "Where did life come from?" "Why is life like it is?" "Are there other forms of life in the solar system or in the universe?" "Is there intelligent life elsewhere?"

This new science of *exobiology* has several goals. It seeks to understand the origin, evolution, and distribution of life and of the chemicals necessary for life, both on Earth and throughout the universe, and it seeks to determine the relationship of life to the evolution of planets. Through research in chemistry, geology, and biochemistry, and from our exploration of the planets, we have begun to pull together some parts of the origin-of-life puzzle. Pieces of the puzzle are being gathered from throughout the universe, from interplanetary and interstellar space, from other worlds, and naturally, from the Earth.



Life in the Solar System

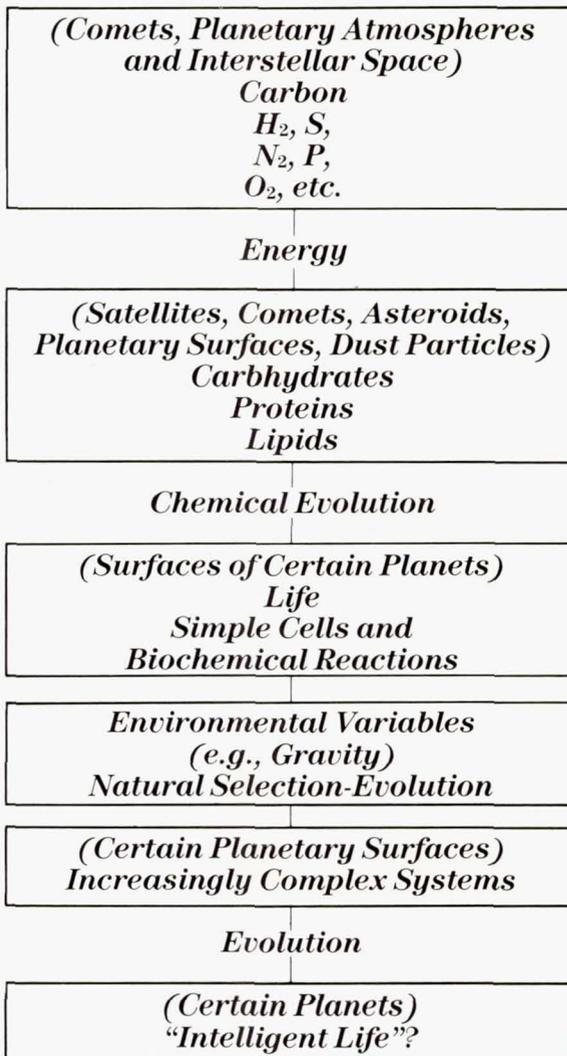
From molecules to Man

It now is generally accepted that the origin of life on Earth was closely tied to the origin of the solar system itself. From this concept, combined with experimental findings, a general model for the beginnings of life on Earth is emerging. It starts, almost immediately after the original accretion of the Earth, with a period of chemical evolution which resulted in the formation of small organic molecules that are essential for life. These molecules were synthesized from the gases that made up the primitive atmosphere. This first atmosphere, which surrounded the newly formed Earth, is believed to have been reducing in nature. That is, it contained no free oxygen and was composed mainly of gases such as hydrogen, methane, ammonia, and water vapor.

As time passed, these gases were activated by energy sources like lightning discharges and ultraviolet radiation from the Sun. The original molecules broke apart, and their atoms recombined to make new, more complex molecules, thus beginning the prebiotic synthesis of organic matter, meaning the reactions that preceded the development of life.

Under the influence of primitive planetary environmental conditions the organic molecules combined to form larger, even more complex molecules. Finally, thousands and millions of molecules were assembled into structures exhibiting key properties of living things: metabolism, respiration, reproduction, and the transfer of genetic information. This stage was reached on Earth about 3.5 to 4 billion years ago, about 0.5 to 1 billion years

after the Earth and the solar system formed. From that point on, the record preserved in Earth's rocks constitutes the raw material for laboratory studies because it is the repository for all evolutionary information from the time of the first living cells through the evolution of today's complex life forms. As the details of this process are being unravelled in terrestrial laboratories by scientists using sophisticated instruments and experiments, we find ourselves also exploring an important related question: Are the same or similar processes producing life elsewhere, beyond the Earth?



Ancient process/modern laboratory. Electric discharge apparatus is used to simulate conditions in the primitive atmosphere of the Earth that may have produced the chemicals of life.

Sequence of cosmic evolution. This scheme places the theory of the chemical origin of life on Earth into the broader context that similar events may occur elsewhere in the universe.

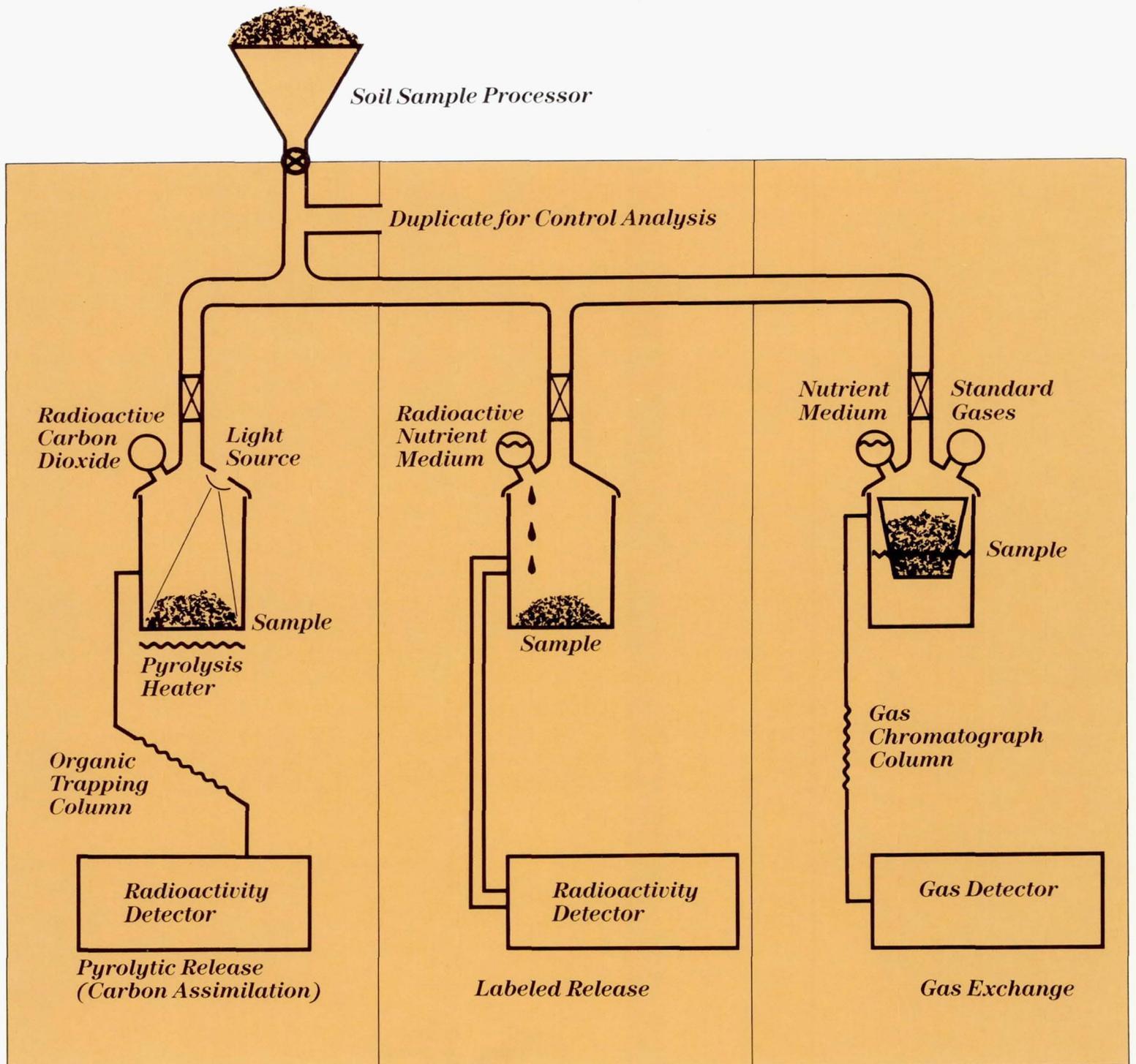
From theory to search

The first opportunity to search directly for extraterrestrial life was provided by the *Apollo* missions to the Moon. Rock and soil samples returned from the Moon were analyzed extensively, but neither living nor fossil life forms were found. Further studies show that the Moon, which has no water, no atmosphere, and no protection from the radiations of space, probably never had the physical characteristics needed to begin the synthesis of organic matter, a required precursory step to the origin of life.

Mars provided our second opportunity. With its obvious atmosphere and polar caps, Mars was deemed (in both scientific papers and the popular press) a much more likely location in the solar system to harbor extraterrestrial life. The search for Martian life began in earnest when the *Viking* Project landed two robot spacecraft on the planet in 1976 to photograph the surface material and analyze it in detail. These missions increased our knowledge of the physical and chemical properties of the remarkable red planet tremendously. Perhaps the most unexpected and fascinating findings, however, were returned by the two instruments designed to search for life and for life-related molecules. One instrument showed that, quite unexpectedly, the Mars soil samples contained no organic materials, not even traces of carbon from meteorites that must hit the planet's surface.

This is probably due to the destructive power of the intense ultraviolet radiation from the Sun, which destroys any exposed organic material. The second instrument, intended to detect biological reactions in the Martian soil, did not detect life on Mars. It did uncover an intriguing chemical property of the soil that, at least in part, does mimic some simple lifelike reactions. Among these are the breakdown of nutrient chemicals and the synthesis of organic matter from gaseous substances.

All in all, Mars remains a planet of extreme interest to exobiologists. Although *Viking* did not detect life, Mars continues to tantalize us. Why were no organic molecules detected? Were conditions in Mars' past history more favorable for prebiotic chemical syntheses than those present today? Are there other locations on Mars today where conditions are more conducive to life or to life-related chemistry? These questions and more require continued exploration of Mars. After all, the Earth is not the most favorable place to look for clues about life's origin, since life itself has altered the planet so drastically that much necessary information has been obliterated. Mars, then, provides us an essential point for comparison with Earth: an environment not extensively modified by widespread life, and perhaps still harboring secrets about the relationship of the origin of life to the origin of the solar system.



Outline of a search for life. Three life detection experiments, schematically described here, were conducted by the biology instruments on the Mars' Viking landers.

The Chemicals of Life

In addition to searching for extraterrestrial life, we pursue the search for extraterrestrial life-related molecules in order to establish the universal nature of prebiotic chemical synthesis. Recent discoveries show that comets, which seem to have remained unchanged since the formation of the solar system, may represent a unique storehouse of information about organic synthesis at the time of formation. We now have evidence that the organic molecules believed to be precursors of molecules essential for life are prevalent in comets. These discoveries have provided further support for the view that chemical evolution has occurred widely beyond the Earth. Comets may even have played a major role in the organic chemical evolution of the primitive Earth itself. Significant amounts of important precursor molecules could have been deposited on the primitive Earth by cometary impacts.

Meteorites, which provide us with solid samples of extraterrestrial material, represent another source of information about the occurrence of prebiotic chemistry beyond the Earth. In 1969, meteorite analyses provided the first convincing proof for the existence of extraterrestrial amino acids, a group of molecules necessary for life. Since then, a large body of information has accumulated to show that many more of the molecules necessary for

life are also present in meteorites, and it now seems clear that the chemistry of life is not unique to the Earth. Future studies of meteorites should greatly contribute to the eventual understanding of the conditions and processes during the formation of the solar system and should provide clues to the relations between the origin of the solar system and the origin of life.

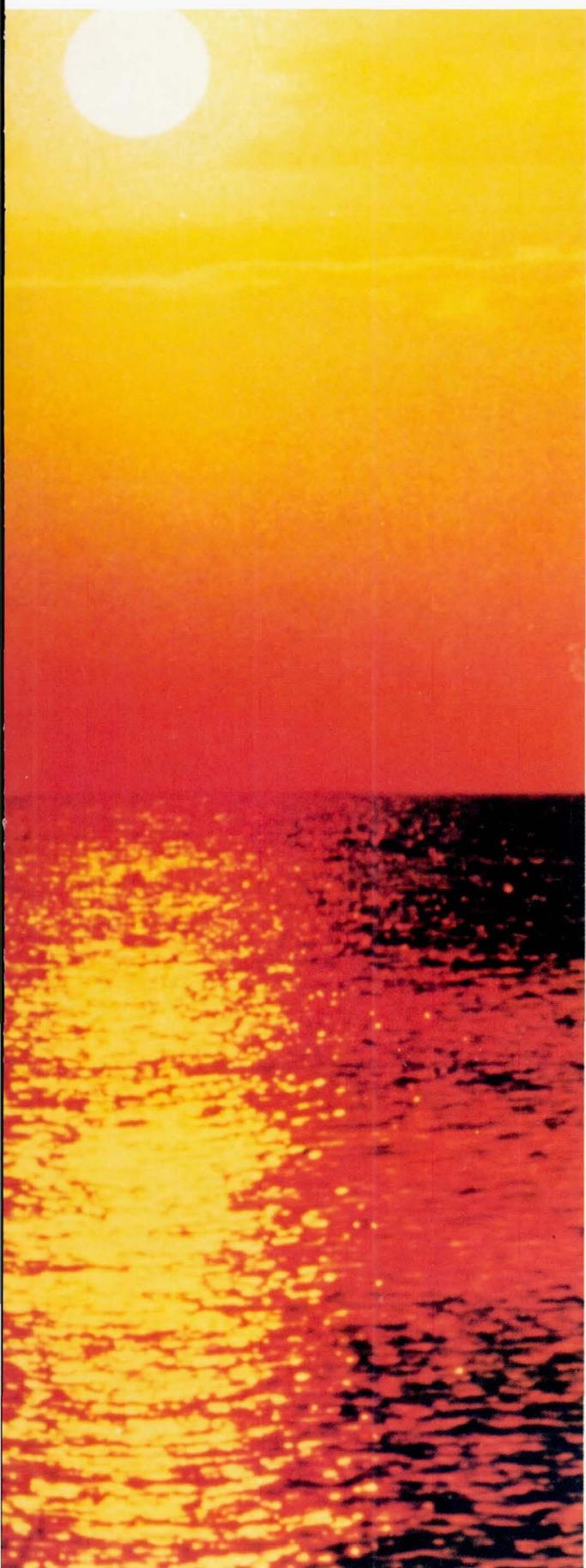
The atmospheres of the outer gas giant planets (Jupiter, Saturn, Uranus, and Neptune) represent yet another extraterrestrial environment in which prebiotic chemistry can occur. In fact, from our knowledge of the composition of Jupiter's atmosphere, many scientists consider it to be a good model for the primordial atmosphere of the Earth. Jupiter's atmosphere contains the same gases (hydrogen, methane, ammonia) that may have been present when the Earth's atmosphere formed, and violent lightning flashes were detected in Jupiter's clouds by the *Voyager* spacecraft. With its abundant organic molecules and electrical energy, Jupiter may be the site of extensive prebiotic chemical reactions that reproduce what occurred on our own planet 4 to 4.5 billion years ago. We expect that further important information on this question will be provided by the *Galileo* spacecraft as it makes direct analyses of the turbulent atmosphere of this giant gaseous world.



Clue in a cosmic mystery. A fragment of the Murchison meteorite, which fell on Australia in 1969. Organic matter of a type not produced biologically was found in the meteorite.



The role of clays. Chemists studying possible mechanisms for the origin of life have emphasized the likely role of clays in providing a suitable environment for the necessary reactions. Experiments with various clay solutions demonstrate the validity of this system as a model for the synthesis of polymers essential for life under conditions simulating the primordial ocean environment.



The View from Earth

We are actively exploring the origin of life on the surface of our own planet. Several recent discoveries have provided new insights into the mechanisms which may have acted to synthesize biomolecules on the primitive Earth. We have discovered that, under geologically reasonable conditions, the surfaces of certain clay minerals can select specific biomolecules (molecules necessary for life) from a dilute solution like sea water, can concentrate them, and can cause them to polymerize, or grow into chains of more complex molecules. Model systems based on this research simulate a primitive tidal basin and provide for the first time an attractive sequence of events to explain how large molecules, like proteins and nucleic acids, could form from simpler molecules present in small amounts in the primordial oceans. These findings indicate that clays could have played a vital role in the origin of life on Earth.

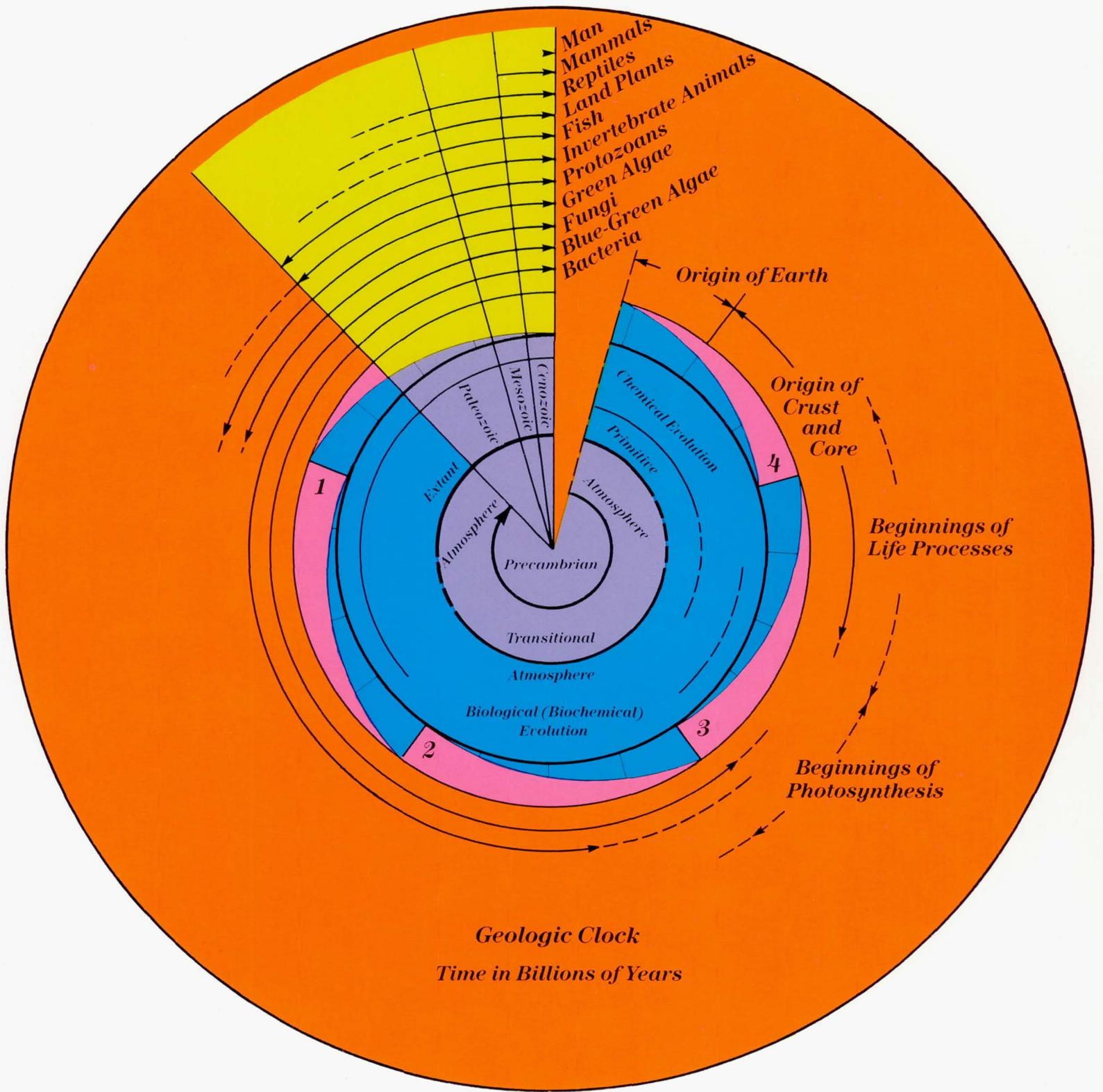
We have also come to understand better the puzzling data sent to us from Mars by the *Viking* landers. During 1979, experiments conducted in several university laboratories finally reproduced the controversial measurements from one of the life detection instruments. Specially prepared clays, when mixed with salts in an amount determined by other *Viking* instruments to be present in the Martian soil, released carbon dioxide in a fashion like that observed in the *Viking* labeled release (LR) experiment. More recently, it has been shown that the activity of these same clay-salt mixtures can be destroyed by heat sterilization. This strong sensitivity to heat, also observed in the LR experiment, was the most lifelike response observed in the Martian soil, and it had been the most difficult feature to simulate on Earth up to this

time. The discovery on Mars that a non-biological system could exhibit life-like behavior was a significant finding with implications for the exobiological history of Mars that remain to be determined. These findings highlight the need for continued exploration of Mars, including the return of samples for detailed study on Earth. The data also reinforce the central role that clays may have played in generating chemical reactions of exobiological importance, both on Earth and on the other planets.

Our present knowledge of the Mars environment indicates that it is quite hostile as far as the survival of Earth-like microorganisms is concerned. Mars is cold, dry, and bombarded by ultraviolet radiation from the Sun. However, Earth-based research continues to discover microorganisms with unique abilities to thrive in environments previously considered to be too severe or extreme for life. The interior of Antarctica was once believed to be devoid of indigenous life forms because of its cold and dryness. But recent work in the dry valleys of the Antarctic has revealed native microbes of three different kinds. Algae, bacteria, and fungi were discovered living comfortably, embedded just below the surface of rocks strewn over more than 100 locations in these frozen deserts. The finding of life in Antarctica's dry valleys extends the known limits of life on Earth to its

driest and coldest climates. At the same time, the discovery suggests that life may exist in similar environments on a planet like Mars, where the climate closely resembles that of the dry valleys of Antarctica. The surface of Martian rocks could provide an effective shield from the harmful radiation of the Sun for microbes dwelling inside.

Another new line of investigation was initiated in an attempt to decipher the long series of events that took place in early biological history after the formation of the first living cell. A multidisciplinary, international team of specialists assembled for a fifteen-month project to discover the details of some of the most significant events in the early biological evolution of the Earth. Some of these events include the origin of early microorganisms that did not use oxygen; the development of the photosynthetic capability to produce food-energy from sunlight; and the advent of oxygen-using or aerobic microorganisms. This group is searching the Earth's ancient rocks for evidence of the chemical reactions which preceded the appearance of the first life forms. They have already succeeded in pushing back in time the direct evidence for life on Earth by discovering microfossils in rocks that are 3.5 billion years old. This unique research team approach should have a major impact on future investigations of the organic geochemistry of early Earth.



Down through the ages. This geologic "clock" diagram summarizes the history of life on Earth and its relation to the geologic eras. (After Prof. J. W. Schopf, UCLA.)

Things to Come

The new information on planetary formation, extraterrestrial chemistry, and the effect of the Earth's environment on the origin and development of life now provides a strong basis for looking for life (in fact, intelligent life) beyond the solar system. Such a search requires a much different approach than sending astronauts and spacecraft to nearby worlds. Because of the incredible distances to even the nearest stars, we need to search for some long-range manifestation of life that can be detected from Earth. We need to detect radio signals rather than metabolic chemical reactions. We need to explore different stars rather than just the planets around our Sun. And finally, we need to use a different technology, radio astronomy, rather than spacecraft. We can now define a program to search for intelligent signals of extraterrestrial origin by using our existing radio telescope antennas with only a small amount of sophisticated auxiliary equipment. The technology needed for such a search is clearly at hand at this very moment.

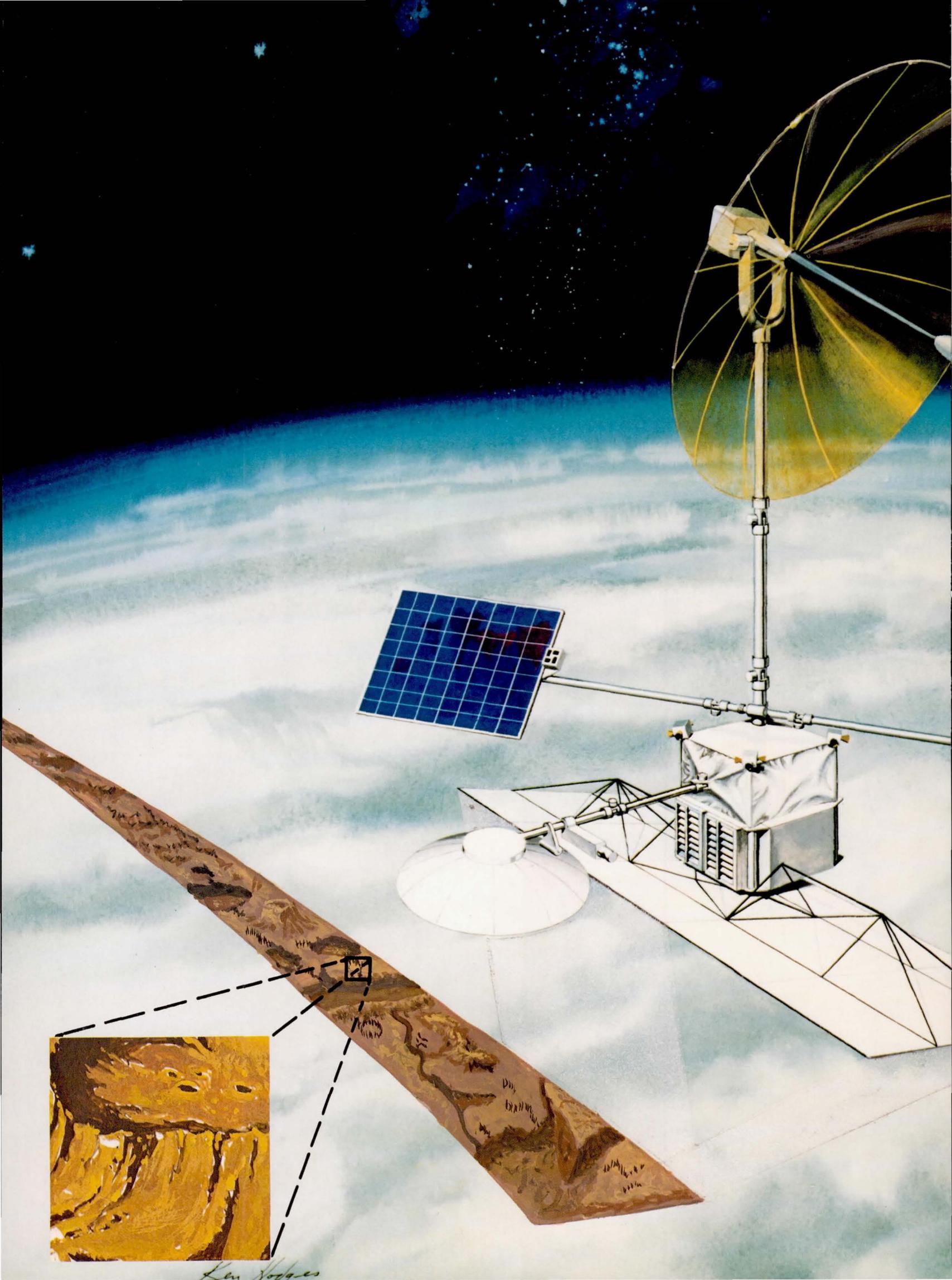
After only two decades of active research, scientists have compiled an impressive list of accomplishments and discoveries in the search for the origin of life. Studies pursued under the auspices of the space program have contributed to a more universal

understanding of the phenomenon of life as a whole. We now have considerably more details than we did thirty years ago. We have direct knowledge of the properties of the Moon, Mars, Venus, Mercury, and Jupiter. We have a wealth of information on proteins and cells, on the low likelihood of life on other planets in the solar system, and on the forces that led to the formation of the solar system and biomolecules. We have found simple organic substances, believed to be the precursors of life, in planetary atmospheres, in meteorites, in comets, and in interstellar space. We can also synthesize them quite readily in laboratory experiments.

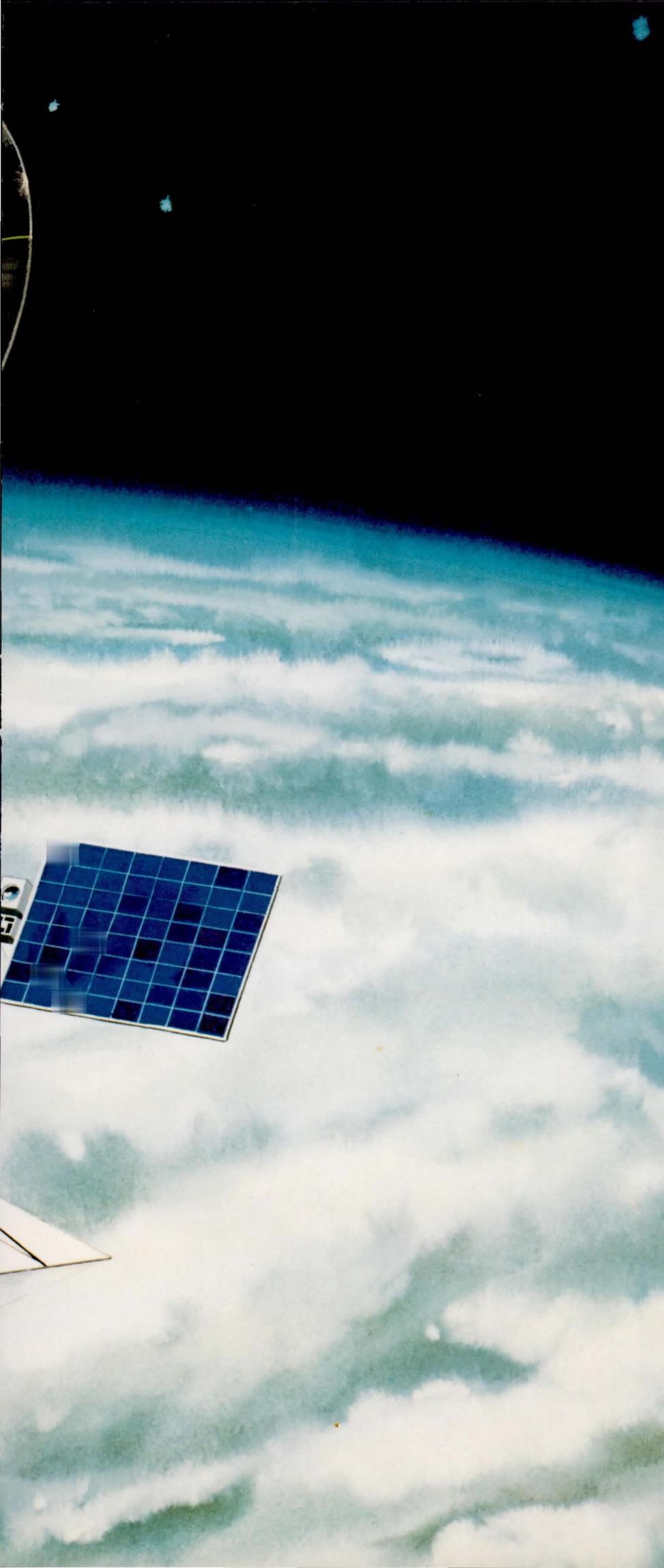
To discover an independent life form on another planet, or even beyond the solar system, still presents a challenge unequalled in the history of scientific inquiry. Although our knowledge has increased dramatically over the past few decades, our ability to obtain new knowledge has increased even more. The Earth's oldest rocks, newly found meteorites, our laboratories, and our huge, sensitive radio telescopes all have important roles to play as we continue our efforts to learn the chemical and biological secrets of ancient Earth and our studies on the existence, nature, and distribution of life in the universe.

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Ken Hodges



Chapter 7

THE LONG CLIMB AHEAD

Bevan M. French

Unlocking Venus' hidden secrets. *The Venus Orbiting Imaging Radar (VOIR) spacecraft would give scientists their first detailed view of the surface topography of Venus. A powerful radar, carried on the spacecraft, will generate detailed images of the planet's canyons, mountains, and continent-sized land masses by piercing through the multiple cloud layers that always shroud Earth's sister world.*

The View from the High Ground

The climb into space has made us unique. We are the first generation of human beings to study the universe directly from the high ground of space itself. From this new perch, we have made discoveries that would have seemed impossible to the ancients and unbelievable even to the scientists of a generation ago.

For all our climbing, we have not reached the summit, only a ridge from which we can better glimpse the mountains beyond. We have reached a point from which to observe, a base from which to explore further, and we have learned how best to continue our investigation of the universe.

Because we have found so much, we now know how much more there is to learn and how to proceed to study it. The necessary tools exist or can be built. The spacecraft can be flown, and their data deciphered. A few new missions, already approved, are under development. Many more are being intensively studied, so that they too may come to fruition. The future missions, and the research that they will undertake, concern the subjects that we have already begun to explore: the solar system, Earth-Sun relations, the outside universe, and life.

“The past is but the beginning of a beginning, and all that is and has been is but the twilight of the dawn.”

H.G.Wells, *The Discovery of the Future*, 1901.

The Worlds that Wait

The *Voyager 2* Saturn encounter in August, 1981, marks the end of an era in planetary exploration. All of the planets known to the ancient astronomers have been visited by spacecraft; the reconnaissance of the inner solar system will be finished. There will be no new planetfall until *Voyager 2* succeeds in getting a close view of Uranus in 1986.

Reconnaissance is not enough, however. Many tantalizing questions cannot be answered by spacecraft flashing quickly past these worlds, and new and unexpected questions have been raised by the very data sent back to us.

We are now ready to begin a different phase in the exploration of the solar system, a period of careful, systematic study. For this we will need heavier, more sophisticated spacecraft, longer observation times, and much larger data returns. Such missions and their new generations of instruments will be based on the immense knowledge that we have already obtained.

The next generation of planetary exploration missions which will be launched in the mid-1980s and beyond will begin with the *Galileo* mission to Jupiter, which is intended to begin

the detailed exploration of the outer gas giant planets.

The concept for *Galileo* is a two-spacecraft mission. One is a probe that would plunge into the Jovian atmosphere, measuring the chemical composition as it descends, until, more than 100 kilometers (62 miles) down, it succumbs to the intense pressure. The second spacecraft would go into orbit around Jupiter, continuously photographing the planet's clouds and weather, measuring the magnetic field, and taking close-up pictures of its moons. *Galileo* would study Jupiter in detail, not on a quick flyby, but over a period of a year or two, and it will bring us a long way toward understanding this giant planet, its huge magnetic field, and its mysterious moons.

Although we have explored the inner terrestrial planets in some detail, one remains hidden. The surface of Venus, beneath its thick, opaque atmosphere, is still largely unknown. We have some crude radar maps made by *Pioneer Venus*, but their resolution is only a few kilometers, not enough to let us compare the details of Venus with those of the other worlds whose surfaces are in full view.

A new spacecraft mission has been proposed to fill this gap. Called VOIR (for *Venus Orbiting Imaging Radar*), it would carry a large radar into orbit around Venus. The radar waves can penetrate the clouds and make accurate images of the surface, detecting features as small as a football field. The resulting maps would cover almost the entire surface of Venus, an area four times as large as the total land area of the Earth, and would be adequate to show such features as volcanoes, meteorite craters, crustal fractures, and river channels. We will then be able to compare the geology and history of Venus in detail with what we have learned from other worlds, to discover how Venus fits in with the rest of the terrestrial planets.

The year 1985 will be a special occasion for the study of small bodies in the solar system. It will mark the return of Halley's Comet to the neighborhood of the Sun. This bright comet, which returns about once every 76 years, has been sighted on over two dozen visits to the inner solar system since its first recorded appearance in the year 240 B.C. Now, however, for the first time we may go out to meet it. Several countries, including Japan and the USSR, are planning to send spacecraft out to investigate the comet as it swings around the Sun. NASA is considering a coordinated program of Earth- and satellite-based observations when the comet appears in our sky.

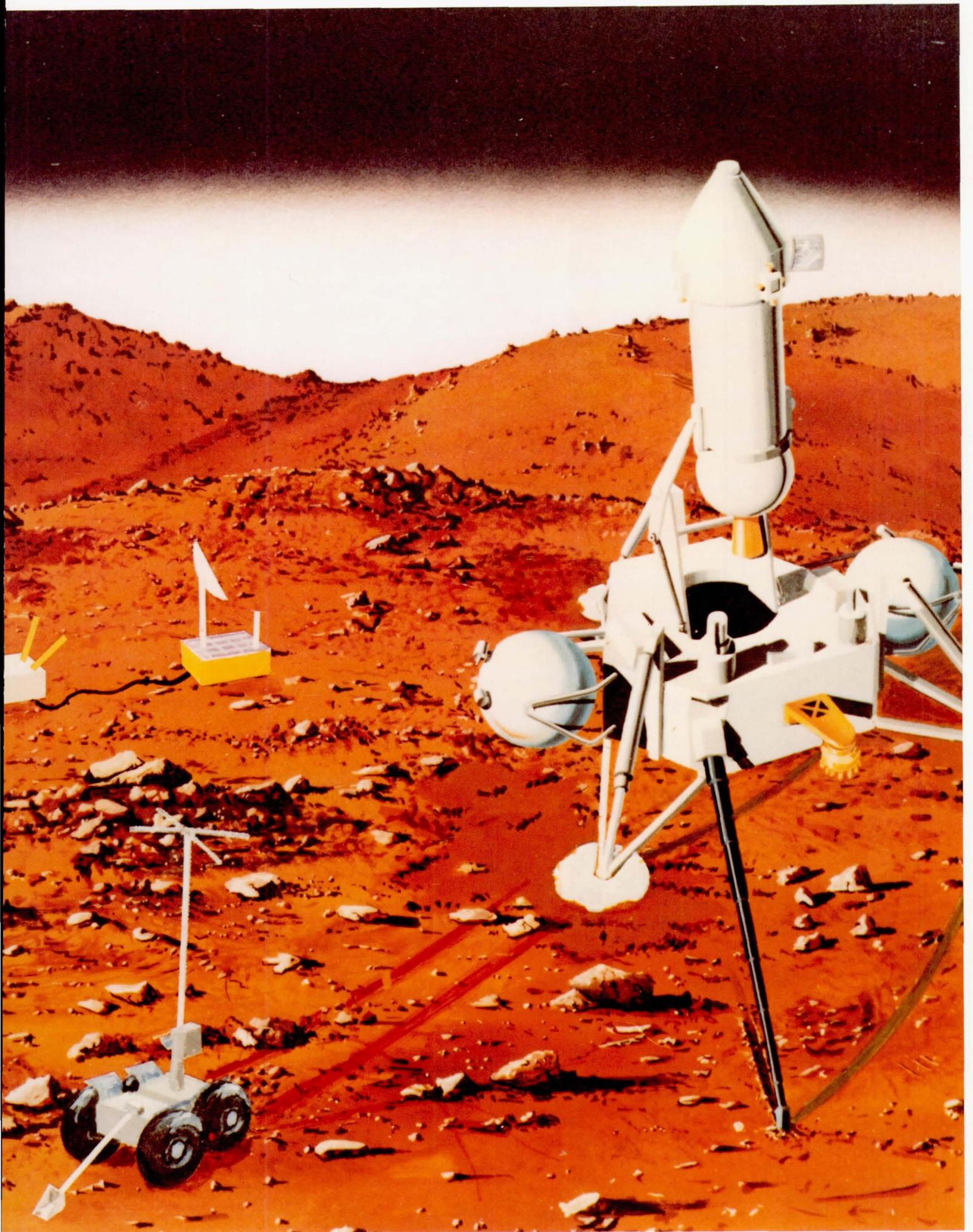
Other missions are under study for the more distant future. After *Galileo* explores Jupiter, Saturn should be the next step in our detailed investigation of the gas-giant planets. Plans are under discussion for a *Saturn Orbiter*, resembling *Galileo*, that would make a long survey of the ringed planet and its family of at least 15 moons. The *Orbiter* might also carry two probes, one to

plunge into Saturn's atmosphere and a second to analyze the atmosphere of the large moon, Titan.

Closer to Earth, among the terrestrial planets, Mars still demands our attention. It is better understood and more hospitable than Venus, but it is still a puzzle in many ways. We need to find out the nature of its rocks and soil and to search more thoroughly for possible life. A more sophisticated lander, a sort of super-*Viking*, is one possibility. A more exciting and advanced, yet wholly feasible, idea is to send a robot spacecraft to land, collect a load of Martian rocks and soil, and return to Earth, just as the USSR *Luna* spacecraft collected samples from the Moon. It may be that only on Earth, with the full resources of our laboratories focused on returned Martian samples, can we finally settle the ancient questions about Mars: its composition, its history, and its life or lack thereof.

Prospecting the plains of Mars. A Mars Sample Return mission, shown here according to one design concept, would carry on where the Viking mission left off. This mission would continue the study of the chemical, geological, and physical properties of Mars and would search further for evidence of past or present life by revisiting the red planet. Upon landing, the robot spacecraft would install instruments and operate a small Rover vehicle (left foreground). Most important, it would collect rock and soil specimens that would be brought back to Earth for laboratory studies by means of a sample return capsule in the spacecraft's ascent stage (streamlined device atop lander spacecraft at right).





The small bodies of the solar system—thousands of asteroids and billions of comets—are also important targets for future space exploration. None of them has ever been visited by a spacecraft, and their compositions and detailed natures are largely unknown. They are primitive objects that date back to the earliest days of the solar system. Comets, preserved in the cold regions beyond Pluto, may give us an unchanged sample of what the original solar nebula was like. The asteroids retain the history of how all the tiny bodies formed and grew in the original solar system, before they were collected into larger worlds like the Earth.

Even after the quick flybys past Halley's Comet in 1986, we will still need to send out more spacecraft to scan these objects at close range, to rendezvous with other comets and study them for long periods of time, to determine the exact nature and composition of asteroidal surfaces, and even to collect and return samples of these bodies to Earth.

To orbit distant worlds like Saturn and Uranus, or to go out to rendezvous with comets or asteroids, we need a boost, a more powerful means of propulsion than we now have. One possible solution is a propulsion system that would operate only in space, the *Solar Electric Propulsion System* or SEPS. SEPS could be used to carry spacecraft launched from the *Space Shuttle* even further and faster into space.

The energy source for SEPS

will be not fuel but sunlight. Large solar panels on the engine convert sunlight into electricity. The electricity is applied to a supply of atoms, perhaps of the element mercury. The atoms become ionized (electrically charged) and are hurled out of the engine. The reaction from this jet of departing atoms pushes the rocket infinitesimally forward. A SEPS engine can produce only a weak thrust, but the thrust can be applied continuously for weeks or months, until the supply of mercury runs out. Even a very small force will accelerate the spacecraft to a surprisingly high speed when it acts over a long time.

SEPS, or something like it, is essential if exploration of the solar system is to continue. Without it, we can do little more than we have done, and many aspects of the solar system will remain a closed book. Our access to distant worlds, and our ability to make more thorough studies of nearby worlds, depend on the thrust that SEPS, or a comparable system, can provide.

Some of the future of space exploration may lie closer to home, on the Moon. We have learned much about the Moon, but it remains mysterious in many ways. We actually have sampled only nine lunar locations. The nature and composition of the rest of the Moon are unknown and much debated. We have no samples at all from the far side of the Moon, that never faces Earth. We do not know what causes the mysterious glows and clouds that have appeared

and disappeared on the Moon on various occasions over the past 200 years. We have not explained the fossil magnetism preserved in lunar rocks, nor unraveled the mystery of whether the Moon has an iron core. We have virtually no information about the Moon's polar regions, where water and other gases may still remain as frozen deposits in the permanent shadows.

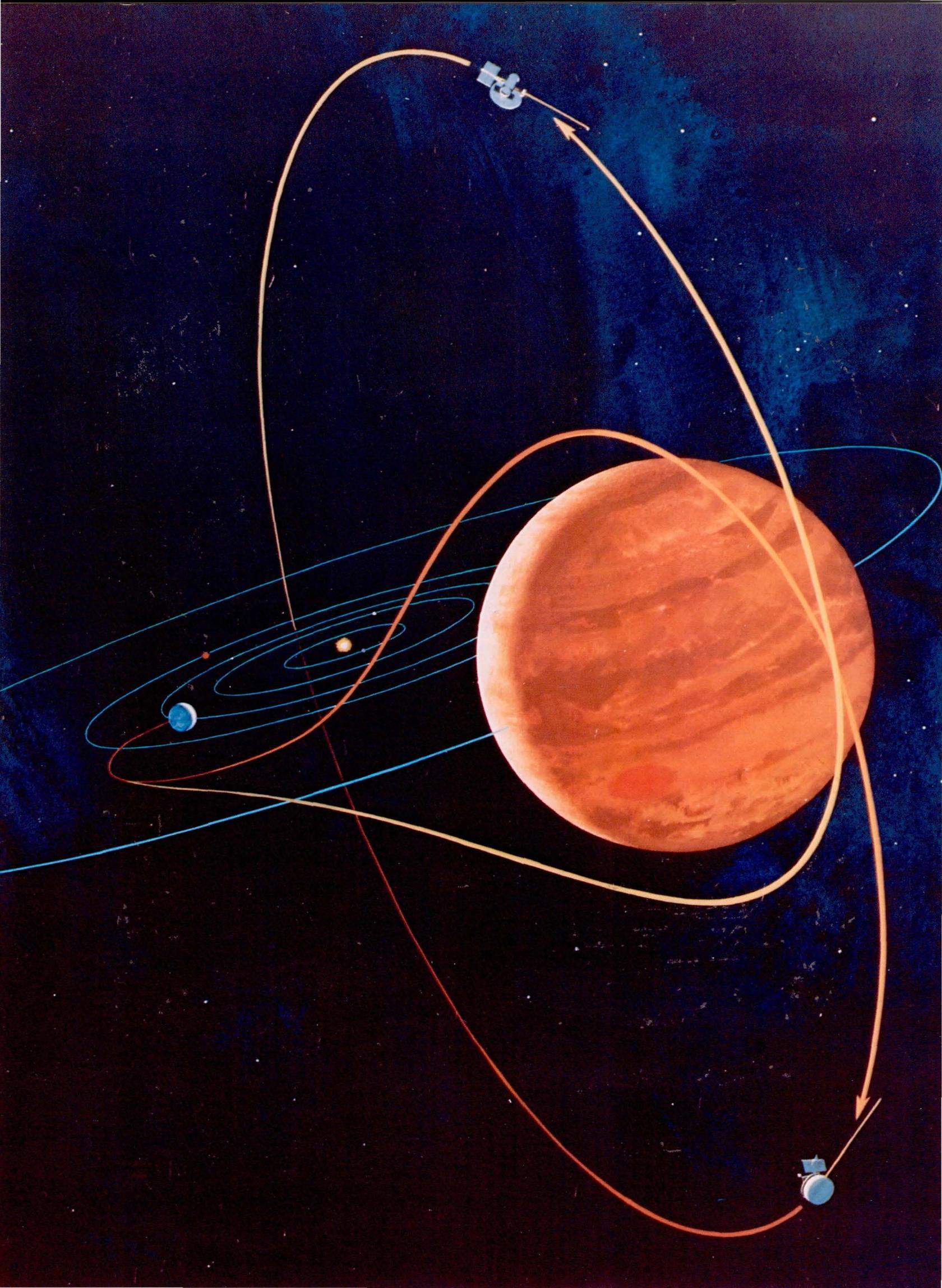
Apollo was a glorious beginning to lunar exploration, but we cannot answer the above questions until we study the Moon on a systematic global basis. The Russians have already demonstrated, with their automatic *Luna* spacecraft, how samples can be brought back, at relatively low cost, from additional regions of the Moon. Another method of global lunar exploration involves a spacecraft that would be placed in an orbit that passes over the Moon from pole to pole. In such an orbit, the spacecraft would eventually scan the entire lunar surface. A battery of instruments would map the chemistry, gravity, magnetism, and thermal properties of the whole Moon. Other instruments would search the polar regions for frozen water in the permanently shadowed areas. This project would complete the mapping begun by *Apollo*. It would give us the first thorough scientific data base for a whole new world, with which we can better understand the global properties not only of the Moon but of other planets as well.

NASA's consideration of such a mission has not proceeded beyond the

study stage. Other countries, including the European Space Agency (ESA), are also considering the polar orbiter project.

The Moon may some day be more than just a scientific treasure. A major concern of our long-term future in space is the question of resources. If we decide to build large structures—power satellites, research stations, or habitats—in space, where will we get the materials? Will we lift them up out of the Earth's strong gravity field at a great cost in fuel, launch facilities, and possible environmental impacts? Or can we use materials that are already present "up there" in space?

Studies of moon rocks and meteorites tell us that the Moon and the asteroids do contain critical and necessary elements: aluminum, silicon, iron, titanium, and oxygen, and even hydrogen and carbon in some asteroids. There is a continuing controversy over whether, how, and when these materials can be mined and used in space. So far, no fundamental barriers have been identified, but there are a host of technical, economic, and social problems to be resolved before a new generation of "forty-niners" goes into space. These discussions and studies should continue, so that we will understand better what we can now do in space if we want to. Only a generation ago, the idea of going to the Moon was science fiction. A generation from now, the mining of the Moon might be routine.



The Sun, the Earth, and "In Between"

We now know that the Sun touches the Earth not only with heat and light but with magnetic fields and streams of charged atoms that fill what we once thought of as empty space. In the near future, for both scientific and practical reasons, we need to study both the Sun itself and the dynamic phenomena in space that bind us to it.

In the past, we have always had to look at the Sun sideways. The Earth's orbit lies near the plane of the solar equator, and from Earth we see clearly only the Sun's midsection. The higher latitudes are harder to see, and the polar regions of the Sun are extremely difficult to study from the Earth. The spacecraft launched from Earth generally are constrained to remain near the plane of the Earth's orbit, and thus are subject to the same viewing limitations.

Yet it is at the Sun's poles, as we learned from observations in space, that some of the most significant and unexpected solar processes occur. Above the Sun's poles, streams of charged particles pour out into space through the coronal holes. To understand the Sun and its effects on Earth, we need somehow to rise up and look at the Sun from above and below. But we do not have an existing propulsion system capable of carrying

a spacecraft over the poles of the Sun.

Nevertheless, a mission is now being planned to send spacecraft over the Sun's poles. The extra thrust needed will come, not from a new kind of thruster, but from the planet Jupiter! In this program to explore the Sun's polar regions, spacecraft would be launched, not toward the Sun, but toward Jupiter. On reaching the giant planet, the spacecraft would cross over its north or south pole and be flung by Jupiter's powerful gravity field back toward the Sun like a pebble whirled from a slingshot. (Similar *gravity-assist* maneuvers around Jupiter were used with the *Pioneer 11*, *Voyager 1*, and *Voyager 2* spacecraft to propel them toward Saturn.)

With the extra speed provided by Jupiter, the spacecraft would be aimed to pass over the Sun's north or south pole. A battery of instruments would be used to measure the streams of solar wind particles and to record the magnetic fields associated with the solar-wind. A variety of other measurements would be carried out as well. This mission would give us our first indication of what the Sun and its surroundings are like in three dimensions, thus literally adding a new dimension to our understanding of the interactions between the Sun and the Earth.

Getting a boost from Jupiter. *To learn more about the Sun, we need to investigate it from closer range and especially from above its polar regions, the last unexplored zones of the solar atmosphere. Present spacecraft propulsion devices are not adequate to send a craft directly over the solar poles, but it would be possible to launch a spacecraft from Earth out around Jupiter, whose powerful gravity can boost a spacecraft out of the plane of the planets' orbits (page 168) and into a new trajectory that would send it racing over the Sun (page 171). This figure shows a mission concept involving two spacecraft, which would simultaneously explore the north and south poles of the Sun.*

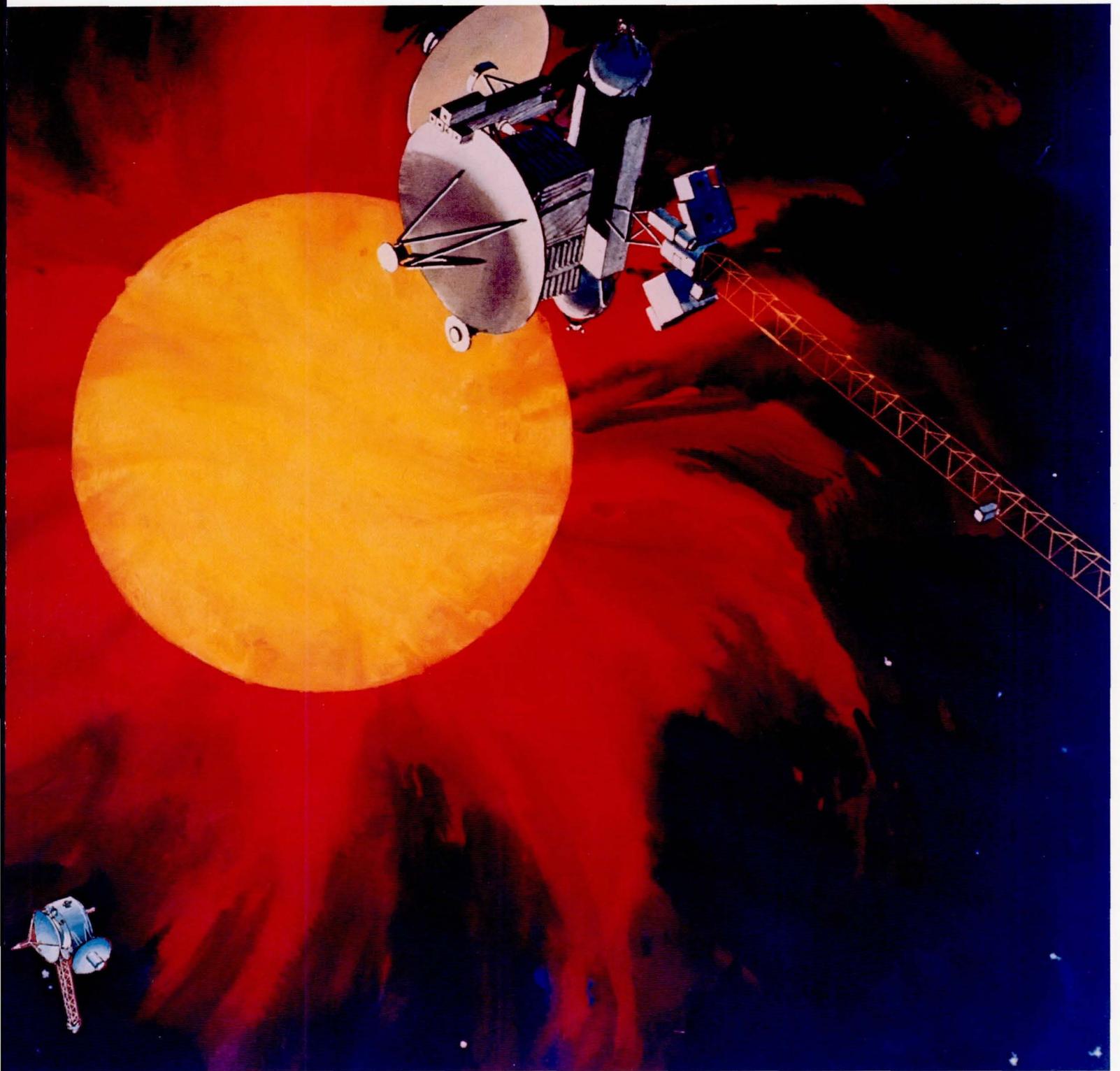
Understanding all the details of the Sun-Earth interactions is a difficult problem. The volume of space that is involved is huge and filled with complex phenomena: magnetic fields, solar-wind streams, the Earth's magnetosphere, and belts of high-energy radiation. These features change constantly, shifting positions and varying in intensity. To follow and understand these changes, we need to make continuous measurements at widely-separated locations simultaneously. So far, we only have data from a few isolated spacecraft moving on limited orbits. Trying to comprehend the full complexities of the Sun-Earth interaction currently is like trying to reconstruct a motion picture from a few individual frames. Inevitably, there are still great gaps in our understanding.

We now need to make a systematic study of the Sun-Earth region. A mission under study would involve the simultaneous launch and operation of four heavily instrumented spacecraft. One would be located between the Earth and Sun to measure approaching disturbances in the solar wind and the interplanetary magnetic field. Two

more would be placed in orbits (one polar, one equatorial) around the Earth to observe the interaction of the solar-originated particles and fields with the Earth's atmosphere and magnetic field. The fourth would be located on the side of the Earth opposite the Sun, to record disturbances that take place in the Earth's magnetic tail downstream from the Sun.

With these spacecraft making simultaneous measurements, we would obtain the data to construct a "movie" of the Sun-Earth interactions. We could detect changes in the Sun's forces and see how the Earth responds to them. We could match the data with information from weather satellites and ground-based weather stations to gauge the effects of the Sun on the weather. This project would be an expedition to explore the space between Earth and Sun, but its discoveries would be used on Earth, hopefully to improve weather prediction, to understand and perhaps prevent communications interference, and to discover the Sun's long-term effects on our climate.





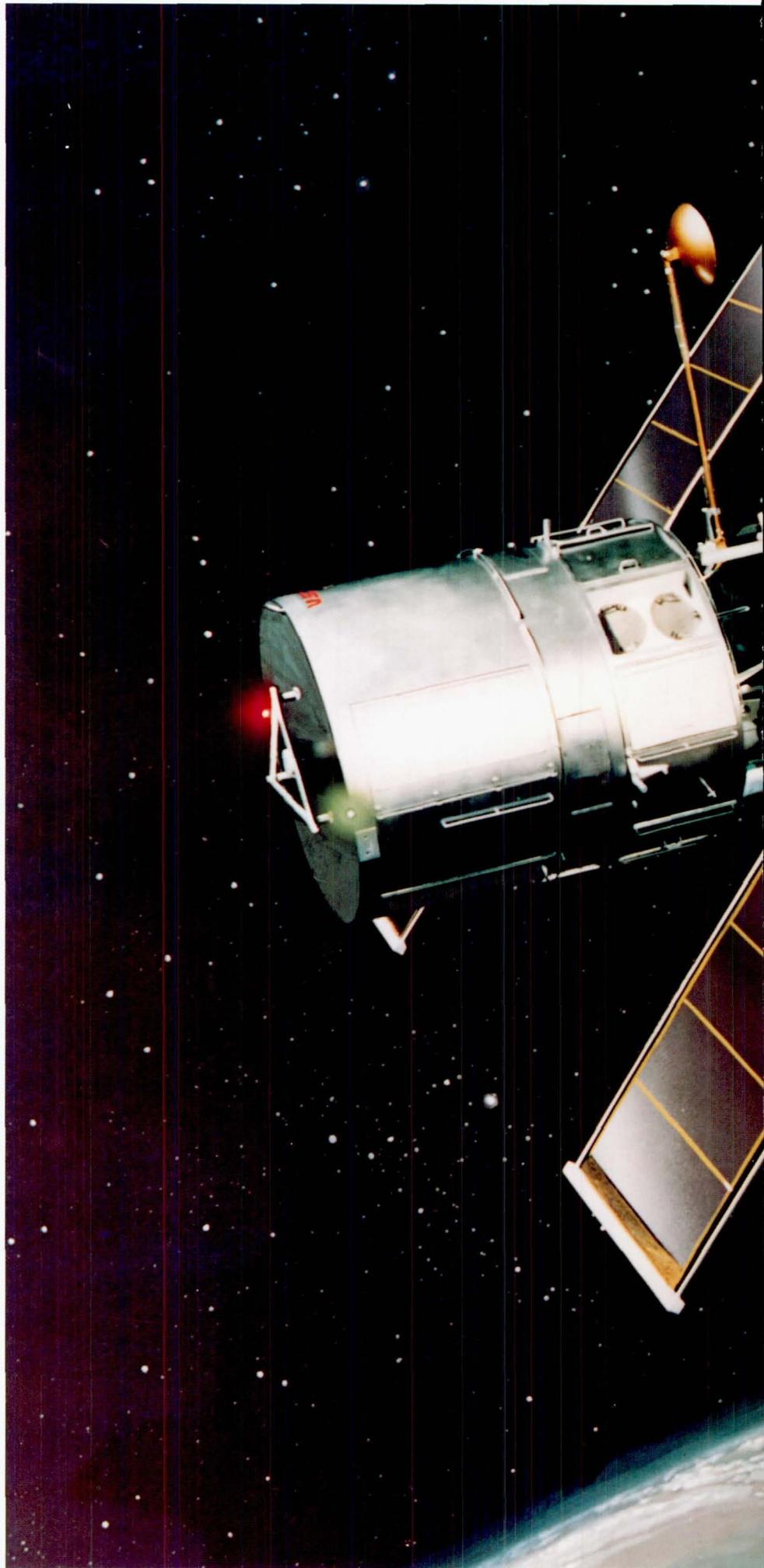
The Violence Around Us

The universe beyond the solar system has become almost unrecognizable since the Space Age began. It is no longer viewed as the peaceful stellar background that earlier astronomers envisioned; instead, it is a region filled with strange forces, turbulent clouds of dispersed matter, and unexplained floods of energy. How can we begin to comprehend it all?

First, we need to observe the universe from space over longer periods of time. Much of our knowledge comes from instruments lifted above our atmosphere, on rockets or satellites, for short periods of time, a few minutes, a few months and, in a few cases, a year or two. Each instrument has seen only a limited spectral range—ultra-violet or X-rays, for example—so that it has been difficult to observe different radiations from a single object at the same time. We have many fragmentary and exciting observations, but still no systematic view of the puzzling and awesome phenomena that have been discovered.

This knowledge gap will be partly filled in the mid-1980s, when we finally realize the age-old dream of astronomers to place a long-lived observatory outside the Earth's atmosphere, where it would command an unobstructed view of space. This project, the *Space Telescope*, is now

Looking toward the dawn of time. The Space Telescope, with a planned launch into Earth orbit in the mid-1980s, will give astronomers the most powerful view yet of the universe around us. Provided with a complement of advanced cameras, spectrographs, and other devices, it will see much further than ground-based telescopes and with far greater clarity, obtaining pictures of unprecedented sharpness and astrophysical measurements of unique sensitivity. Researchers can then observe distant galaxies as they appeared when light rays left them billions of years ago.





under way and scheduled for launch in the mid-1980s aboard the *Space Shuttle*. The spacecraft will carry a mighty telescope 2.4 meters (94 inches) in diameter, highly automated, and capable of seeing, not only in visible light, but in ultraviolet and eventually in infrared as well.

The launch of *Space Telescope* will be a major event in astronomical history, like the construction of the great Mount Wilson and Mount Palomar reflectors several decades ago. It will truly be a major observatory in space. Although the *Space Telescope* is only about half the size of the 200-inch (5-meter) Hale Telescope on Mount Palomar, it has no cloudy, wavering air to look through, and it will see five times as far into the universe as well as obtain images of unprecedented sharpness. With the *Space Telescope*, we can study many other galaxies almost as easily as we now study the stars of our own Milky Way. We will see more clearly the distant, energetic objects that puzzle us: quasars, active galaxies, and neutron star binary systems. Because we will see galaxies so much further away, we will view the universe as it was long ago, and we can begin to better comprehend how it has evolved. We will doubtless see

many strange new things that we cannot now imagine because we have never been able to see so far or so well before.

Space Telescope cannot do everything, however. It cannot detect all the radiations and energies that astronomers need to examine. Although it will be the heart of astronomical research during the 1980s and 1990s, other specialized space instruments are required to complement its work. Among these is IRAS (*Infrared Astronomy Satellite*), which is under development as a collaborative project by the United States, the Netherlands, and the United Kingdom. This is a smaller telescope that can detect infrared radiation of types that the *Space Telescope* cannot observe. IRAS will give us a view of the cooler regions of the universe, the dust clouds that are the birthplaces of the stars, and the core of our galaxy, where intense and unseen energies apparently are hidden behind a screen of dust.

The Space Age has shown us not only a universe of light and heat, but a universe of high-energy radiations—X-rays, gamma rays, and cosmic-ray particles—which come from violent and mysterious sources. To study this aspect of the universe, we need more

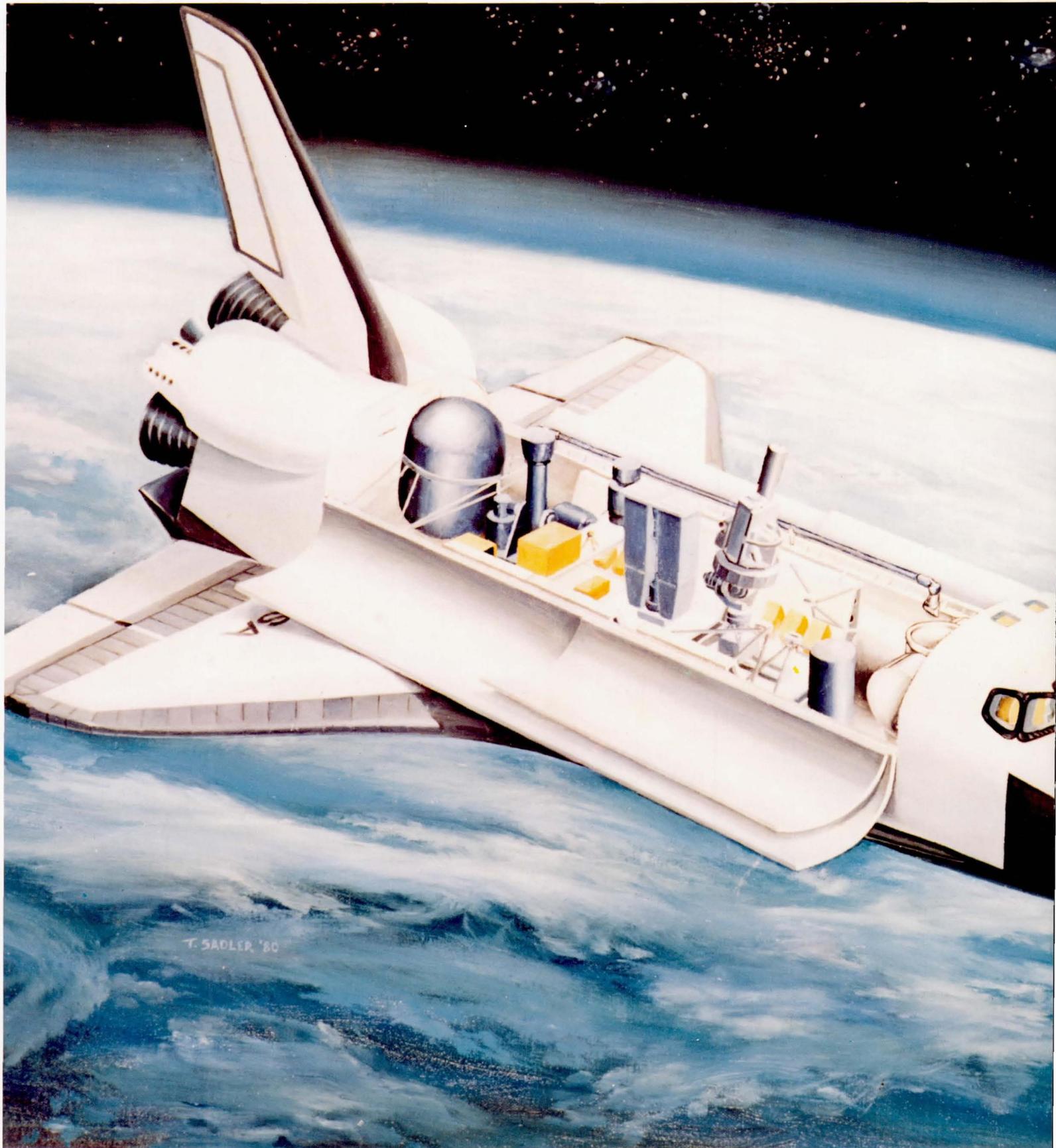
sensitive and capable instruments in space. No single instrument or spacecraft can record all of these radiations at once, so a series of projects is under consideration. Each would observe a part of the complex array of radiation; together they would give us a better view of the energetic side of the universe.

One project would focus entirely on the highest-energy radiations of all—gamma rays. An Earth-orbiting spacecraft (the *Gamma Ray Observatory*) will carry several detectors to look at gamma rays of all kinds and energies. It will detect and observe new gamma ray sources in the sky, investigate the gamma ray background radiation that comes toward Earth from all directions in space, and analyze the “bursters,” those mysterious powerfully erupting sources of intense gamma rays. During the few seconds of a typical gamma ray burst, its unknown source briefly outshines the whole universe in gamma rays.

Different instruments, carried by other spacecraft, could make detailed observations of the other powerful radiations from space. A wide variety of possible programs could be pursued. For example, an advanced system for detecting X-rays would

make a systematic study of the X-ray sky and its puzzling sources and explosions. Another spacecraft, carrying instruments to detect weak microwave and infrared radiation, would look even further out and much further back in time. It would look for radiation from the early expanding universe and would scan the sky for slight differences in the background that should give us clues to the details of exactly what happened shortly after the universe was born.

When such advanced instruments are finally placed in space, above the blanketing atmosphere in which we live, we will have made a major step forward in seeing the universe as it really is. We can then sense all of its energies, from the weakest microwave (radio) radiations to the strongest bursts of gamma rays. We will see faint and mysterious objects clearly, and we will be able to look steadily at objects that have only been seen in quick, snatched glances. We will then begin to accumulate the facts we need to answer the many questions about the universe, to plan future experiments and new missions, and to discover new mysteries and questions whose existence we do not now even suspect.



***A laboratory in space.** Spacelab, an orbiting laboratory facility provided by the European Space Agency and flown on NASA's Space Shuttle, will be instrumented with experiments designed by scientists from many different fields of space research. A few researchers, called payload specialists, may fly along with the astronaut crew, to conduct the experiments. Shown here is an artist's conception of Spacelab 2, which will conduct investigations planned by eleven U.S. scientific teams and by two groups in the United Kingdom. Fields of study include life sciences, astronomy, solar physics, plasma research, and liquid helium technology.*

Return of the Humans...

The 1960s were the first decade of Man in Space. The 1980s will be just as significant, but in a different way. The launch and operation of the *Space Shuttle* have begun a new kind of space travel. Large numbers of men and women, astronauts and scientists, will soon travel almost routinely into space, not to explore an unknown and possibly dangerous environment, but to observe, work, and live in space.

The *Space Shuttle* flights, lasting from one to four weeks, will provide time for long scientific and biomedical experiments that have not been possible since the *Skylab* flights of 1973-1974. In the natural or "shirtsleeve" environment inside the *Shuttle*, instruments can be operated, modified, and even repaired by scientists on the spot. Among other missions, the *Shuttle* will carry a complete scientific laboratory called *Spacelab* into space. Chemical and materials-processing experiments will be done to investigate suitable applications of the weightless ("zero G") environment.

A major advantage of the *Space Shuttle* is that it makes possible more detailed biomedical experiments on the human ability to adapt and function in space. These studies are especially important for the future, because they will provide the information we need to plan longer missions for humans in space.

Looking beyond the *Space Shuttle*, there is much to be done before astronauts can set out for Mars, before we can staff permanent space stations or build bases on the Moon. We must first discover whether people truly can live in space for long periods of time. What are the psychological effects of weightlessness? Can calcium loss from bones in space be controlled or reversed? What are the long-term effects of space radiations

on human beings? Can humans readjust to Earth's gravity after long periods spent in space? Some of the answers can be found in studies on Earth. For most of them, however, we need the experience that flights of the *Space Shuttle* will provide.

If humans are to live in space on a permanent basis, we must then design the systems that they will need. Our spacecraft systems to date—*Gemini*, *Apollo*, even the *Space Shuttle*—have all carried the full complement of supplies needed for their short missions, enough to allow for the consumption of food and the gradual exhaustion of oxygen. These systems are both wasteful and inadequate for long missions. For longer trips, we need to design life-support systems that will recycle water and oxygen over long periods of time. We also need to develop ways of producing food in space, whether from plants, from small animal farms, or even from the products of our own metabolism. We do not need these systems to operate the *Space Shuttle*, but we will need the experience from *Space Shuttle* to develop the systems for future use.

Because we have been so successful in going into space, serious consideration is now given to ideas that, not long ago, were found only in science fiction. Current scientific workshops and political debates focus on such possibilities as mining the Moon, building space-based solar power stations, even establishing sizable populations in space. We do not know yet if these things are possible. In the next few years, research, both on the ground and in space, should provide the answer to whether humans can be permanent residents of space and should illuminate the prospects for what can be accomplished there.



...*And Others?*

The discovery of extraterrestrial life, whether intelligent or not, remains for the future. The negative results from the Moon and the ambiguous results from Mars give no indication that we have company in the solar system, but the intense interest in this subject leads us to explore other possible habitats for life: Jupiter, Saturn's moon Titan, and certain as yet unexplored regions of Mars. Spacecraft observations or the return of samples to Earth may yield definite answers, even if they are negative.

Regardless of whether the solar system outside the Earth proves inhospitable and lifeless, there are billions of stars beyond it. Here we must deal both with speculation and with probabilities. A certain percentage of the stars are like the Sun, a fraction of *those* suns may have planets, a percentage of *those* planets may have life, on a percentage of *those* planets life may have evolved to the intelligent state, a percentage of *those* planets with intelligent beings may be the sites of technical civilizations. . . . The odds against each individual step may be tremendous, but there are so many billions upon billions of stars in our galaxy and so many galaxies in the universe that the odds in favor of life— even intelligent life— somewhere else in space seem overwhelming. Just

as the radio and television signals broadcast on Earth a few years ago now are spreading out past the stars in our own neighborhood, so might signals from other life-forms be passing us at this very moment.

The stars are far away, and we can't go to them to look for life, not for awhile anyway. Even so there are methods that we can adopt on Earth, at modest cost, to look for life elsewhere in the universe. One thing we can do is look for planets around the nearer stars, to check our theory that the solar system is not unique, to verify at least one link in the chain of logic which suggests that intelligent life must be common in the universe.

We may not be able to see planets around the nearest stars, even with the *Space Telescope*. Planets are too small and dim, and the nearest stars are still too far. But we can detect other planets—possibly even from the ground—by making careful measurements of the motions of nearby stars. Planets orbiting around a star would cause tiny wiggles in its motion across the sky. With high-precision observations, we perhaps can determine that a star has planets, even though we could not see them. Proof that the solar system is not unique would be a major scientific discovery in any case. It would also be an impor-

Listening to the stars. Radio telescopes in NASA's Deep Space Network regularly track interplanetary spacecraft. With minor modifications, some day they could also be used to search for signals from intelligent beings on the planets of distant stars.



tant step toward the eventual discovery of life elsewhere.

Another way to discover extraterrestrial life is simpler: sit back and listen. The huge and highly developed radio telescopes now operating on Earth can be equipped to detect artificial signals amid the cacophony of natural radio sources in the sky. (Suitably instrumented antennas many light years away could likewise pick up and recognize the radio and video signals now escaping into space from the Earth.)

A few limited attempts to detect communications from other civilizations have already been made. We can begin now to listen more sensitively and systematically for such signals from other civilizations, and we could detect them whether they were addressed to us or not. Some ideas for doing this have already been developed, and most of the necessary equipment is already in place. With a modest investment for improvements in existing radio telescopes, and some shrewd guesses about where and how to listen, a systematic search for other life could be started now. The "First Contact," about which so many science fiction stories have been written, may yet come in our own lifetime, if we take the trouble to listen.

Space Science on the Ground

The future exploration of space will need more than spacecraft and astronauts. Much research and study can, and must, be done on the ground if we are to go further. Ground-based studies and observations provide the data needed to plan space missions, to support the missions while they are in progress, and to make detailed analyses of the data that spacecraft gather. In many cases, ground-based observations are our only source of data about things that spacecraft cannot yet explore: the outermost planets, celestial radio sources, and some aspects of very unusual and distant objects in the universe.

Ground-based astronomy will not die out in the *Space Telescope* era. There are still many aspects of astronomical research that cannot be accommodated by observatories free of the Earth's atmosphere. Our present radio telescopes are much larger and better equipped for many kinds of observations than anything we can send into space. They not only can listen for the natural and artificial (if any) sources in the radio sky, but they also can transmit radio waves from Earth, to bounce off distant moons, asteroids, and planets, and even the Sun itself. Such measurements can yield hard information on the surface structure and gross physical properties of large asteroids, well before we can hope to explore them with a spacecraft. Optical and infrared telescopes are needed to carry out sur-

veys, to analyze new problems, and to conduct cooperative observations in support of X-ray telescopes and other space instruments.

The collections of extraterrestrial material that we now have—moon rocks, meteorites, and cosmic dust—are still important sources of new data on problems that no spacecraft or telescope currently can properly attack: the physical and chemical nature of asteroids, the early history of planets, the past history of the Sun, and the nature of the solid materials in comets. Even past missions still have much to contribute. The data from our recent *Pioneers*, *Vikings*, and *Voyagers*, which arrived in such floods, are still being studied, sifted, and compared. The continuing analysis of these data is providing further information on the worlds that the missions explored, as well as insight for planning more extensive return visits.

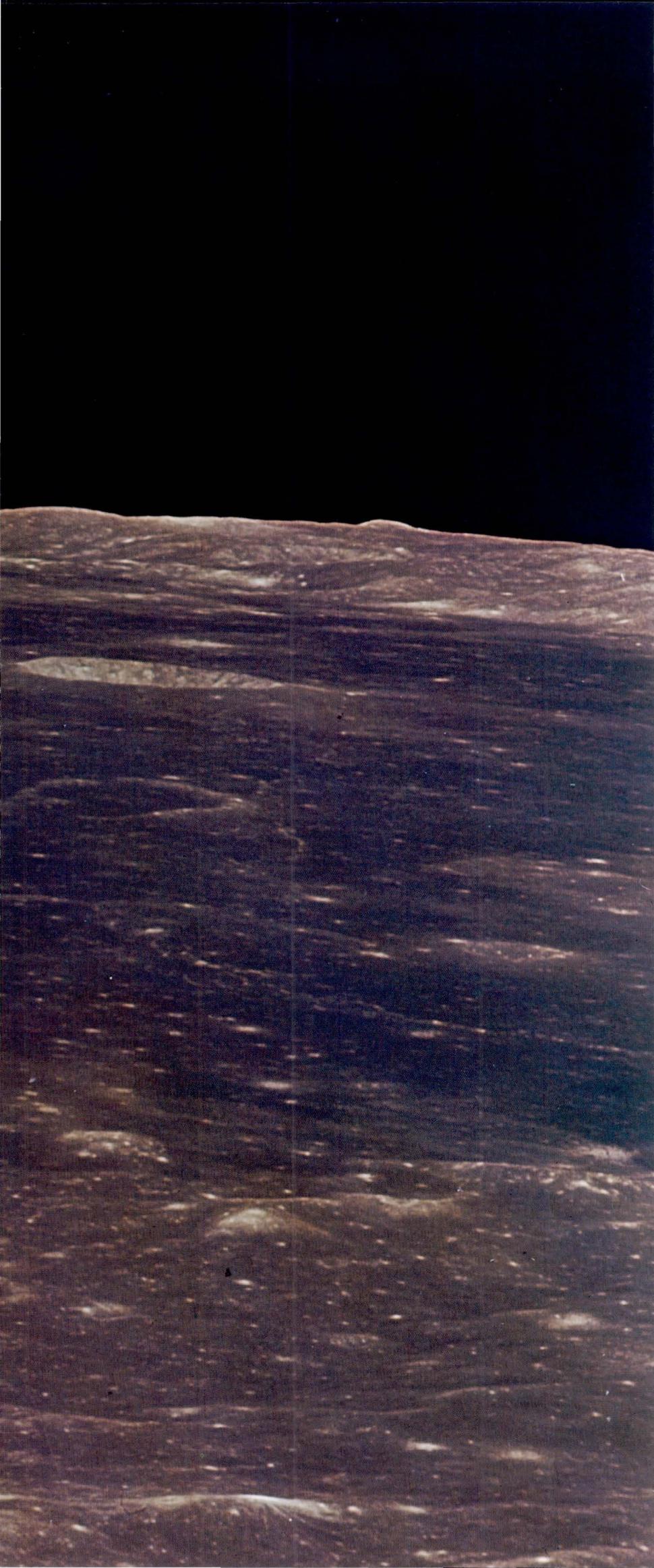
Ground-based scientific studies are the foundation on which all of our explorations of the universe from space have been built. This work is still essential in planning and carrying out future explorations. Just as a spacecraft should not be flown from a poorly constructed and badly maintained launch pad, so our future studies of the universe will necessitate that our ground-based facilities and research capabilities be maintained.

The View Ahead

From our new vantage point, the universe awaits us, still holding the answers to unexplored questions. What are the mechanisms that sustain the tremendous energy sources that we have found in space? What is the surface of Venus like, and why is it apparently so different from those of the other terrestrial planets? How will the Sun affect our weather and climate in the future? What are we doing to our own atmosphere, and what are the consequences? Is there life on Mars? Or elsewhere? Can people live and work permanently in space?

Finding the answers to these questions depends on us. We see no technical barriers to going further into space or to living there. How we proceed depends on our purpose, our will, and on economic, political, and cultural factors that are beyond scientific calculation. The lesson of space explorations so far is simple: *We can go on if we want to.* The future is in our hands.





APPENDIX

This appendix summarizes some significant developments in the fields of space science that are discussed in the preceding chapters of the book. In order to put the findings in the appropriate scientific and historical contexts, certain discoveries not stemming from the Space Program are also included. Due to the abbreviated form of the appendix entries, the technical level is higher than that of the main text.

From our new foothold in space, we look back at ourselves.

Lunar Exploration



Today's Moon: a view from Apollo 17.

First spacecraft impact on the Moon:
Luna 1 (USSR), 1959.

Discovery that the lunar farside consists almost entirely of highland regions, with no maria (large dark basins): *Luna 3*, 1959.

Investigation of the details of the lunar surface by the U.S. *Ranger 7, 8, and 9* spacecraft in 1964-1965 revealed a gently rolling terrain with no sharp relief; there is a layer of powdery rubble, with rocks and craters down to at least one meter in diameter everywhere.

Luna 9 and *Surveyor 1* landed on the moon in 1966, found that the surface is firm and capable of supporting machines and astronauts.

Surveyor 5, in 1967, found that the surface chemical composition of the maria resembles that of terrestrial basalt lava.

Surveyor 7, in 1968, found that the highlands composition differs from that of the maria and is aluminum-rich.

Rock hunting on the Moon.



Data from five *Lunar Orbiters* showed in 1968 that mascons or concentrations of excess mass exist under circular maria. This showed that the lunar crust must be sufficiently cool and strong to support the extra mass.

The manned *Apollo* missions to the Moon from 1969 to 1972 succeeded in collecting and returning rock and soil samples, emplacing instruments, including sensors for long-term measurements, and performing remote sensing from lunar orbit. From 1969 to the present time, the samples and data have been the subject of numerous scientific studies on Earth.

Nature and History of the Moon

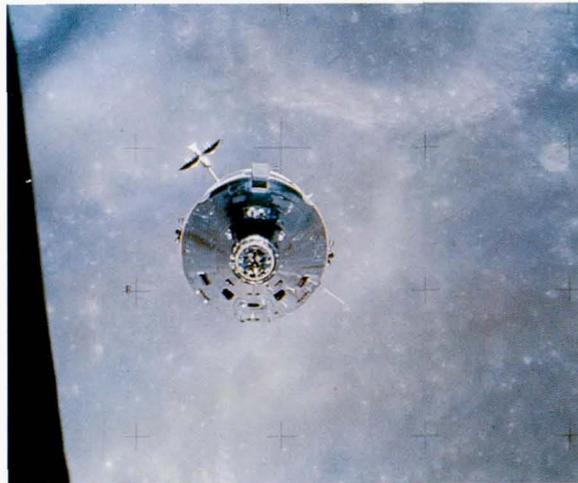
The Moon was found to be a complex, evolved planet, with three basic rock types: (1) volcanic lavas in the maria; (2) aluminum-rich rocks in the highlands; (3) unusual rocks (called KREEP basalts) that are enriched in silica and radioactive elements.

Evidence was found relating to the early history of planetary development (4.6 billion to 3.0 billion years ago): extensive primordial melting, catastrophic meteorite impacts, and major volcanic eruptions. The Moon was formed 4.6 billion years ago, along with the Earth and the rest of the solar system.

It appears that the lunar surface has been basically quiet and unchanging over the past 3 billion years.

No life, past or present, was found on the Moon.

The lunar surface material, or "soil," is a layer of powdery rubble, 10 to 100 meters (about 33 to 330 feet) deep, formed by meteorite impacts over billions of years.



Apollo 16 command module in orbit above the Moon.

The lunar surface composition is fairly uniform over large areas, judged from the 20 percent of the Moon that has been analyzed from orbit. There is a basic division between iron- and magnesium-rich lavas in the maria and calcium- and aluminum-rich rocks in the highlands.

The Rocks

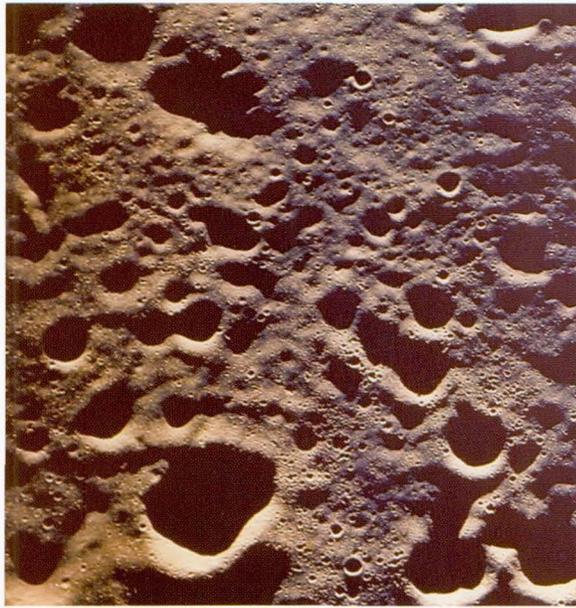
All of the lunar rocks are igneous (formed by cooling from molten lava) or derived from igneous rocks. There are no sedimentary (derived from water-deposited sediments) rocks.

The rocks are very fresh and chemically unaltered, due to the lack of water.

The rocks are generally like those of Earth in chemistry and minerals, but are deficient in volatile elements such as hydrogen, sodium, and potassium.

Three new minerals, never found on Earth, were discovered in the Moon rocks: tranquillityite, armalcolite, and pyroxferroite.

The Moon rocks range in age from 3.0 billion to 4.6 billion years; the older ones thus are older than any remaining rocks on Earth.



A dead, cratered Moon, seen by Apollo 8.

The Lunar Interior

The Moon was found to be slightly egg-shaped, with the small end pointing toward Earth.

The interior of the Moon consists of a crust, a mantle, and perhaps a core. The possible core may be metallic.

The thick, rigid, outer portion of the Moon, the *lithosphere*, was found to lack the plate tectonic motions that occur on Earth.

It was found that the Moon is not seismically active. There are weak, infrequent quakes, some triggered by tidal forces.

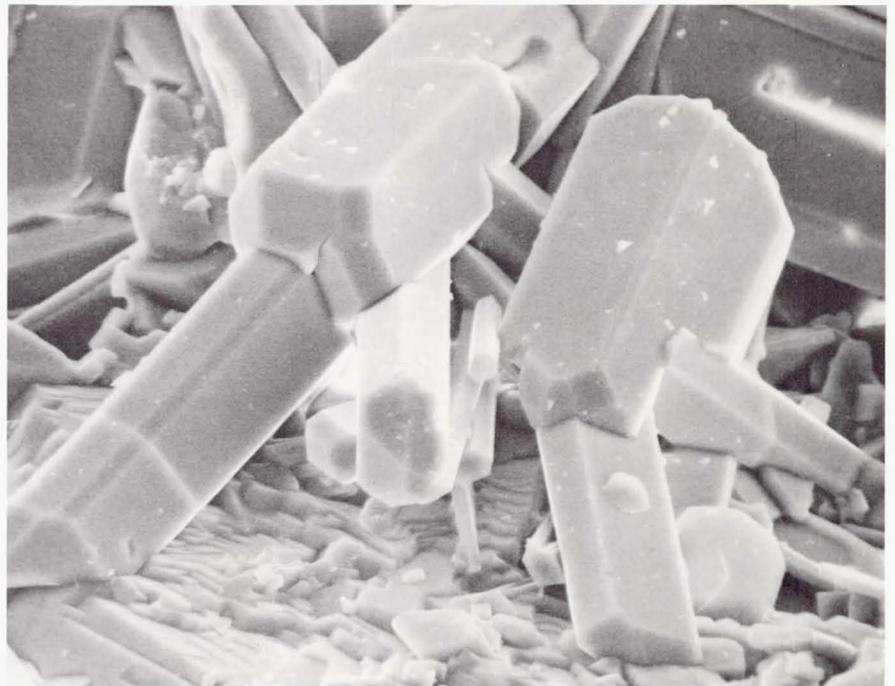
Fossil magnetism was found in lunar rocks, although the Moon has no magnetic field. The source of the fossil magnetism is still unexplained.

A large magnetic anomaly was found on the lunar farside, near the crater Van de Graff.

There is some outgassing underway from the lunar interior, as shown by the detection of radon from lunar orbit.



The huge lunar crater Langrenus, photographed in stereo by Apollo 8.



Tiny crystals line a crack in a lunar rock.

Solar History and Space Environment Discoveries

Bombardment by cosmic dust (which produces microcraters on the lunar rocks) seems to have occurred at a constant rate over the last few million years.

Rocks have remained exposed on the lunar surface for periods as long as 500 million years without being destroyed.

Specific impact craters on the Moon have been dated: Copernicus was formed 900 million years ago; Tycho, 100 million years ago; smaller craters at the *Apollo* landing sites, 2 million to 50 million years ago.

The solar wind striking the Moon was found to have a higher hydrogen/helium ratio than the Sun itself.

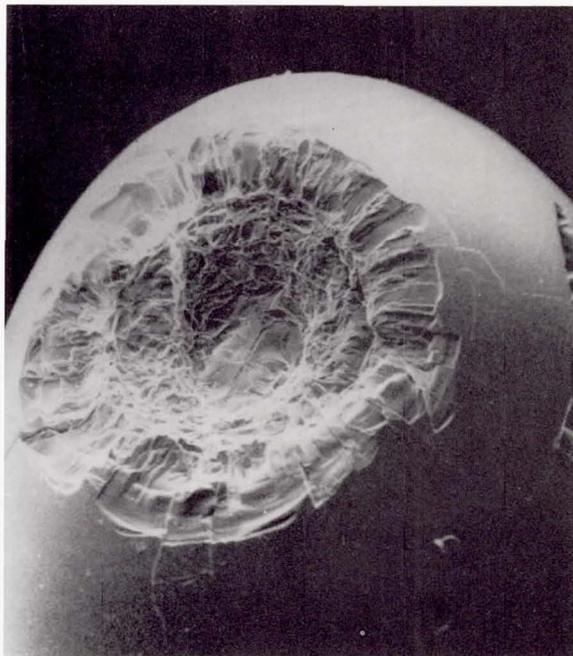
Lunar soil analyses show that major variations in the amount and isotopic composition of solar wind nitrogen have occurred during the past 2.5 billion years.

There do not appear to have been major changes in the intensity of solar flares and the composition of particles erupted from them over the past 100,000 years.

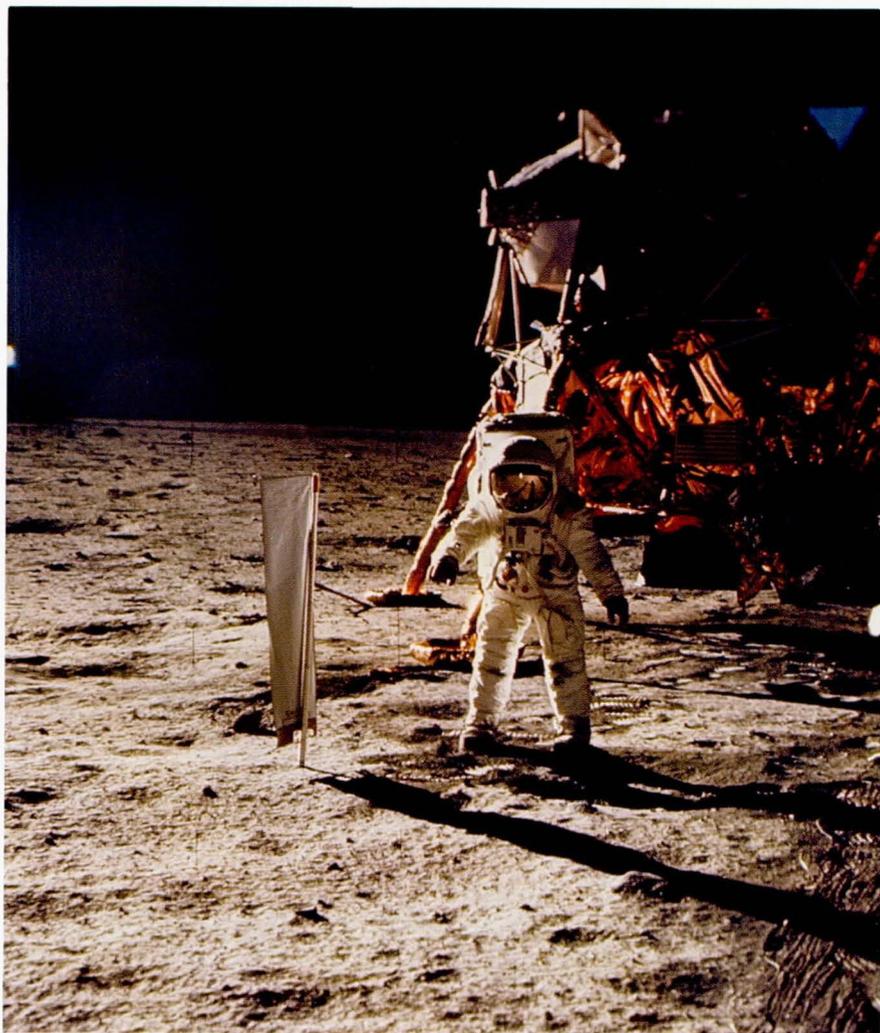
Study of the *Surveyor 3* television camera lens, which was retrieved from the Moon by the *Apollo 12* crew, revealed that there is a higher iron/hydrogen ratio in solar flare particles than in the Sun as a whole.

The flux of galactic cosmic rays has apparently been constant on the Moon over the past 1 billion years.

Capturing the Sun: an aluminum panel ("the windowshade") traps atomic particles from the Sun during the Apollo 11 mission.



Tiny microcrater, made when a particle of cosmic dust struck a small bead of lunar glass on the Moon's surface.



Planetary Exploration

Mercury

Ground-based radar measurements determined (1965) that the rotation period is 59 days, not 88 days as had long been believed.

Mariner 10 made the first spacecraft flyby of Mercury in 1974 (in fact, it flew past Mercury three times), and obtained several thousand photographs.

Among the results of the *Mariner 10* investigations were the following:

- The mass of Mercury was accurately determined.
- Any residual atmosphere has less than a million-billionths the pressure of the Earth's atmosphere at sea level. However, a trace of helium, perhaps

derived by outgassing from Mercury's interior, was found.

- It was discovered that Mercury has an internal magnetic field, similar to but weaker than that of Earth.
- Mercury's surface is heavily cratered and resembles that of the Moon.
- A huge circular impact basin (Mare Caloris), about 1300 kilometers (810 miles) in diameter, was discovered.
- A planetary feature unique to Mercury was found, consisting of long scarps, or cliffs, that apparently were produced by compression in a major shrinkage of the planet.
- Flat plains, perhaps lava flows, were found.
- Mercury was found to be closer to a perfect sphere than is the Earth.



The surface of Mercury: ancient craters and a strange trench.

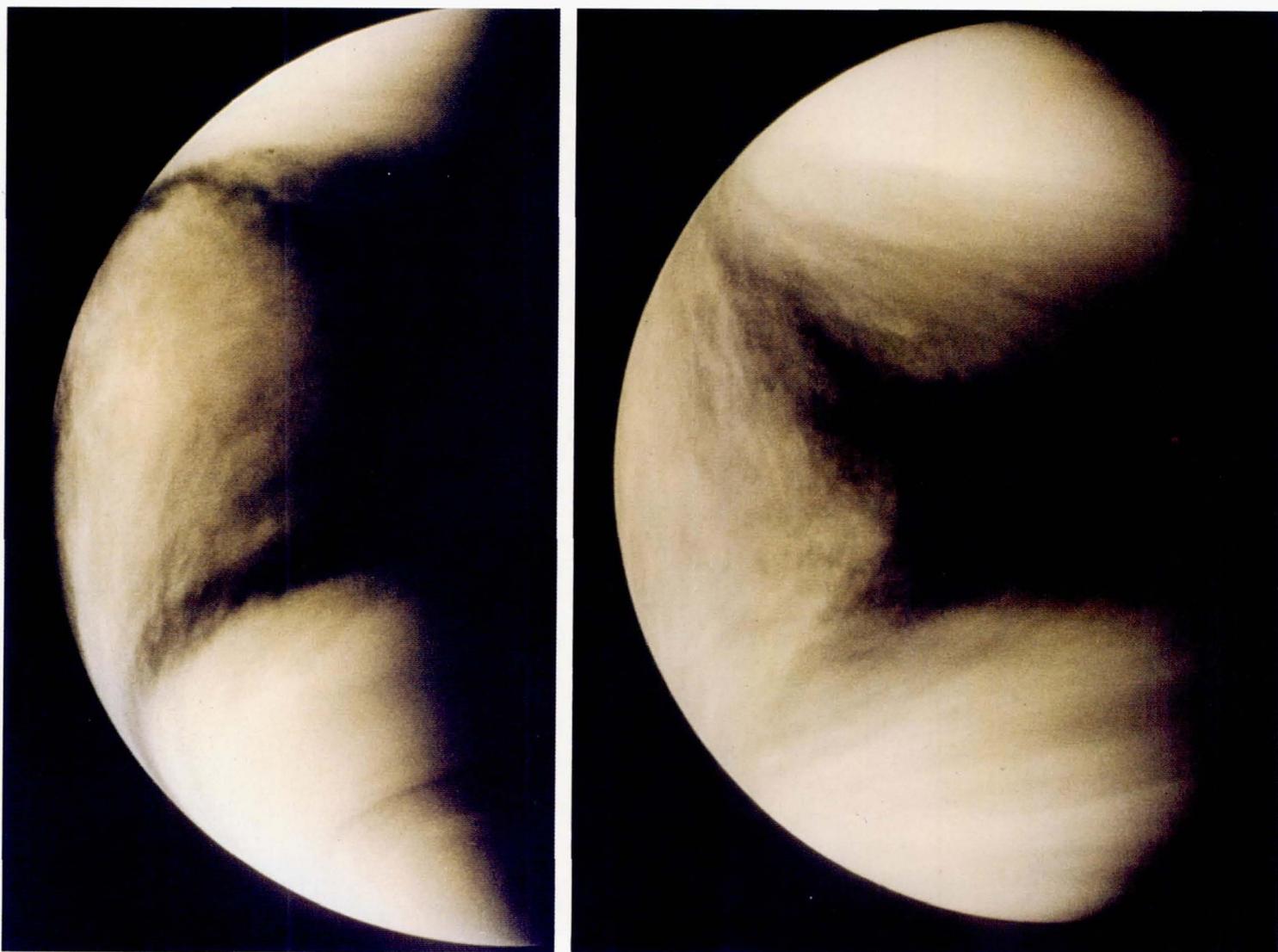
Venus

Ground-based radar measurements in the early and mid-1960s showed that the rotation period of Venus is about 240 days and that the rotation is retrograde, so that it spins in the opposite sense with respect to the Earth.

The 1962 flyby of Venus by *Mariner 2* led to an accurate determination of the planet's mass. This spacecraft, and ground-based observations, also measured high temperatures, around 300° C, in the atmosphere of Venus.

Ground-based observations detected various minor components of the Venus atmosphere, including the gases hydrochloric and hydrofluoric acid (1967), carbon monoxide (1968), water (1972), and sulfuric acid (1978). In 1973, it was found that the upper cloud layer is composed of sulfuric acid droplets.

From the USSR's *Venera 7* in 1970, it was found that the atmosphere is largely carbon dioxide, with a pressure at the planetary surface about



The changing swirls of Venus' thick atmosphere, recorded day by day by the Pioneer Venus spacecraft.

100 times that of the Earth's atmosphere. *Venera 7* also measured a surface temperature of about 500° C.

Mariner 10 flew past Venus in 1974. Among the results were:

- Venus has no significant magnetic field.
- A notable disturbance in the solar wind is produced as it flows past Venus.
- Venus is closer to a perfect sphere than the Earth.
- Ultraviolet images of the atmosphere revealed streamline and circulation patterns, including Y- and C-shaped structures.
- The upper atmosphere was found to rotate much more rapidly (once in about 4 Earth days) than Venus itself, a result also suggested by ground-based measurements.
- Hydrogen and helium were detected in the atmosphere.

In 1975, the *Venera 9* and *10* lander spacecraft found that the surface of the planet is firm and rocky. Their other results included:

- The measured surface winds had velocities of about 3 to 13 kilometers per hour (2 to 8 miles per hour).
- A significant amount of sunlight reaches the surface.
- The surface rocks vary in radioactivity and have compositions resembling those of granite and basalt.

The 1978 *Pioneer Venus* mission included both atmospheric probes and an orbiting spacecraft. Among the results were:

- The atmosphere was found to circulate in large planetwide systems, much simpler than the circulation patterns on the Earth.
- A collar of polar clouds was discovered, which may be part of a large atmospheric circulation vortex.

- At least four distinct cloud and haze layers were found at different altitudes.
- The haze layers contain small aerosol particles, perhaps sulfuric acid droplets.
- Accurate measurements of the atmospheric composition showed that it was about 96 percent carbon dioxide, 4 percent nitrogen, with small amounts of water, oxygen, and sulfur compounds. Rare gases such as argon and neon detected in the atmosphere suggest that Venus is richer in volatile elements than the Earth or Mars.
- The surface of Venus was found to be generally smooth, much less irregular than that of the Earth.
- Radar measurements from the *Pioneer Venus Orbiter* and from ground-based observatories revealed the presence of two broad plateaus as well as apparent volcanic structures, craters, and canyons.

Lightning and thunder are present on Venus, according to results from the *Venera 11* and *12* landers in 1978.

Mars

Ground-based observations detected water vapor on Mars in 1964.

Mariner 4 flew past Mars in 1965 and photographed a heavily cratered, moonlike surface.

Mariner 4 found that the Martian atmosphere is thin, with less than 1 percent the pressure of the Earth's atmosphere, and is composed largely of carbon dioxide.

The *Mariner 6* and *7* flybys took place in 1969. Instruments on these spacecraft found that nitrogen is virtually absent from the atmosphere and that solid carbon dioxide ("dry ice") occurs in the clouds and near the polar caps.

Mariner 6 and *7* found that the dust particles in the Martian atmosphere probably consist of silicate materials derived from the planetary surface.

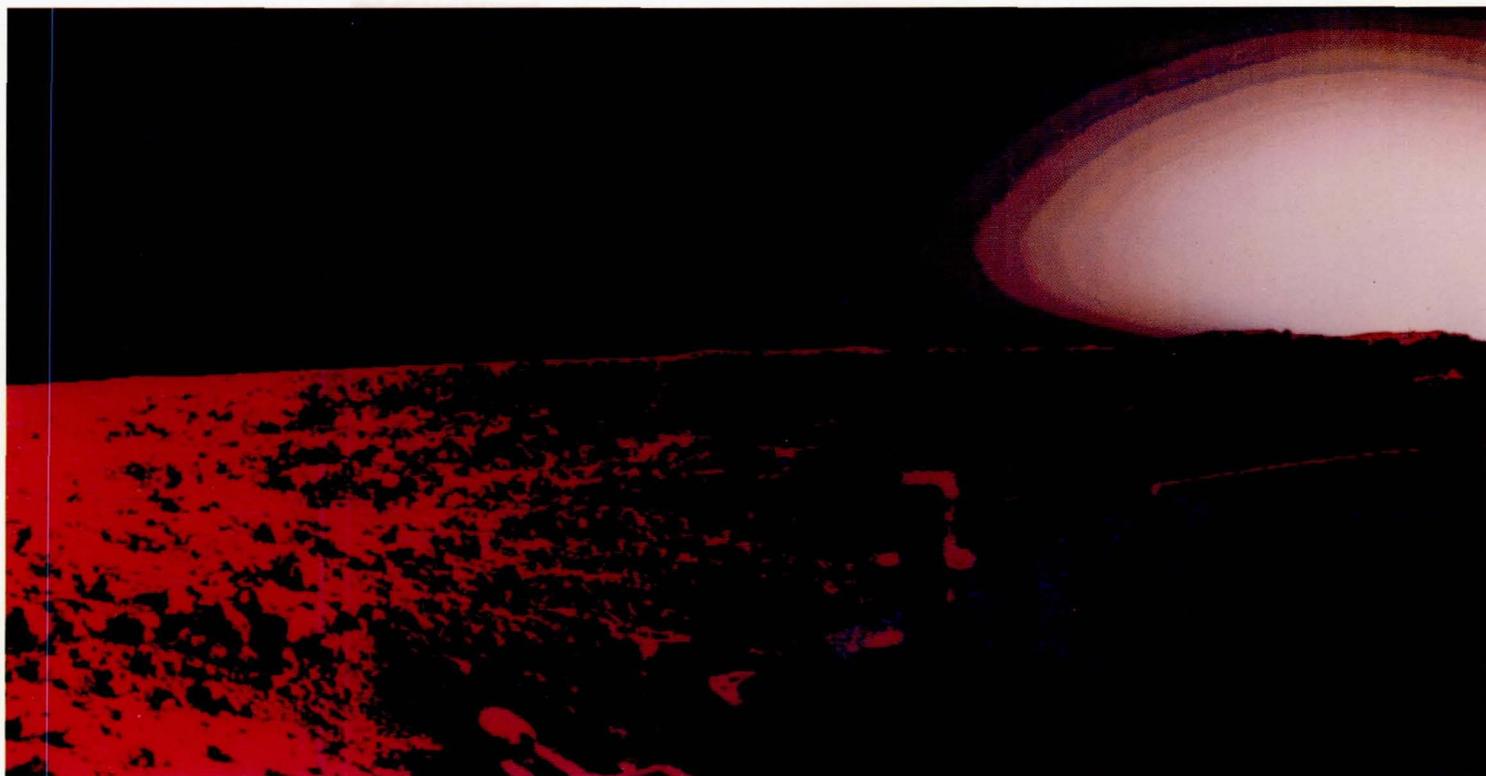
The first soft landing on Mars was executed by the USSR *Mars 3* spacecraft in 1971; the spacecraft ceased operating 20 seconds after the landing.

Mariner 9 became the first Mars-orbiting spacecraft in 1971. It obtained over 7300 photographs. Among the results of this mission were:

- Mars is actually a two-part world, with an ancient cratered surface in the Southern Hemisphere and a geologically younger surface, with volcanoes, canyons, and dry river channels, in the Northern Hemisphere.
- The Martian volcanoes include a few huge ones, rising to heights of as much as 25 kilometers (16 miles), with fresh-looking lava flows.
- Mars has a huge valley (Vallis Marineris), about 5000 kilometers (over 3000 miles) long.
- Sinuous channels, with braided and streamlined formations, appear to be former river beds.



Landfall on Mars: the Viking 1 spacecraft approaches the Red Planet.

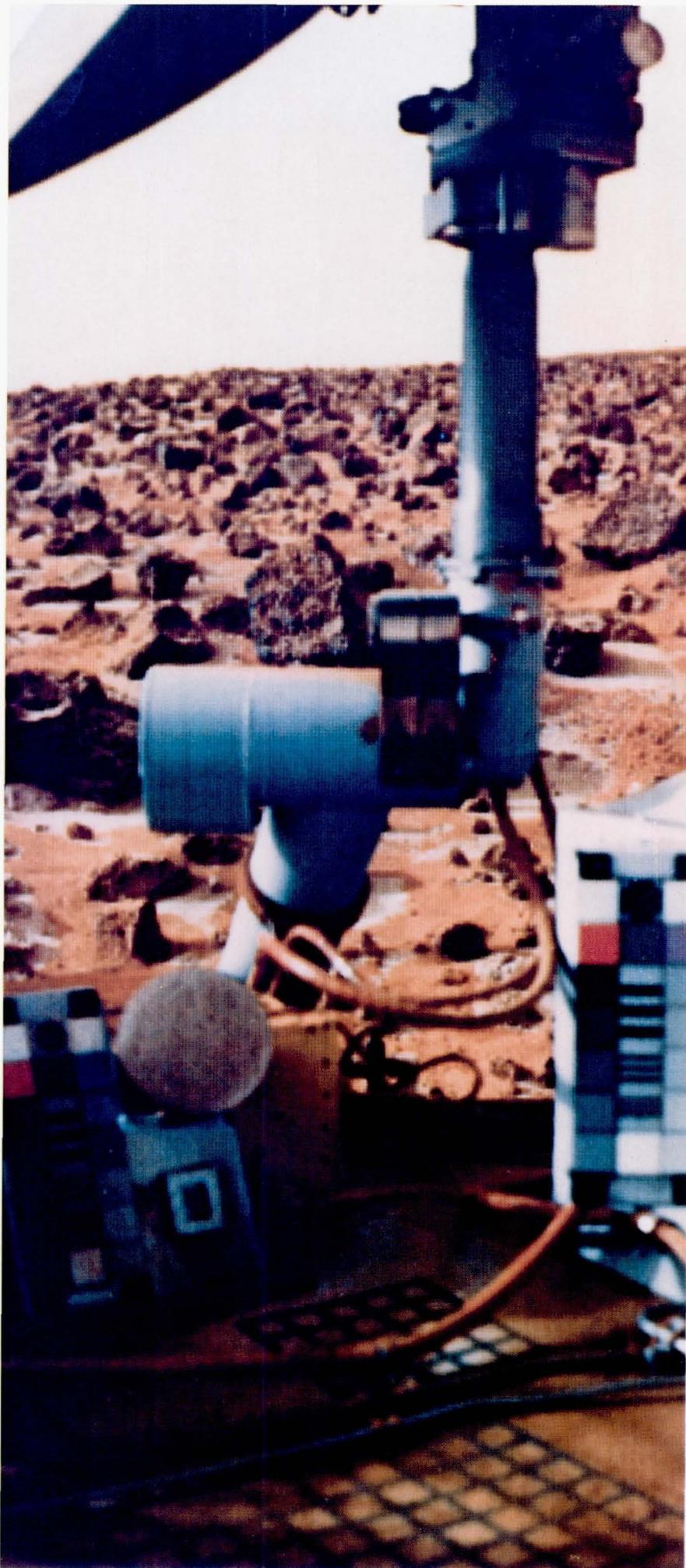


Martian sunset: the Viking 1 lander records the last fading light on the red surface of Mars.

- Landforms resembling lava flows occur in flat regions.
- There are layered deposits in the Martian polar regions, perhaps indicating glacial periods in past times.
- Solar ultraviolet light is not absorbed by the atmosphere and hence reaches the surface of Mars.
- Periodic global dust storms were observed in detail.
- The two small moons of Mars were photographed and found to be very dark and to have irregular shapes and cratered surfaces.
- The soil is fine-grained and cohesive, like firm sand or soil on Earth.
- The surface rocks resemble basalt lava, and the soil chemistry is like that of weathered, altered basalt.
- There are water and sulfur compounds in the soil.
- The sky is not blue but pink, its color caused by fine suspended particles of red dust.
- The polar caps are largely made of water ice.
- The winds at the surface of Mars are light, about 24 kilometers per hour (15 miles per hour).
- The surface temperature ranges from about -84°C (-120°F) at night to -29°C (-20°F) in the afternoon.
- Fog and clouds occur despite the fact that the water content of the atmosphere is less than 0.1 percent that of the air on Earth.
- The surface pressure of the atmosphere, only about 0.8 percent that of

The *Viking 1* and *2* landers and orbiters reached Mars in 1976. Among their many findings were:

- The highly oxidized soil produced unique chemical reactions in the life-detection instruments (see Appendix section on Exobiology).
- The reddish color of the soil is due to oxidized iron.



the Earth's atmosphere, varies seasonally in accord with the evaporation of the polar caps.

- The isotopic ratios of carbon and oxygen in the Martian atmosphere resemble those of the Earth's atmosphere.
- The atmosphere has been modified over time by the escape of nitrogen to space; this has produced nitrogen isotopic ratios that differ from those on Earth.
- Mars may have had a much denser atmosphere in the past, and could have had liquid water on its surface.
- The abundances of rare gases such as argon and neon suggest that Mars has a lower volatile content than either the Earth or Venus.
- The Martian moons are grooved, indicating that fracturing may have occurred; they may be asteroids that were captured by Mars.

The Viking 2 lander, surrounded by a crowd of Martian rocks.

Jupiter

The Planet

According to a theory formulated in 1958, the interior of Jupiter includes a large core of metallic hydrogen.

Pioneer 10, in 1973, and *Pioneer 11*, in 1974, made the first flybys of Jupiter; both spacecraft survived passage through the asteroid belt and through the Jovian trapped radiation. Among the findings from these spacecraft were:

- Aside from its polar flattening, Jupiter is very symmetrical and has no gravitational anomalies; it behaves like a liquid planet.
- Jupiter is slightly more massive than had been indicated from ground-based observations.
- As suggested from ground-based measurements, Jupiter emits twice as much energy as it receives from the Sun.
- The temperature at the center of the planet may be 30,000° C.

The Atmosphere

From ground-based studies, it was deduced that the atmosphere of Jupiter must consist mostly of hydrogen and helium, in an approximately 2 to 1 ratio. The bright bands in the atmosphere ("zones") are cooler than the dark ones ("belts").

A theory proposed in 1958 interprets the great Red Spot as the top of a rotating column in the atmosphere.

Among the results of the *Pioneer 10* and *11* missions were:

- The general banded structure of the Jovian atmosphere is not present near the poles; there, oval circulation patterns develop.

- At the poles, a thick, aerosol-free, or "blue sky", atmosphere was found.
- The bright zones consist of rising cloud masses at higher altitudes, while the belts are descending masses that allow a deeper view into the atmosphere.

- Two cloud layers are present; the thick, low cloud deck is topped by a thinner, clearer region.

- Detailed study showed rapid motions among the clouds and changes in the wind speeds.

- Bright plumes of warm material were observed rising from deep in the atmosphere.

- Changes in the flow patterns of the Red Spot were observed between 1973 and 1974; the Red Spot and other features were interpreted as hurricane-like storms.

- Helium was detected, confirming the earlier deduction of the Jovian atmospheric composition.

Voyager 1 and *Voyager 2* flew past Jupiter and its moons in 1979; among the findings from this pair of spacecraft were:

- Eruptions of warmer material from below are signalled by brightenings followed by cloud spreading.

- Along the boundaries of the belts and zones, there occur atmospheric jet streams, plumes, and extensive turbulence.

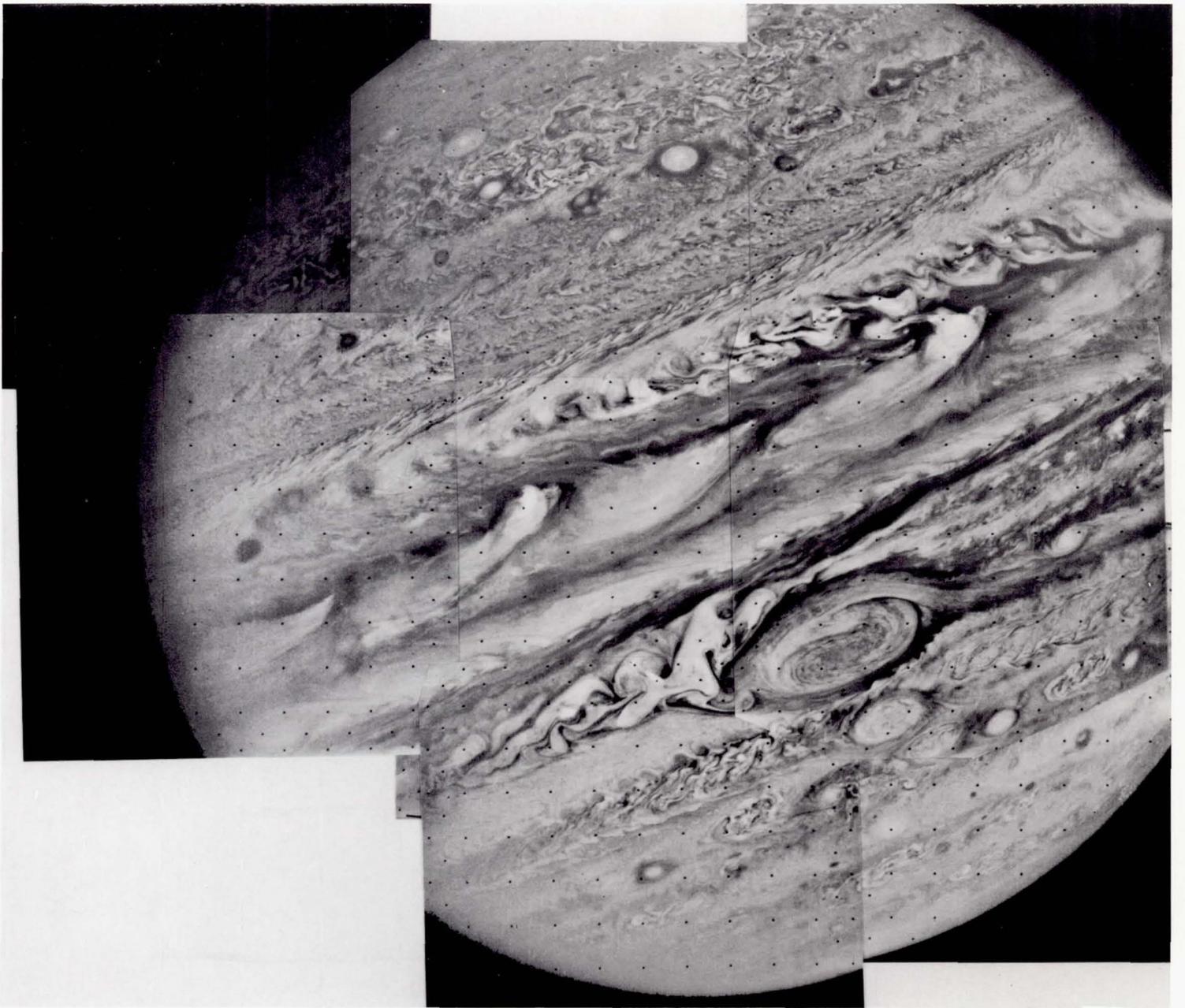
- There is actual mass movement, rather than simply wave motions, in the Jovian atmosphere.

- An east-west wind structure is present in the polar regions.

- The Red Spot rotates counterclockwise in about 6 days, as estimated from ground-based observations.

- The fraction of helium by volume in the Jovian atmosphere is 0.11.

- Aurorae were discovered in the polar regions and are related to the magnetic field lines and currents between Jupiter and its moons.



Swirls and storms in Jupiter's atmosphere, recorded by Voyager 1.



Stormy weather around Jupiter's great Red Spot.

Jupiter's moon Io, with a large active volcano.

- Lightning “superbolts” were detected in the cloud tops.
- There is intense ultraviolet emission from the atmosphere.

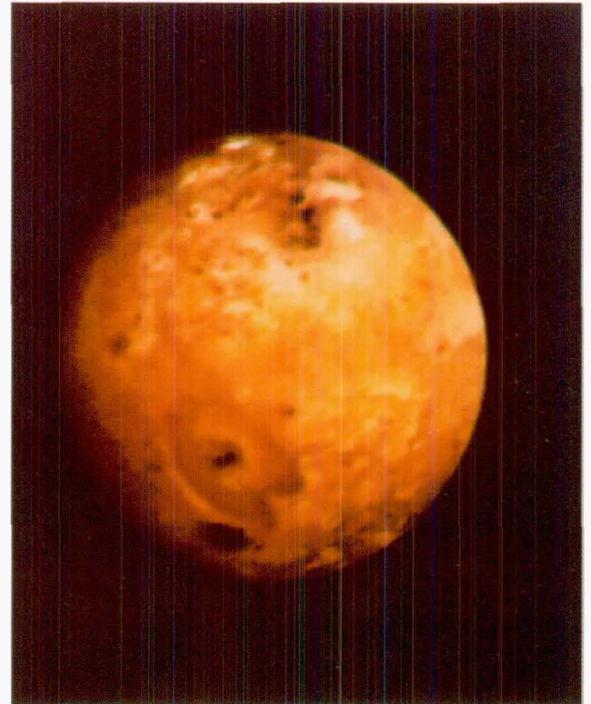
Minor components of the Jovian atmosphere that have been detected at various times include deuterium (heavy hydrogen) compounds; organic molecules such as ethane and acetylene; water vapor (found using the Kuiper Airborne Observatory in 1975); carbon monoxide; phosphine (PH_3); and germane (GeH_4).

The Magnetic Field and Trapped Radiation of Jupiter

The discovery of naturally generated radio bursts from Jupiter was accomplished with a ground-based radio telescope in 1955. Theory indicated that a strong magnetic field must be present in order to account for the bursts, and additional radio observations showed that the occurrence of many bursts is related to the position of the Jovian moon Io.

Among the findings of *Pioneer 10* and *11* were:

- The magnetic field was detected and found to be huge. The bow shock of the Jovian magnetosphere had a measured width of 26 million kilometers (16 million miles). The Jovian magnetic tail extends to beyond the orbit of Saturn. If the magnetosphere were visible in the sky from Earth, it would appear larger than the Sun or Moon.
- The Jovian magnetic field is 10 times stronger than Earth's and contains 20,000 times as much energy.
- The axis of the magnetic field is tilted 11 degrees from the Jovian rotation axis and is offset from the center of Jupiter in a manner similar to the axis of the Earth's field.
- The Jovian magnetic field has the opposite sense to Earth's field; the



“north” magnetic pole is at the south pole of Jupiter.

- The magnetic field fluctuates rapidly in size on the sunward side of Jupiter because of pressure variations in the solar wind, an effect studied in further detail by the two *Voyager* spacecraft.
- Energetic protons were found and measured in the Jovian radiation belt.
- It was discovered that streams of high-energy atomic particles are ejected from the Jovian magnetosphere and travel as far as the orbit of the Earth.
- Electric currents were detected flowing between Jupiter and some of its moons, particularly Io.

Among the findings of *Voyager 1* and *2* were:

- Within the Jovian magnetosphere is a huge sheet of plasma (a gas of electrically charged atomic particles), 4.8 million kilometers (3 million miles) in diameter. The plasma sheet rotates along with Jupiter and its magnetic field.
- Some of the magnetospheric plasma has a remarkably high temperature, in the millions of degrees. Among the high energy particles in the plasma are ions of hydrogen, sulfur, and oxygen.

Io: a volcanic landscape sculptured by flows and eruptions of molten sulfur lava.

- A sulfur-rich plasma, which was not present in 1973, was detected near Io, with a temperature of about 100,000° C.
- The electrical current between Jupiter and Io was measured at about 5 million amperes.
- It was found that radio emissions may be generated in the plasma near Io.

The Moons and Ring of Jupiter

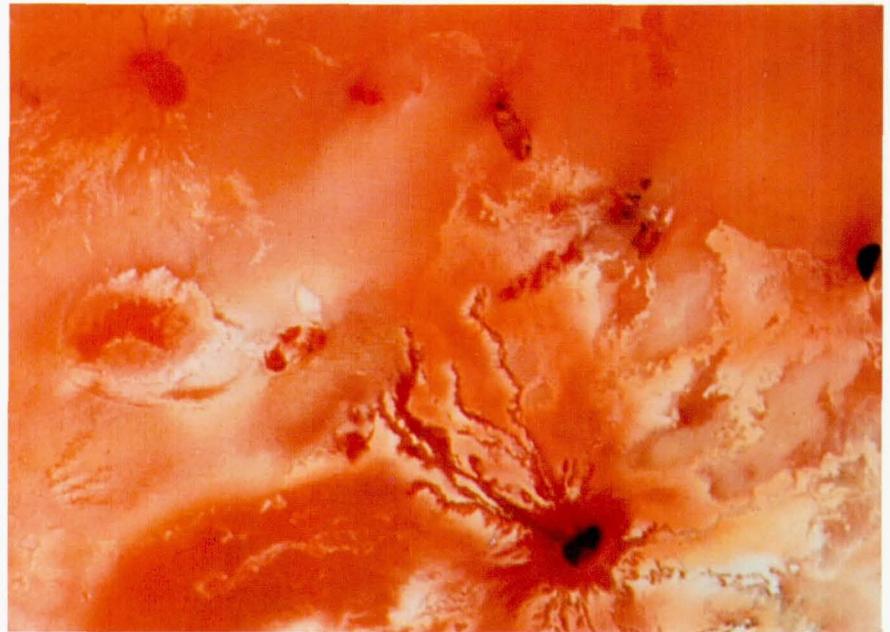
Groundbased studies of the jovian moons in the 1970's revealed the presence of two additional small moons and the existence of water ice on the surfaces of the three outermost Galilean satellites, Europa, Ganymede, and Callisto.

Findings about the jovian satellites from *Pioneer 10* and *11* included:

- The two outermost Galilean moons, Ganymede and Callisto, are less dense than the Earth's Moon.
- Io was found to be 28 percent more massive than had been calculated from groundbased observations and to be 1.22 times more massive than our Moon.
- A thin atmosphere, about 1/20,000 of the density of Earth's atmosphere and extending to about 115 kilometers (70 miles) above the surface was discovered on Io.
- A cloud of sodium vapor around Io and its orbit, detected from the ground, was detected and found to be immersed in a cloud of hydrogen as well.

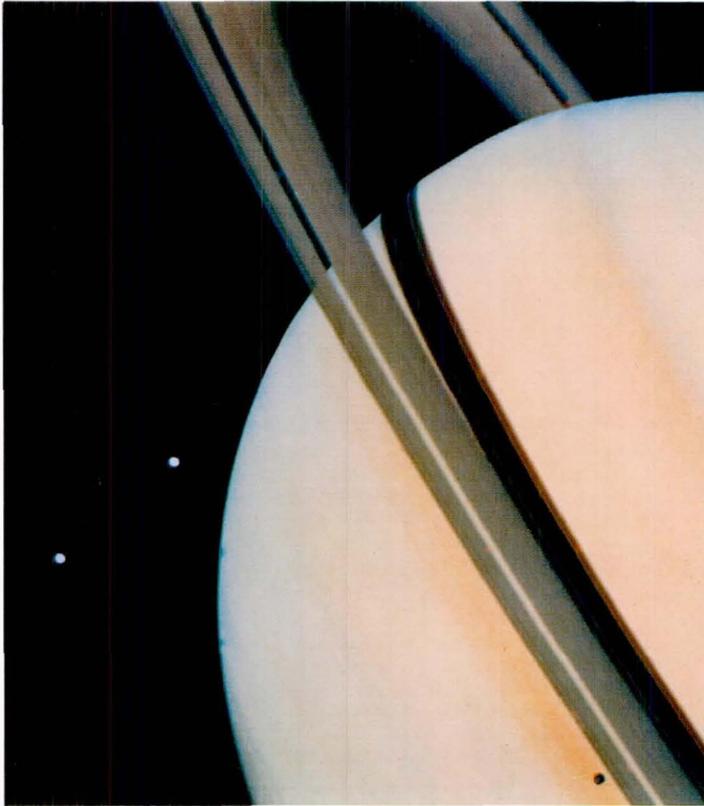
Results of the *Voyager 1* and *2* missions included:

- Three additional moons were discovered.
- Amalthea, the small inner moon of Jupiter, was found to have an elliptical shape. In effect it is a big rock, about 265 x 140 kilometers (165 x 87



miles) in size.

- Volcanic eruptions were discovered on Io, the first evidence of active volcanism found outside the Earth. The volcanism is probably induced by tidal heating. The erupted plumes extend up to 320 kilometers (200 miles) above the surface, and the volcanic activity varies over times of a few months.
- A hot spot on Io, 150° C warmer than the rest of the surface, and associated with volcanic features, was discovered.
- Europa was found to be a world of essentially flat terrain, with virtually no topographic relief. It is marked by intersecting linear features, not cracks, and the surface is very young, as indicated by the lack of impact craters.
- Both cratered and grooved terrains are present on Ganymede; the icy crust of this moon appears to have been globally deformed.
- Ganymede was found to produce distinct disturbances in the jovian magnetic field and trapped radiation belts as far as 200,000 kilometers (124,000 miles) away.
- Callisto's crust is ancient and heavily cratered, with large impact basins.
- A ring around Jupiter was discovered inside the orbit of the innermost moon. It apparently extends down to the top of the jovian atmosphere.



Ringworld: giant Saturn and two of its moons.

Saturn The Planet

Among important recent findings from Earth-based observations of the Saturn system have been the detection of a deuterium compound in the atmosphere of Saturn, indications that the small ring particles are composed of or covered by ice, the detection of ice on the moons Rhea, Iapetus, and Dione, and the discovery of methane in the atmosphere of Titan.

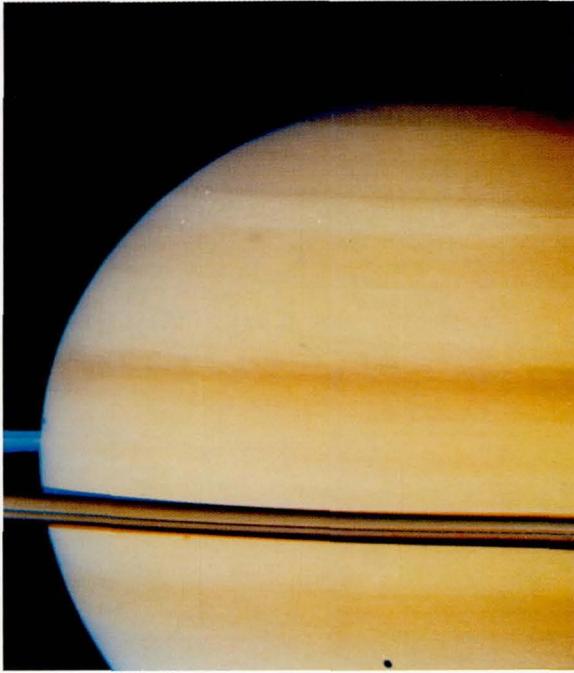
The first spacecraft flyby was accomplished by *Pioneer Saturn* in 1979. Among the findings were:

- Confirming ground-based studies, Saturn has an internal heat source like Jupiter and radiates about twice as much energy as it receives from the Sun.
- As suspected, Saturn must have internal shells of liquid and metallic hydrogen, small amounts of helium, ammonia, and water, and perhaps a small rocky core.
- A magnetic field was discovered around Saturn, larger than the Earth's, but smaller than that of Jupiter. It is five times as weak as predicted by theory.

- The axis of Saturn's magnetic field is aligned parallel to the planet's rotation axis, contrary to the circumstances in both the Earth and Jupiter.
- The boundary of the magnetic field varies due to changes in the pressure of the solar wind on the sunward side, as was found in the case of Jupiter.
- The atmosphere of Saturn has weak bands, rather than the conspicuous belts and zones seen on Jupiter.
- There is a high haze, perhaps composed of crystals of ammonia ice, above the clouds.
- Apparent high-speed jet streams were detected in the atmosphere.
- Confirming ground-based measurements, the cloud-top temperatures were measured at about -200°C (-330°F), only about 73°C (130°F) above absolute zero.
- Radiation belts were discovered that are weaker than those of Jupiter. The radiation is absorbed (cut off) by the rings and moons of Saturn. Cutoffs in the radiation data were used to infer the presence of additional rings and moons beyond those already known from visual observations.

The *Voyager 1* encounter (November, 1980) provided a closer look at Saturn and its surroundings. Some of the new discoveries were:

- The details of Saturn's atmosphere appear similar to Jupiter's, with alternating light and dark bands and circulating storm systems.
- Wind speeds up to 1500 kilometers per hour (930 miles per hour) were measured near Saturn's equator; these winds are four to five times as fast as those measured on Jupiter.
- Unusual atmospheric features include a ribbonlike wave feature, large and small clouds, and a red oval similar to, but smaller than, Jupiter's Red Spot.
- Aurorae were observed in the atmosphere above Saturn's poles.



Saturn's atmosphere: belts of quiet colors.

- Although lightning bolts were not observed on Saturn, radio signals typical of lightning flashes were recorded. The signals may be produced by electrical discharges in the rings rather than in Saturn's atmosphere.

The Rings

The *Pioneer Saturn* flyby in 1979 made several new discoveries about the rings:

- The rings consist largely of particles several centimeters in diameter. They are extremely cold and possibly composed of frozen water and other ices.
- An extensive cloud of hydrogen was discovered around the rings.
- Two new rings (called F and G) were discovered, and a gap between rings was confirmed.

Voyager 1 provided much more detail on the beauty, complexity, and sometimes baffling nature of the rings. Among the discoveries were:

- The six known rings are actually composed of hundreds of tiny, thin ringlets with intervening spaces, so that the whole ring system looks something like the grooves in a phonograph record. Even the Cassini division, once thought to be empty space between the A and B rings, contains several dozen ringlets. There are far

too many rings to be explained by our present theories of how planetary rings form and remain stable.

- Elongated radial features that last for hours to days were observed in the B-ring. These "spokes" may be clouds of electrified dust rotating around Saturn above the plane of the rings.
- The thin outer F-ring, discovered by *Pioneer Saturn*, was resolved into three distinct but intertwined ringlets. This braided ring structure is very difficult to explain; it seems likely that both electrical and gravitational forces are at work.
- Two small moons, one on each side of the F-ring, may act as "shepherds," their gravitational attraction keeping the ring particles on track between the orbits of the two moons.

The Moons

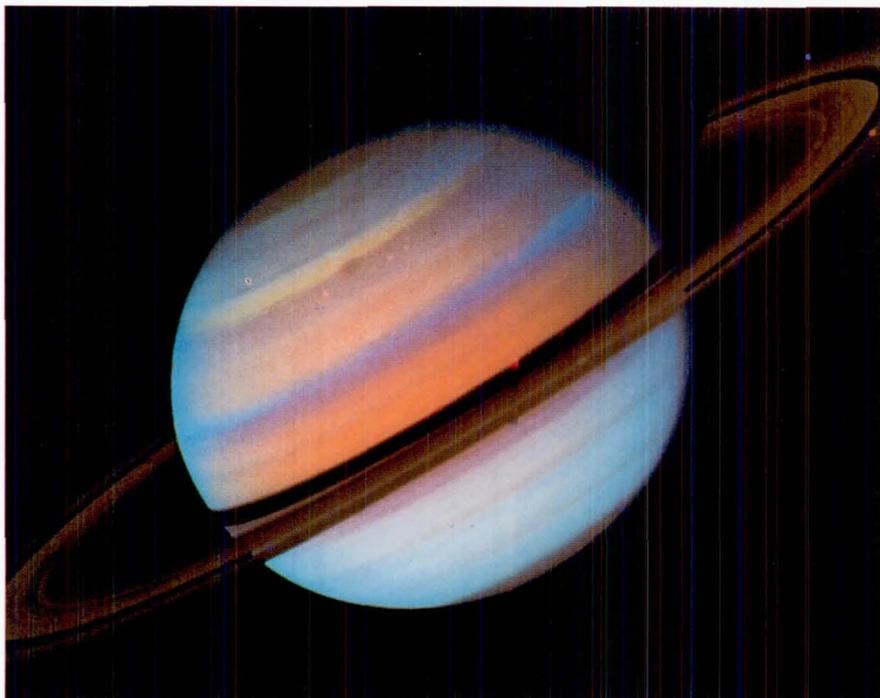
Nine (possibly ten) moons had been detected from Earth. The encounter of *Pioneer Saturn* (September, 1979) provided several new discoveries:

- At least two new moons were discovered by *Pioneer* and ground-based observations.
- Accurate masses were determined for the moons Rhea and Iapetus.
- The cloud-top temperature of Titan was found to be very low, about -200°C (-330°F), and a hydrogen cloud was discovered around Titan.

A much closer look at several of Saturn's moons was provided by *Voyager 1*. The new results included:

- Six tiny, unnamed moons were photographed, some of them for the first time. Satellites 10 and 11 share the same orbit and must frequently undergo some orbital "evasive actions" to avoid colliding. Satellite 12 shares the orbit of the larger moon Dione. The shepherd Satellites 13 and 14, on either side of the thin F-ring, may

Saturn's atmosphere, color-enhanced to bring out details.



exert gravitational forces to keep the ring in place, while Satellite 15, located just outside the large A-ring, likewise may help keep that ring in place.

- The inner moons Mimas, Tethys, Dione, and Rhea all have heavily cratered surfaces like those of the Moon and Mercury, although Saturn's moons are composed largely of water ice. This shows that meteorite bombardment, even as far out as Saturn, has been a major process in shaping the solar system. Mimas is marked by a huge impact crater that is fully one-fourth the diameter of Mimas itself. This crater makes Mimas look like a staring eyeball, and the impact that formed it was almost intense enough to blast Mimas into fragments.

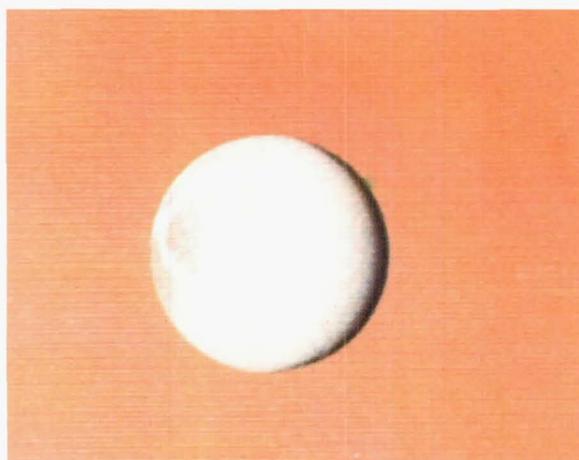
- The inner moons also show traces of internal geological activity. Tethys has a rift-like valley that stretches 800 kilometers (500 miles) across its surface. Dione shows several sinuous, branching valleys. Both Dione and Rhea have bright, wispy streaks on their surfaces.

- Although Enceladus orbits between two heavily cratered moons, Mimas and Dione, it seems smooth and entirely uncratered, as viewed from *Voyager 1*.

- Titan, Saturn's largest moon, has a diameter of 5120 kilometers (3180 miles), which makes it smaller than

Jupiter's moon Ganymede. Titan's dense, hazy atmosphere is at least 400 kilometers (250 miles) thick and completely shrouds the surface from view. Titan's atmosphere was found to be mostly nitrogen (like the Earth's), with minor methane and other hydrocarbons. At the surface, the pressure of Titan's atmosphere is at least twice that on the Earth. The surface temperature, about -175°C (-280°F), is low enough to permit lakes and streams of liquid nitrogen to form on its surface.

- Long-range *Voyager 1* photographs of Iapetus, an outer satellite, confirmed Earth-based observations by showing that the satellite has light and dark faces, but no explanation for this puzzling difference was found.



Saturn's moon Dione against the red background of Saturn itself.

Uranus

A wholly unanticipated system of thin and narrow rings was discovered around the planet Uranus in 1977 by telescopic observations from the Kuiper Airborne Observatory. There may be as many as nine of the very dark rings.

Neptune

Cloud patterns were detected in the atmosphere of Neptune by ground-based observations in 1978.

Pluto

All studies of Pluto thus far have been done from the ground. In recent years, a surface layer of frozen methane has been detected, and a moon (Charon) was discovered. It appears that Pluto is much smaller, less dense, and less massive than previously believed.

Asteroids and Meteorites

Although nearly all asteroid observations thus far have been made from the ground, the asteroid belt was safely traversed by *Pioneer 10* in 1973 and subsequently by other spaceprobes.

Based on the study of reflected sunlight, asteroids have been classified into six major compositional families since 1970.

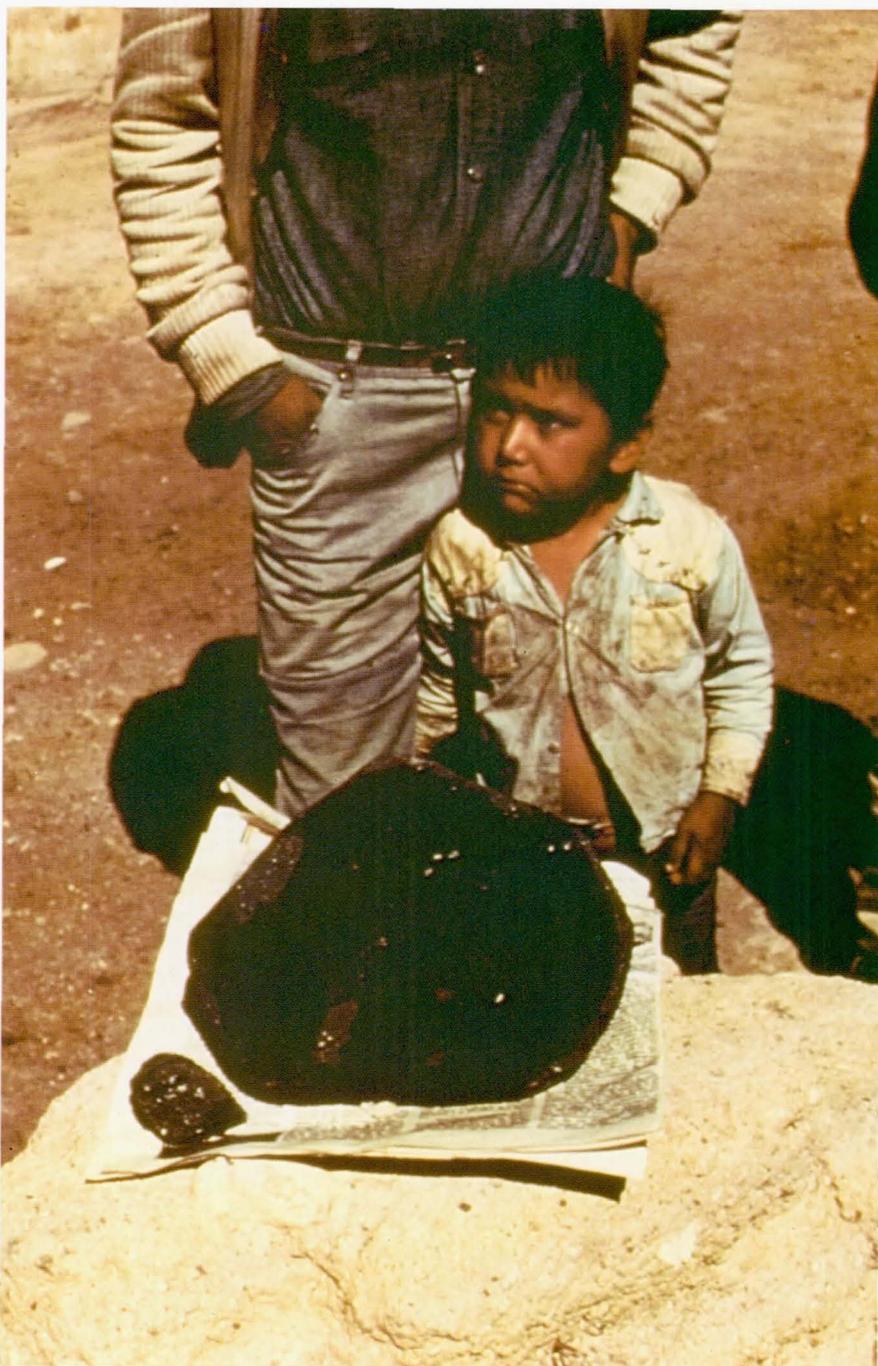
Since 1970, diameters have been estimated for an increasing number of asteroids by means of infrared observations.

In 1968, a radar echo was successfully obtained from the small asteroid Icarus during its close approach to the Earth. Another radar contact was made in 1980.

Since 1976, several new Earth-crossing asteroids, i.e., those which cross the orbit of the Earth, far from the inner boundary of the asteroid

belt, have been discovered. Among them was Ra-Shalom, discovered in 1979.

Most asteroids have been found to be very dark, perhaps a symptom of carbon content, and chemically-bound water has been detected on some of the darker surfaces.



Sample from the stars: the Allende, Mexico meteorite and a puzzled Earthman. (Photograph courtesy of Brian Mason, National Museum of Natural History, Smithsonian Institution.)

The mass of the large asteroid Vesta has been determined, and it has been found that the surface composition of Vesta resembles that of basalt lava.

In 1979, a minor planet (Chiron) was discovered between the orbits of Saturn and Uranus, far outside the known limits of the asteroid belt.

Laboratory study of meteorites reveals that they typically have spent only 10 million to 100 million years exposed to the space environment, a finding that suggests that relatively recent collisions have occurred in the asteroid belt.

Some meteorites are composed of lava, indicating that early melting and volcanic eruptions occurred on their parent asteroids.

Daughter products of extinct, primordial, radioactive isotopes, such as iodine-129, plutonium-244, and aluminum-26, have been found in meteorites. These isotopes, when still present in the parent objects of the meteorites, may have served as important heat sources.

Amino acids have been found in meteorites (see Appendix section on Exobiology).

White inclusions of minerals formed at high temperatures have been found in the Allende meteorite. These may be samples of the first material to solidify in the original cloud from which the solar system was born.

Elemental anomalies found in the white Allende inclusions indicate that some matter may have been introduced into the solar system cloud from another star, presumably a supernova.

The formation ages of meteorites date back 4.6 billion years, providing a firm estimate for the age of the solar system.

Gases from the solar wind have been found to be trapped and preserved in meteorites.

The rates at which iron meteorites cooled from the molten state within their parent objects have been determined; they range from 1 to 20 degrees centigrade per million years. This cooling is too rapid to have occurred within the iron core of a large planet.

Comets

In 1970, the existence of huge hydrogen clouds around the comets Tago-Sato-Kosaka (1969 IX) and Bennett (1970 II) was discovered with the OAO-2 satellite. The clouds, also observed by OGO-5, are detectable only in ultraviolet light. The existence of such clouds had been predicted on the basis of the icy conglomerate or "dirty iceball" model of comets, and thus the discovery helped to confirm the theory.

The predicted presence within the cometary hydrogen cloud of high velocity material, with speeds of about 20 kilometers per second (12 miles per second), was found to be consistent with the intensity distribution of the hydrogen clouds mapped by OAO-2 and subsequent spacecraft. It was recently confirmed by spectroscopic observations from the *Copernicus* satellite.

The hydrogen clouds provide direct evidence for a rate of mass flow from the nucleus of a comet that is adequate to account for the so-called "nongravitational force" that disturbs the motions of comets.

Radio telescopes have observed the hydroxyl (OH) radical in several comets and have made apparent detections of the substances CH_3CN , HCN, and CH in Comet Kohoutek (1973 XII).

The first definite detections of carbon and oxygen atoms in a comet were made by ultraviolet spectroscopy from two sounding rockets launched to study Comet Kohoutek in 1974.

Infrared measurements made from the ground have revealed the presence of silicate dust grains in several comets.

Radio observations of Comet Kohoutek and Comet West (1975n) revealed the presence of transient microwave emission apparently produced by the icy-grain halo, a structural feature of comets that had been predicted to exist.

Observations of Comets Seargent (1978m) and Bradfield (1979l) with the IUE satellite revealed the presence of atomic sulfur and CS in the coma and showed that these species are produced from an extremely short-lived (less than about 100 seconds) parent molecule, perhaps CS_2 . The forbidden neutral oxygen line at 2972 Å was identified; it is thought to come from photodissociation of water and thus provides a means of determining the spatial distribution of water vapor in the coma.

Using IUE, the water vapor production rate of Comet Bradfield was determined over a range of heliocentric distance from 0.7 to 1.5 astronomical units, the first time this has been measured for a comet. The variation was inconsistent with the idea that the vaporization might depend only on the input of heat from the Sun.

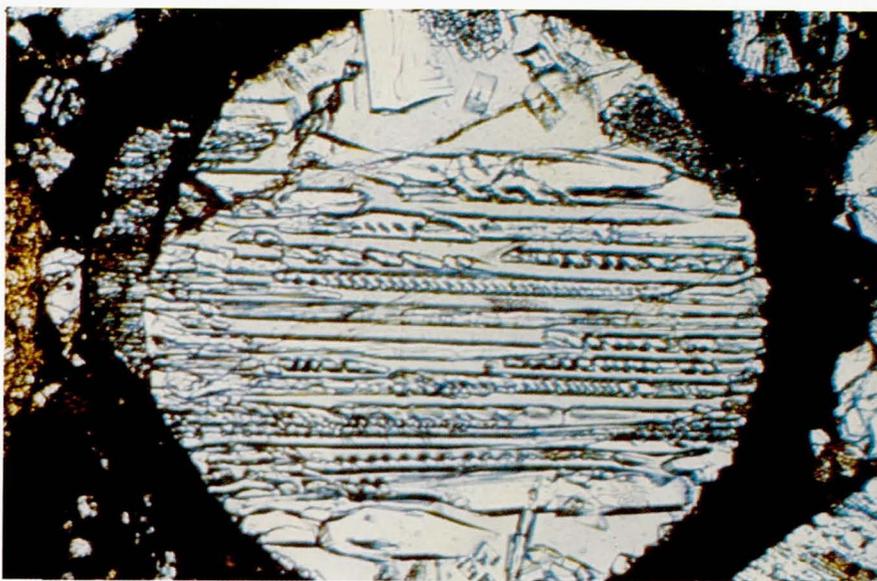
Interplanetary Dust

Pegasus 1, in 1965, and other spacecraft showed that interplanetary dust particles are about 10,000 times less abundant than had been indicated by early space experiments.

Pioneer 10 and *11*, in 1973 and 1974, found that Mars sweeps up the interplanetary dust near its orbit.

Pioneer observations also showed that the zodiacal light is produced by dust that orbits the Sun at great distances from the Earth.

The first definite samples of interplanetary dust have been collected by high-altitude research aircraft since 1978.



A tiny bead (chondrule) in a meteorite displays a jewel-like arrangement of microscopic crystals and glass. (Photograph courtesy of Laurel Wilkening, University of Arizona.)

Solar-Terrestrial Physics

The Sun

The solar ultraviolet spectrum has been mapped and studied, first with sounding rockets in 1946 and later with the *Orbiting Solar Observatories* (OSO satellites).

With radio telescopes, it was found that radio bursts of many kinds are emitted by the Sun.

Ground-based telescopes discovered "supergranulation," the existence on the Sun of convection cells with typical sizes of 30,000 kilometers (19,000 miles).

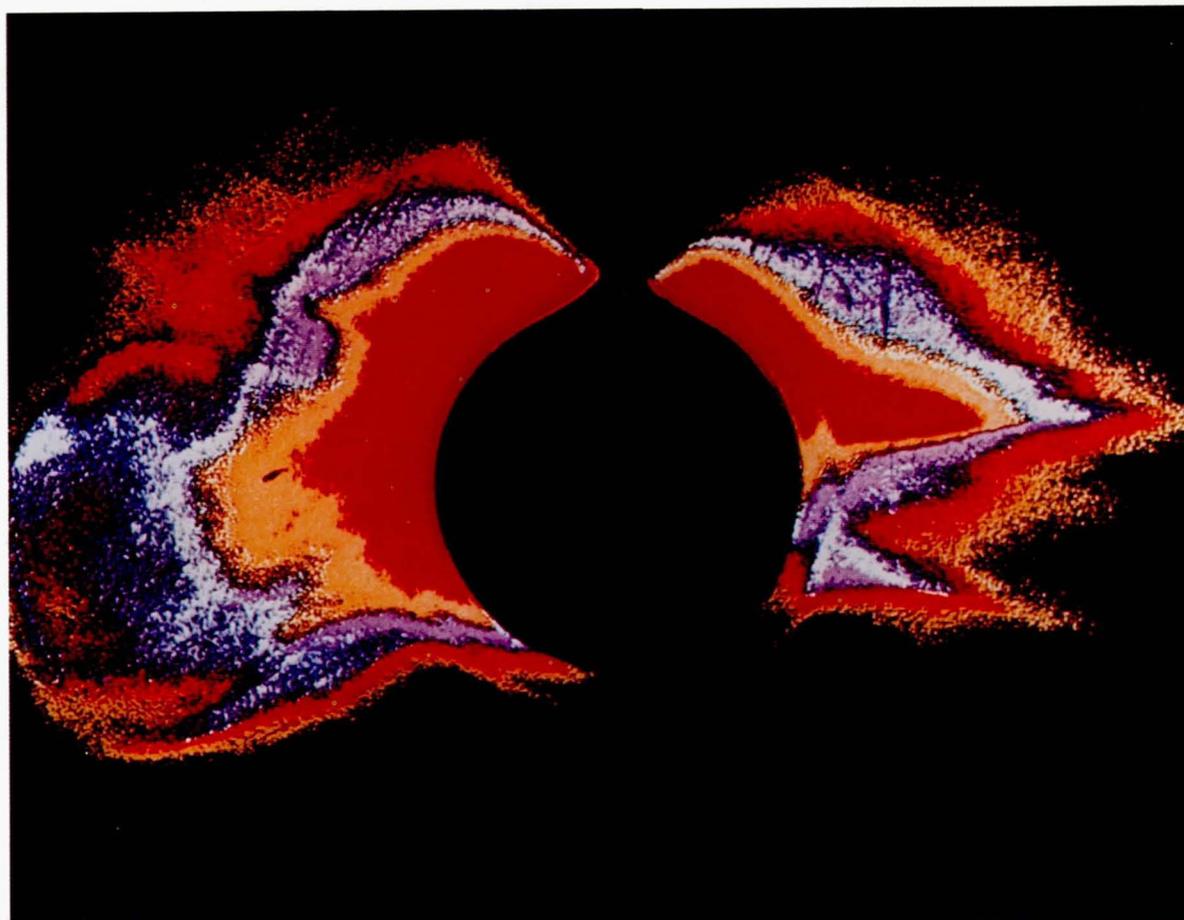
Sounding rocket instruments discovered that solar soft (lower energy) X-rays are produced primarily by active regions.

OSO instruments revealed that bursts of hard (higher energy) X-rays accompany solar flares.

Sounding rocket observations unexpectedly detected neutral hydrogen emission from the solar corona, allowing astronomers to measure the temperature of the coronal hydrogen and to infer the speed of the solar wind moving out through the corona.

Ground-based telescopes show that the five-minute oscillations of the Sun are composed of superposed oscillation modes.

An OSO instrument discovered gamma ray emission lines, indicating that nuclear reactions sometimes occur in solar flares.



The Sun's huge corona, color-enhanced to distinguish different brightness levels. (The Sun is the blacked-out disk in the center.)

Observations from *Skylab* revealed that:

- The corona consists largely of arcades of magnetic-field arches.
- The basic structure of a solar flare is a magnetic arch or loop.
- Coronal holes do not exhibit the differential rotation which characterizes the solar photosphere, but rotate as though they were solid objects.
- The top of a flare loop is hottest, and its foot points are relatively cool.
- There are numerous small regions of emerging magnetic flux, which appear as bright points on the Sun in soft X-rays, with lifetimes of three to six hours.

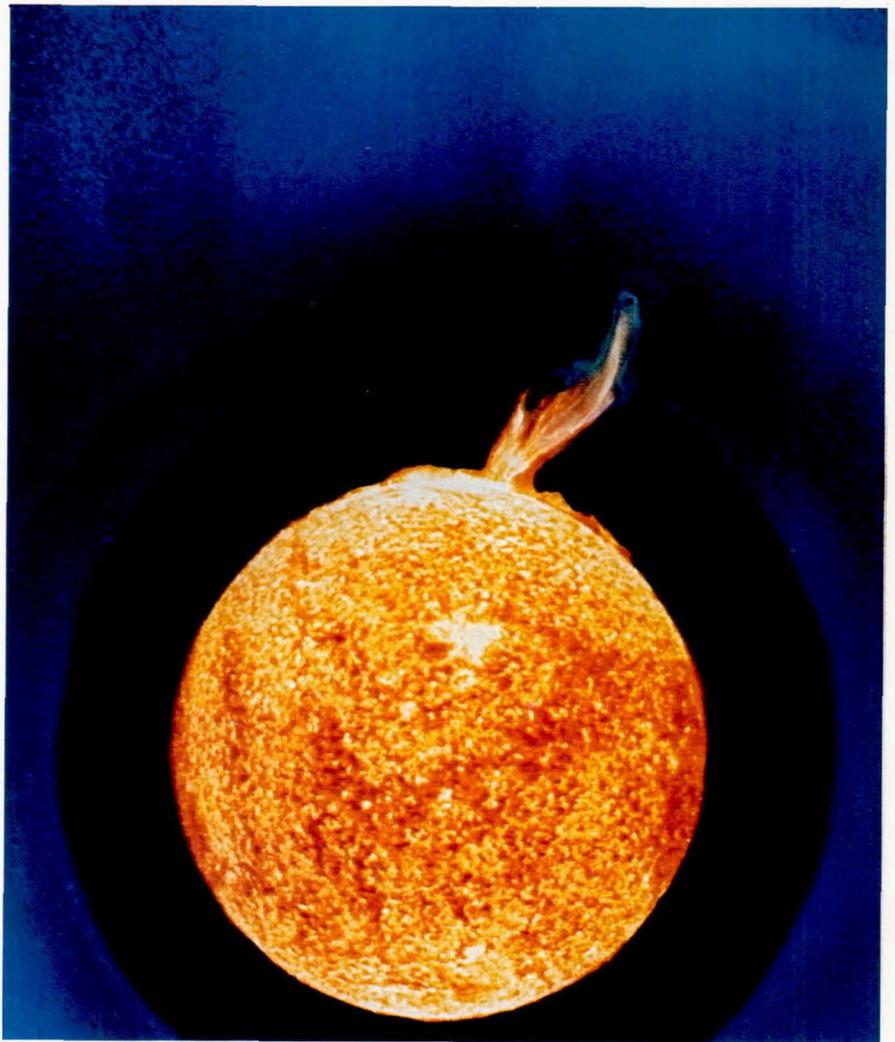
Observations from *OSO-7* and *Skylab* showed that large "solar bubbles" or coronal transients pass outward through the corona after flares and prominences erupt.

OSO-8 measurements showed that, contrary to earlier expectations, acoustic waves do not carry sufficient energy to heat the corona. Perhaps the dissipation of magnetic energy is responsible for the high temperature of the corona.

Sounding rocket observations showed that jets, perhaps related to the spicules seen with ground-based telescopes, are ejected from the solar surface and reach speeds of 300 kilometers per second (190 miles per second).

Combining the results of observations from the *Solar Maximum Mission* (SMM) satellite and ground-based radio telescopes, it was found that hard X-rays are emitted at the foot points of flare loops, while microwave radio bursts are emitted at the tops of the loops.

An instrument on SMM discovered



A giant prominence leaps outward from the Sun, disturbing the solar corona (in blue).

that the total light of the Sun varies from week to week by amounts of plus or minus 0.05 percent and that there are some larger variations as well.

SMM observations revealed how solar flares occur after hot plasma fills pre-existing magnetic loops, which then explode.

Heliospheric Physics

Ground-based measurements found that there is an inverse correlation between solar activity and cosmic ray intensity.

Interplanetary spacecraft including the *Mariners* detected and measured the solar wind.

The abundances of such atoms as carbon, nitrogen, oxygen, and iron have been measured in the solar wind.

Enhanced amounts of the isotope helium-3 were discovered in the matter ejected from solar flares and in high-speed streams of the solar wind.

Waves and discontinuities were discovered in the solar wind.

The interplanetary magnetic field was found to possess sector structure that rotates with the Sun.

Skylab observations identified coronal holes as the sources of high-speed wind streams and showed that coronal holes are the cause of recurrent geomagnetic storms on Earth.

Correlation of the interplanetary magnetic field with the magnetic field at the solar surface was accomplished.

A warped-disk model for the magnetic neutral sheet in interplanetary space has been developed.

Pioneer 10 has established that the heliosphere extends out beyond the orbit of Uranus.

The *International Sun-Earth Explorer* (ISEE) mission discovered electron bursts that originate in the outer corona and traced the paths of the bursts outward through the corona, along the spiral magnetic field.

Magnetospheric Physics

The Van Allen radiation belts of the Earth were discovered by *Explorer 1*.

The magnetopause, or boundary between the solar wind and the Earth's magnetosphere, was located at a distance of about 20 Earth radii toward the Sun.

The Earth's "bow shock," a collisionless shock wave, was found to be slightly closer to the Sun than the magnetopause and separated from the latter by a region called the magnetosheath.

The Earth's magnetic tail (magnetotail) was found to extend far into space, beyond the distance of the Moon.

Large electrical current systems were found to flow through the magnetosphere.

It was determined that significant numbers of charged particles enter the magnetosphere directly from the solar wind.

Evidence was found for a magnetic-field reconnection process in the magnetotail, which accelerates charged particles to high velocities.

Displays of the aurora on Earth were found to originate from disturbances in the magnetotail.

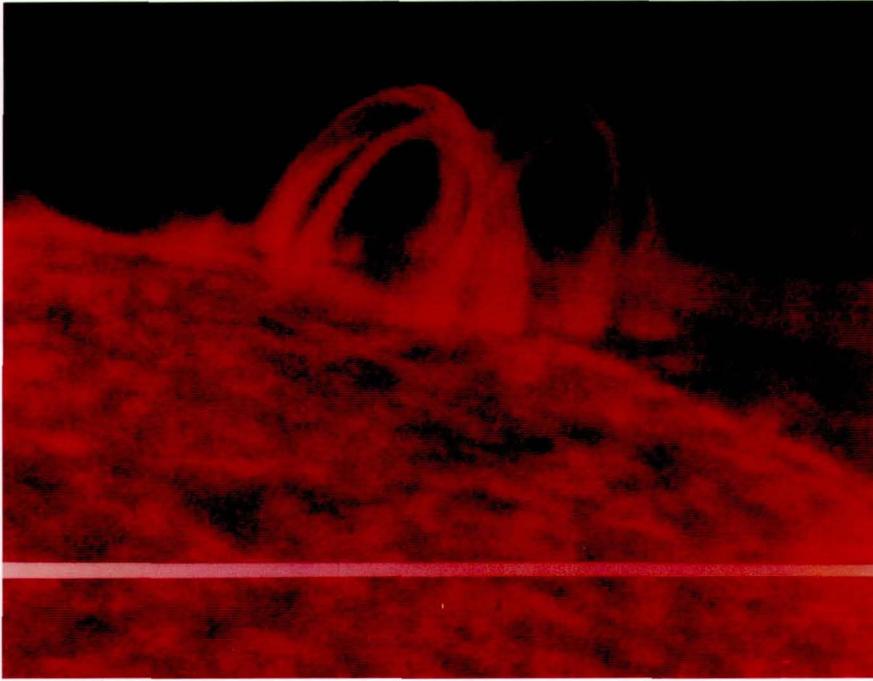
Low-frequency waves were detected in the magnetosphere.

It was found that electric currents move along the magnetic field lines above the Earth's polar regions. These currents are maintained by electric fields aligned along the magnetic field, which once were thought to be impossible.

Ionospheric Physics

Rocket-borne ion mass spectrometers showed that molecular ions predominate among the charged particles in the lower layers of the Earth's ionosphere, at altitudes of 90 to 200 kilometers (about 55 to 125 miles).

Rocket observations showed that the



An immense magnetic loop of hot gas arches above the Sun's surface.

charged particles in the upper layers of the ionosphere, at altitudes of 200 to 800 kilometers (125 to 500 miles), are mainly ions of oxygen.

Metallic ions derived from meteorites were discovered in the E region of the ionosphere.

Measurements showed that the temperatures of the ionospheric electrons are higher than those of the ions; the ion temperatures are higher than those of the neutral gas.

Observations by *Explorer* satellites showed a division between the polar ionosphere and the ionosphere over lower latitudes of the Earth.

Plasma instabilities were artificially excited for study in the ionosphere by means of radio-wave injection.

Extensive satellite measurements solved the long-standing problem of why there are more electrons in the winter ionosphere than in the summer ionosphere at the low- to medium-activity phases of the sunspot cycle. (More electrons would be expected in the summer, since the Sun is then more nearly overhead.) Systematic measurements by the *Atmosphere Explorers* provided a large data base.

This allowed variations associated with satellite height, latitude, time of day, and season to be statistically separated. Three factors were found to contribute to the winter anomaly. First, there is an increase in neutral atomic oxygen due to atmospheric circulation and dynamics; this results in an increase in electron production due to more ionization by the Sun. Second, the temperature of the neutral nitrogen is lower in winter, so that the existing ionization is removed more slowly by a chemical recombination process. Third, there is a more rapid production of ionization in winter due to increased quenching of an intermediate excited state of atomic oxygen.

Convective bubbles that cause the equatorial "spread-F" effect were detected. These involve electron density variations by factors of 100 within scale sizes of approximately 10 meters (33 feet). The bubbles move at speeds of hundreds of meters per second.

A "polar wind" of ions that are convected rapidly upward from the ionosphere above polar regions was discovered. The ions either travel out along magnetic field lines to interplanetary space or are transported into the magnetotail.

Astrophysics

Selected Results Summarized
Historically

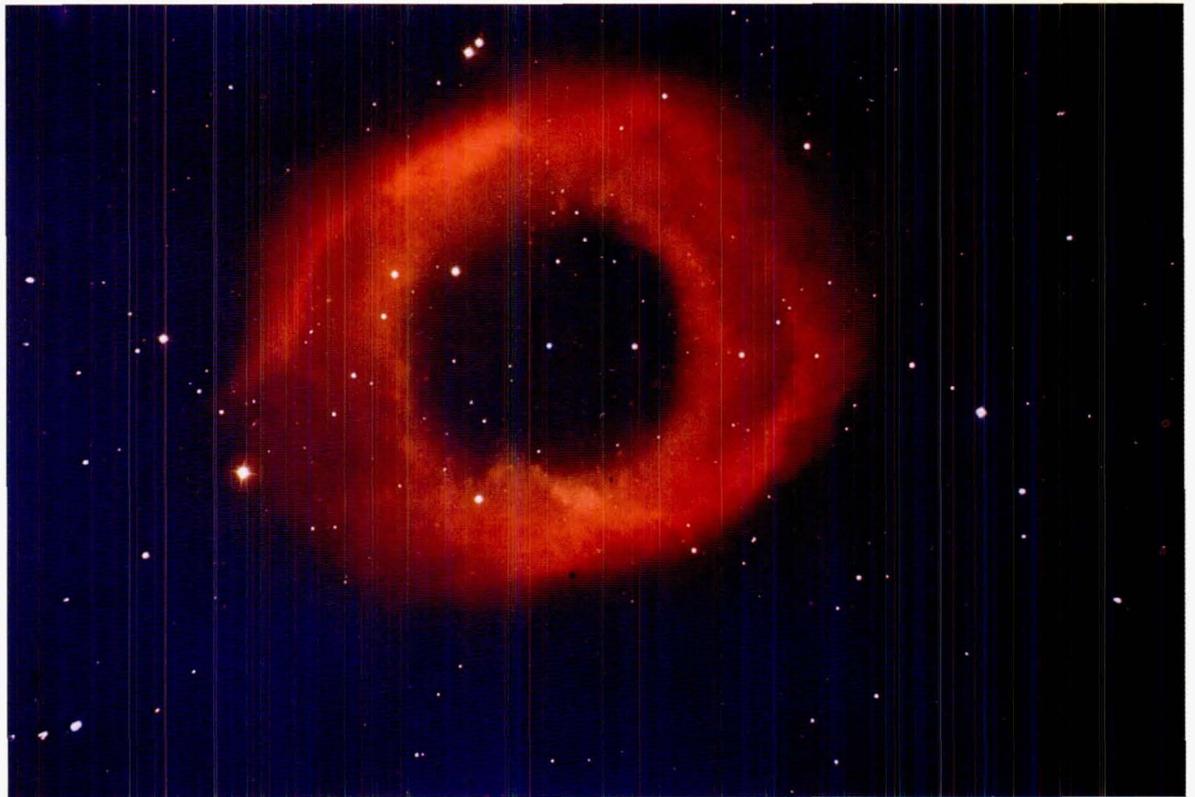
Cygnus X-1

- 1964 Strong source Cygnus X-1 discovered with an X-ray telescope carried on a sounding rocket.
- 1971 *Uhuru* satellite monitored time dependence of Cyg X-1 and found periodicity matching that of visible-light spectral changes in a faint blue star in the direction of the X-ray source. A radio source also found at this position. The spectral changes revealed that the blue star has a dark companion star so massive that, according to current theory, it cannot be a neutron star and presumably is a black hole.

- 1973 X-ray telescope on a sounding rocket found very rapid intensity changes in Cyg X-1 of type predicted to accompany accretion of matter onto a black hole.
- 1975 Analysis of X-ray intensity changes of Cyg X-1 showed that flares of about 0.5 seconds duration occur randomly, a phenomenon not found in other X-ray sources.

Gamma Ray Bursts

- 1973 Physicists announced that celestial gamma ray bursts of unknown origin, arriving from random directions in space, were discovered with the *Vela* satellites, a set of Earth-orbiting spacecraft designed to monitor the Limited Test Ban Treaty. The bursts were first



The Planetary Nebula in Aquarius, a huge circular cloud of dust amid the stars. (Copyright 1965 by California Institute of Technology and Carnegie Institution of Washington.)

recorded in 1967, but were not immediately recognized as extraterrestrial events.

- 1974 Study of a gamma ray burst found in data recorded in 1972 by an instrument on *Apollo 16* showed that it had more than five prominent intensity peaks. Earlier known bursts had one or two peaks.
- 1978 Statistics of the occurrence of gamma ray bursts of weak intensity, as measured with balloon-borne instrumentation, showed that the bursts must arise in sources located inside our Milky Way galaxy.
- 1979 Interplanetary network of gamma ray detectors on nine spacecraft observed the strongest gamma ray burst yet on March 5th, with a remarkably fast rise time of less than one thousandth of a second. The source was pinned down to the direction of a supernova remnant in the Large Magellanic Cloud, companion galaxy of the Milky Way. The implication, if this identification is correct, is that the burst came from a neutron star that remained from the supernova. An eight-second recurrence of intensity peaks was observed, perhaps to be interpreted as the rotation period of the neutron star. Astronomers cautioned that the burst's properties were exceptional and that it might represent a different phenomenon than the other observed gamma ray bursts.



The mysterious object SS 433, glimpsed from Earth by the Einstein observatory satellite.

Cosmic Rays

- 1912 Cosmic rays discovered in a balloon experiment. However, it was thought that they were gamma rays rather than subatomic particles.
- 1929 Cosmic rays found to be electrically charged, thanks to measurements from the newly-developed Geiger-Muller counter.
- 1936 Muon recognized as a cosmic ray that reaches the ground. The first discovery of an unstable subatomic particle, this finding launched the discipline of elementary particle physics and showed that the primary cosmic rays which don't reach the ground are something other than muons.

- 1939 Primary cosmic rays found to be positively charged, with the flux of particles from the west slightly greater than that from the east, as would be predicted for positively charged particles moving in the Earth's magnetic field.
- 1960 Balloon experiments at high altitude discovered that about one percent of the cosmic rays are relativistic electrons.
- 1964 The flux of cosmic rays studied over a complete solar cycle was found to vary so that the flux reaching the Earth is reduced by as much as 20 percent when the Sun is in its active phase.
- 1974 Balloon measurements determined the average amount of matter traversed by cosmic rays in space between their sources and the Earth (five grams per square centimeter) by measuring the ratio of the number of light nuclei in the cosmic rays (lithium, beryllium, boron) to the number of heavy nuclei (carbon, oxygen). Light nuclei are probably produced when the heavier ones collide with interstellar matter, thus the larger the ratio, the more matter has been traversed by the heavy nuclei.
- 1977 The age of cosmic rays was found to be about 20 million years from two kinds of experiments. First, the IMP-7 and IMP-8 satellites measured the ratio of the beryllium-10 and beryllium-9 isotopes in cosmic rays; both are produced by the interaction of carbon and oxygen nuclei with the interstellar matter, but beryllium-10 is un-
- stable, with a half-life of 2.5 million years. Second, balloon-borne telescopes observed the energy spectrum of relativistic cosmic ray electrons and found it to bend at 20 GeV, a result predicted for a 20-million-year exposure to galactic magnetic fields and the microwave background radiation.
- 1979 Launch of HEAO-3 satellite with two large cosmic ray experiments, one to study isotopes and one to observe very heavy nuclei. A new theory of cosmic ray variations due to phenomena of the solar wind and interplanetary magnetic fields was advanced on the basis of data from many interplanetary spacecraft.

Quasars

- 1962 The position of radio source 3C273 was determined when it was occulted by the Moon, and a faint star-like object with a jet was photographed at the position. Its spectra showed unusual emission lines.
- 1963 The spectral lines were identified as familiar hydrogen lines, but redshifted by about 16 percent of their wavelength, so that 3C273 must be extremely far away and hence thousands of times more luminous than a galaxy.
- 1970 Sounding rocket telescope discovered X-rays from 3C273.
- 1972 Variability of infrared radiation from 3C273 was reported; the time scale of variation is too short for the radiation to arise from hot dust grains, so the



The Great Galaxy in Andromeda, our nearest galactic neighbor in space. (The two smaller Magellanic Clouds are actually satellites of our own galaxy.) (Copyright 1959 by California Institute of Technology and Carnegie Institution of Washington.)

emission mechanism must be nonthermal.

- 1978 COS-B satellite observations revealed a weak gamma ray source in the direction of 3C273. X-ray observations of the quasar OX 169 showed that its intensity changed by a factor of six in only six hours. If (as one theory maintains) the source of the X-rays is matter accreting onto a black hole, then this rapid change implies that the black hole has a mass at least a million times greater than that of the Sun.
- 1979 An X-ray quasar reported to have a redshift of 3.2, corresponding to a velocity of recession of 97 percent of the speed of light. (The most distant known quasar has a redshift of 3.5.)

Pulsars

- 1967 Discovery of the first radio pulsar, CP1919, with a pulse period of 1.337 seconds and a pulse width of 0.04 second.
- 1968 Publication of theory that pulsars are rotating, magnetized neutron stars. Observations showed that the pulsars are gradually slowing down.
- 1969 Visible light pulses were discovered from the pulsar in the Crab Nebula. Then, discovery of X-ray pulses from this object showed that the power radiated in the form of X-rays is more than 10,000 times the luminosity of the Sun at all wavelengths.
- 1972 Gamma ray pulses at high energies observed from the Crab

Nebula pulsar. There are two gamma ray pulses per pulse period, mimicking the X-ray pulse behavior, and they are exactly in phase with the radio pulses. Radio studies of many pulsars were sensitive enough to study them pulse by pulse; these investigations discovered a rich variety of phenomena, including drifting subpulses, so-called "giant pulses," and "nulling," when an entire pulse fails to occur.

1975 SAS-2 satellite discovered gamma ray pulses from the pulsar in the Vela X supernova remnant. Radio observations of this object had shown one pulse per period, although there are two gamma ray pulses in the same interval, neither one coinciding with the phase of the radio pulse. Also, the first radio pulsar in a binary system was discovered; continued monitoring over several years suggested that the orbital period is slowly changing, perhaps as the system loses energy in the form of gravitational waves, as predicted from the General Theory of Relativity.

1977 Optical pulses discovered from the Vela pulsar. Again, two pulses seen per pulse period, but not coincident with either of the gamma ray pulses nor with the radio pulse.

Interstellar and Intergalactic Media

- 1951 Detection of 21-cm (8.3-inch) wavelength radio emission from interstellar atomic hydrogen.
- 1956 Theory that there exists a galactic corona was proposed.
- 1969 Model of cold clouds and warm intercloud medium in pressure balance was proposed. The average density of interstellar matter was found to be one atom per cubic centimeter and thought to be equally divided between thin, warm gas and cool, denser clouds.
- 1972 Another *Orbiting Astronomical Observatory* (OAO-3), also called *Copernicus*, was launched, carrying the first instrumentation for ultraviolet spectroscopy of stars from Earth orbit.
- 1973 *Copernicus* results showed that: (1) The ratio of deuterium to hydrogen in interstellar gas is very low, a result that is evidence for the "Open Universe" theory, according to which the expansion of the universe will never end; (2) many of the heavier elements are much less abundant in the interstellar gas than in the stars that supply mass to the gas, which indicates that atoms of these elements have condensed to the solid state and are present in interstellar dust grains.

- 1974 *Copernicus* data lead to the theory that low-density cavities in interstellar space are caused by supernova explosions and are filled with hotter gas than the surrounding regions. It was suggested that a series of supernovae may cause cavities that connect to form tunnels of hot gas, threading through the cold clouds and warm intercloud medium.
- 1975 White dwarf stars were detected with an extreme ultraviolet telescope on the *Apollo-Soyuz* mission. The results show that there is very little gas (less than 1 atom per 100 hundred cubic centimeters) in the vicinity of the Sun, out to at least 200 light years.
- 1976 According to *Copernicus* results, the bulk of the neutral interstellar gas is contained in small dense clouds rather than uniformly distributed.
- 1979 Discovery of an X-ray "superbubble" in the constellation Cygnus, made with an X-ray telescope on HEAO-1. Discovery by IUE of a corona of 100,000° C gas around the Milky Way galaxy, as theorized in 1956. The corona perhaps is fed with hot material by superbubbles expanding from the galactic plane. Discovery by IUE of coronae around the Magellanic Clouds; coronae must be very common around galaxies.

Cosmic Background Radiation

- 1946 Prediction made that a cosmic background radiation exists due to the origin of the universe in the Big Bang.
- 1962 X-ray background radiation discovered by an instrument on a sounding rocket.
- 1965 Cosmic microwave background discovered with a radio telescope.
- 1968 Measurements of the isotropy of the X-ray background showed that the radiation must come from very great distances, because the universe is homogeneous and isotropic only on very large scales.
- 1977 Anisotropy found in the microwave background. The measurements indicate that our galaxy is moving at about 300 to 400 kilometers per second (190 to 250 miles per second) in the direction of the constellation Leo.
- 1979 The diffuse X-ray background at energies around 1 keV was found to be dominated by emission from many very distant individual objects, perhaps quasars and young galaxies.

*Biomedical Research**

Early 1960s: *Mercury, Vostok*

Considerable weight loss of 3.5 kg (8 pounds) postflight.

12 percent increase in heart rate, normalizing after 9 to 19 hours.

Mid-1960s: *Gemini, Voskhod*

Decreased capacity to work postflight.

12 to 15 percent decrease in bone density; bone decomposition potentially dangerous.

Heart rate as high as 180 beats per minute during extravehicular activity.

Blood abnormalities:

- Loss of red cells and plasma volume.
- Decrease in important electrolytes (sodium, potassium).
- Changes in hormone levels.

Abnormalities in urinary excretion:

- Progressively increasing calcium loss.
- Increased nitrogen, aldosterone, and catecholamines.
- Reduced sodium and chlorine postflight.

Late 1960s-Early 1970s: *Apollo, Soyuz*

Adaptation to weightlessness; high work capacity in flight, but significantly lower capacity postflight; two weeks needed to recover.

Muscle atrophy:

- Decreased strength, reflexes, and size of muscle.
- Variable complaints of muscle pain in flight and up to five days postflight.

Cardiovascular and hemodynamic adaptation:

- Decreased cardiac size and output.
- Reduced blood pressure postflight.
- Decline postflight in orthostatic tolerance (ability to stand without fainting).

Unpredictable incidence of motion sickness, vomiting, and/or tumbling sensations; on occasion, functionally incapacitating.

Changes in quality (types, viability) and quantity of bacteria normally associated with Man; significant implications for epidemiology of diseases, immunity, and digestion.

Observations of visual light flashes by all crew members, resulting from the impact of cosmic rays.

Mid to Late 1970s: *Skylab, Salyut*

Decreased rate of weight loss with increased flight duration; pattern of weight loss indicative of early fluid loss and later tissue loss.

Roughly half the body volume loss occurred in the legs alone.

Shift of blood toward head region early in flight, contributing to a sensation of fullness in the head that persisted throughout flight.

Leg muscle atrophy; little or no change in sizes of arms and chest.

Rigorous in-flight exercises were successful in facilitating recovery postflight.

No mineral loss in upper extremities, although significant loss in heel bone after 84-day flight.

Postflight reduction in cardiac output and stroke volume and increase in heart rate.

Red cell mass loss during first 30 days, but gradual recovery after 60 days. Thus, decrease in red cell mass immediately after 84-day flight was approximately one-half that of earlier (28-day and 59-day) *Skylab* flights.

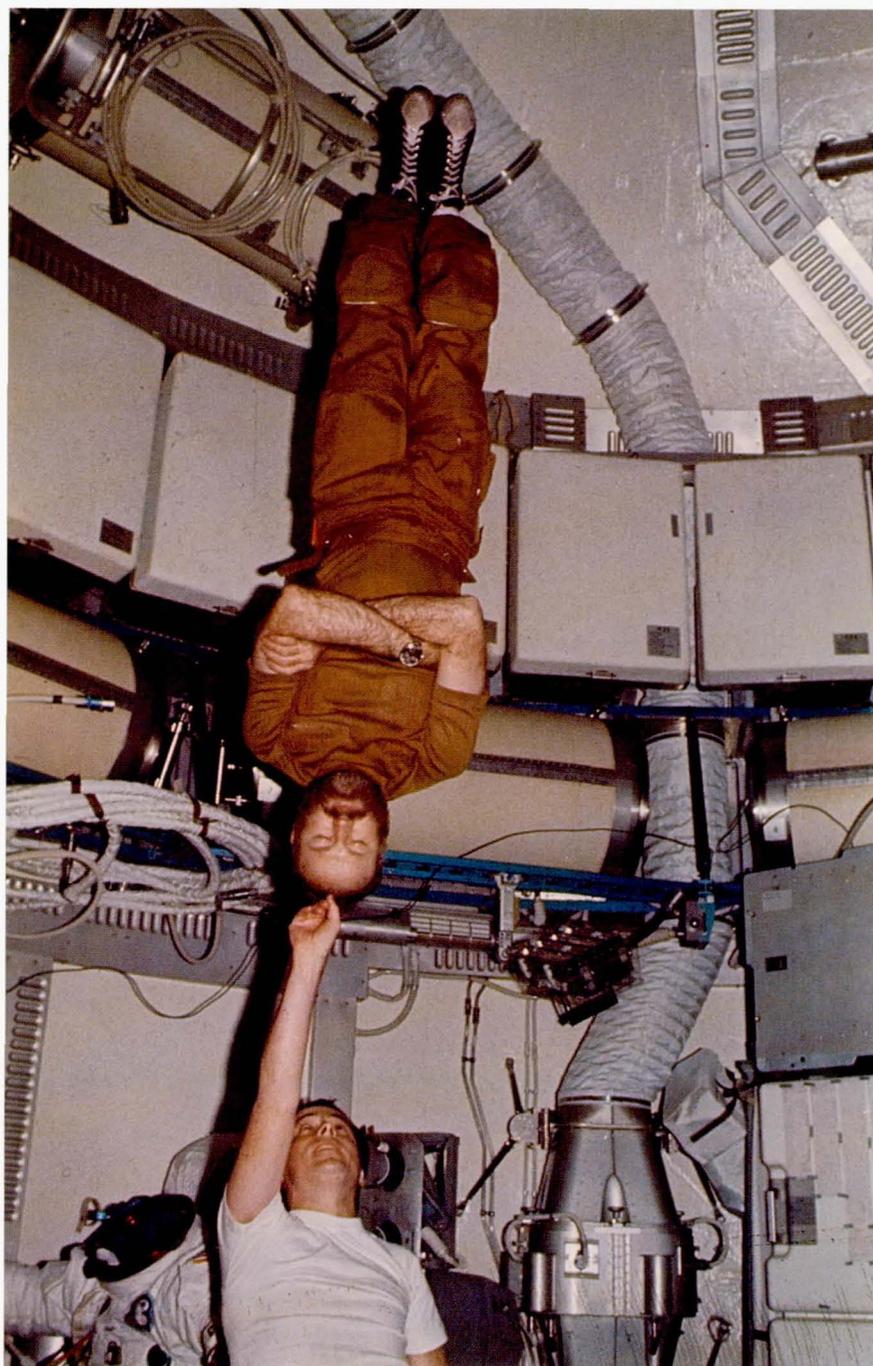
Decreases in various enzymes involved in red blood cell metabolism.

Elevated white blood cell levels in-flight, with rapid recovery postflight. Also, slight changes in humoral immunoglobulins.

Sensory changes, including slightly decreased visual acuity and depth perception postflight and differences in taste of food samples between in-flight and postflight periods.

Postflight impairment of coordination and balance with eyes closed, although fairly normal with eyes open; implications for vestibular adaptation involving reliance on visual sensory input.

Level of overall microbial contamination greater in 84-day flight than in previous flights, mostly due to increased population of fungi; implications for environmental control of future long-duration missions.



A headstand in space: demonstrating weightlessness in Skylab.

**These are selected biomedical findings, not an all-inclusive list. Results are noted only under the first flight program in which they were found, except when significantly modified by data from subsequent flights. Thus, although weight loss was observed after every flight, it is mentioned here for the first flight program and then, when modified by longer duration, for the last.*

Exobiology

Amino acids have been synthesized non-biologically under conditions that simulate those postulated for the primitive Earth, followed by the synthesis of most of the biologically important molecules.

A laboratory model was developed for the evolution of cell structure from nonbiological precursors.

Ammonia and water molecules were detected in interstellar space with radio telescopes, followed by the discovery of many more important organic molecules and precursors.

Amino acids and other biologically significant organic substances have been found to occur indigenously in meteorites and to be of nonbiogenic origin.

Analysis of rock and soil samples returned from the Moon provided no evidence for past or present life and only traces of the precursors of amino acids.

Simulations of the atmospheric chemistry of the outer planets showed that these atmospheres may be sites where extensive abiotic synthesis of organic molecules is presently occurring.

Spectroscopic observation of comets has revealed the presence of biologically important ions, molecules, and fragments.

Viking lander experiments found no existing life or organic chemicals in the soil at two locations on Mars.

The Martian soil was found to possess intriguing chemical properties that mimic, in some respects, certain reactions of biological systems.

A third kingdom of microorganisms, the *Archaeobacteria*, was shown to be distinct from the prokaryotes and eukaryotes, thus altering concepts of the earliest lines of descent of species on the Earth.

Clay minerals were found to markedly influence the rate and direction of chemical evolution processes.

Algae, bacteria, and fungi were discovered living inside rocks from the coldest and driest deserts of the Antarctic, which represent the closest terrestrial analog to the environment of Mars.

Microfossils were discovered in rocks 3.5 billion years old, a finding that pushed back the estimate of the time when life originated on the Earth to within the first billion years after the Earth was formed.

Nucleic acid polymers in the biological size range were synthesized in a non-random manner, under geologically plausible conditions.

INDEX

(Names of individual missions and spacecraft are in italics.)

- accretion energy 103
- Advanced X-ray Astrophysics Facility (AXAF)* 113
- Aldebaran (star) 95
- Aldrin, Edwin E. 4
- alpha Centauri (star) 106
- amino acids
 - extraterrestrial 152
 - laboratory synthesis 216
 - meteorites 53, 202, 216
 - Moon 216
- Andromeda
 - galaxy 108, 110, 111, 113
 - distance 110
 - mass 108
 - ultraviolet light 110
 - X-ray sources 110
- Antarctic dry valleys 156
- Antarctic microbes 156, 216
- Antares (star) 95
- Antenna, spacecraft tracking 7
- Apollo* 185, 214
 - Apollo 8* 133
 - Apollo 9* 131, 133
 - Apollo 11* 1
 - Apollo 12* 187
 - Apollo 15* 16
 - Apollo 16* 17, 209
 - Apollo 17* 1, 123
- Archaeobacteria 216
- armalcolite (mineral) 185
- Armstrong, Neil 4
- asteroid belt 51
 - collisions in 202, 194
 - traversed 201
- asteroids 50ff, 201, 202
 - Apollo-Amor 51
 - Ceres 51
 - chemical composition 201, 202
 - Chiron 202
 - collisions 202
 - compositional families 201
 - Earth-crossers 51, 201
 - Icarus 51, 201
 - infrared observations 201
 - origin 53
 - radar contacts 201
 - Ra-Shalom 50, 201
 - Vesta 202
 - volcanic eruptions 58, 202
- astronauts (see also individual names) 124ff
- astrophysics 208ff
- Atmosphere Explorers* 207
- atmospheres (planetary)
 - evolved 60
 - original 60
- aurorae
 - Earth 76, 82, 83, 206
 - Jupiter 31, 194
 - Saturn 198
- bacterial and microbial changes in space 214, 215
- Bean, Alan 132
- Betelgeuse (star) 95
- bicycle ergometer 129, 130, 132
- Big Bang 7, 8, 90, 94, 108, 117, 213
- biomedical research 214ff
- biosphere 126
- BL Lacertae objects 116
- black holes 90, 97, 100, 103, 121, 208, 211
- blood, changes in space 128, 129, 214, 215
- blue supergiant stars 95
- bombardment meteoroidal 58, 59
 - Callisto 33, 59
 - Dione 43, 200
 - Earth 58, 59
 - Mars 21, 59
 - Mercury 18, 19, 58
 - Mimas 43, 200
 - Moon 16, 17, 58, 187
 - near Saturn 200
 - Rhea 43, 200
 - Tethys 43, 200
 - Venus 59
- bone, changes in space 130, 214
- cardiovascular changes in space 128, 129, 214, 215
- Cassiopeia A 89
- Centaurus A 109
- Cernan, Eugene 1, 123
- chemical evolution 149, 216
- chimpanzee flight 127
- chromosphere, solar 70, 72, 75
- chromospheres, stellar 73
- circulatory changes in space 128, 129
- clays, role in origin of life 154ff, 216
- climate, planetary 61, 62
- closed ecology food systems 134
- Columbus, Christopher 4
- comets 54ff, 107, 202, 203
 - Bennett 202
 - Bradfield 203
 - chemical composition 203
 - cloud of 54
 - coma 54
 - dirty ice ball theory 203
 - dust grains 202
 - Halley 55, 57, 164
 - hydrogen clouds 202
 - icy-grain-halo 203
 - Kohoutek 54, 203
 - non-gravitational force 202
 - nucleus 54, 202
 - Seargent 203
 - Tago-Sato-Kosaka 202
 - tails 54
 - water vapor 203
 - West 54, 203
- Conrad, Pete 129
- Cooper, L. Gordon 128
- Copernican theory 5
- Copernicus* 202, 212, 213
- coronae, stellar 73, 90, 99
- COS-B satellite 211
- Cosmic Background Explorer (COBE)* 116, 120
- cosmic evolution 149
- cosmic rays 93, 187, 205, 209, 210, 214
 - biological effects 137
 - light flashes 137, 214
- Crab Nebula 100ff, 211
 - pulsar 211, 212
- Cygnus X-1 103, 208
- Delta rocket 4
- density 93
- diet, in space 134
- dust, interplanetary 56, 57
- Earth
 - acid rain 61
 - atmosphere 60, 61, 84
 - bow shock 206
 - climate 61, 62, 85
 - diameter 121
 - electric currents 59, 206
 - future 63
 - history of life 156
 - Ice Ages 61
 - impact craters 51, 58, 59
 - Meteor Crater, Arizona 59
 - ionosphere 66, 84, 206, 207
 - magnetic field 59, 60, 66, 67, 76, 80ff, 210
 - magnetopause 206
 - magnetosphere 80ff, 206
 - magnetotail 80ff, 206
 - Mississippi River 131
 - orbit diameter 121
 - ozone layer 84
 - polar ion wind 207
 - prebiotic synthesis 149
 - primitive atmosphere 149, 152, 216
 - seen from the Moon 9
 - temperature history 72
 - Tunguska event 59
 - weather 59, 60, 84, 85
- electromagnetic radiation 93
- energy 92
- eta Carinae (star) 90, 91
- eukaryotes 216
- European Space Agency (ESA) 167
- exobiology 147, 216
- Explorer* satellites 207
 - Explorer 1* 80, 81
- extraterrestrial life, search for 158, 178ff
- extravehicular activity 125, 214
- extreme ultraviolet telescope 213
- flares, solar 66, 70, 73, 76, 204ff
- flares, stellar 73
- flyby missions 12

- Gargarin, Yuri 124, 126
galactic corona 113, 212, 213
galactic magnetic fields 210
galaxies 92, 108ff
 Andromeda 108, 110, 111, 113
 Centaurus A 109
 dwarf 108
 Magellanic Clouds 108, 109, 113, 209, 213
 Milky Way 108, 209, 213
 NGC 4151 114
 normal 109ff
 radio 108
 recession speeds 94
 Seyfert-type 108, 114, 116
 spiral 108, 113
 X-ray emission 113, 116, 213
 young 116, 213
galaxy clusters
 Virgo 117
 X-ray 113
Galilean satellites, of Jupiter 31
Galileo 31, 35, 68
Galileo mission 152, 163, 164
gamma ray background 116
gamma ray bursts 109, 175, 208, 209
Gamma Ray Observatory
 (GRO) 120
gamma ray pulsars 102
Garriott, Owen 128, 130, 135
gas giant planets 12, 13, 28ff, 60
 prebiotic synthesis 152
Geiger-Muller counter 209
Gemini project 214
Gemini 4 125
General Theory of Relativity 212
geocorona 67
geologic clock diagram 157
geomagnetic storms 79
G-force 124
Gibson, Ed 54
Goddard Space Flight Center 99
gravitational waves 212
gravity, biological aspects 126
gravity-assisted maneuvers 169
greenhouse effect 25
- Hale Telescope 174
Ham (chimpanzee) 127
heart rate, space effects 214
heliosphere 83, 206
 heliospheric physics 205, 206
Hercules X-1 103
High Energy Astronomy Observatory
 HEAO-1 109, 213
 HEAO-2 89, 99, 100, 110, 113, 116
 HEAO-3 94, 210
high-velocity streams 79
hormones, changes in space 214
HZE radiation particles 124, 137
- immune deficiency disease 142
Infrared astronomy 107
infrared Astronomy Satellite
 (IRAS) 120, 174
intergalactic space 117
International Solar Polar Mission
 (ISPM) 169
International Sun-Earth Explorer
 (ISEE) 206
International Ultraviolet Explorer
 (IUE) 98, 99, 113, 203, 213
interplanetary dust 203
interplanetary magnetic field 78ff, 210
 neutral sheet 206
 sector structure 78, 79, 206
Interplanetary Monitoring Platform
 IMP-1 78
 IMP-7 210
 IMP-8 210
interstellar bubbles 99, 104ff, 213
interstellar clouds (gas) 212, 213
interstellar dust clouds 90
interstellar dust grains 107, 212
interstellar gas 105ff, 211ff
 near Sun 213
interstellar matter 210, 212, 213
interstellar molecules 216
ionizing radiation, biological
 effects 137
ionospheric physics 206, 207
- jet streams
 Earth 61
 Jupiter 31, 61, 194
 Saturn 38, 198
Jupiter 11, 28ff, 194ff
 atmosphere 28, 30, 31
 aurorae 31, 194
 chemical composition 28, 30, 194, 196
 circulation patterns 194
 clouds 28, 194
 diameter 121
 electric currents 196, 197
 energy excess 196
 energy sources 30
 high-energy particle
 emissions 196
 interior 194
 jet streams 31, 61, 194
 lightning 31, 196
 magnetic field 30, 33, 59, 60, 83, 196, 197
 magnetic tail 30, 196
 magnetosphere 30, 33, 83, 196, 197
 mass 121
 moons 30ff, 197
 Amalthea 31, 197
 Callisto 31, 33, 197
 Europa 11, 30, 33, 197
 Ganymede 31, 33, 197
 Io 11, 30, 32, 33, 44, 58, 197
- orbit diameter 121
plasma sheet 196
polar regions 194
radio bursts 30, 197
Red Spot 11, 28, 29, 31
ring 31, 197
shape 194
storms 28, 29
temperature 194
- KREEP basalts, on Moon 185
Kuiper Airborne Observatory 46, 196, 201
- lava
 asteroids 58
 lunar 16, 58
 Martian 21, 58
 Mercury 58
Leo constellation 119, 213
life
 extraterrestrial 145ff, 185
 origin of 146ff, 216
 detection experiments 150, 151
 support systems 177
light, speed of 91
lightning
 Jupiter 31, 196
 Saturn 199
 Venus 190
Lower Body Negative Pressure
 Device 128
Luna sample return mission 164, 167
 Luna 1 (USSR) 184
 Luna 3 184
 Luna 9 184
lunar bombardment 187
lunar craters
 Copernicus 187
 Tsiolkovsky 2
 Tycho 187
lunar crust 16, 17, 185, 186
lunar exploration 184ff
lunar highlands 16, 184
lunar lithosphere 186
Lunar Module 133
Lunar Orbiters 185
lunar outgassing 186
Lunar Roving Vehicle 1, 123
lunar sample missions 15, 185
lunar soil 17, 185, 187
lunar terrain 184
lunar valleys
 Littrow 15
- Magellanic Clouds (galaxies) 108, 109, 113, 209
 coronae 213
magnetism, planetary 12, 13, 59, 60
 Earth 59, 60, 66, 67, 76, 80ff, 210
 Jupiter 30, 33, 59, 60, 83, 196, 197

- Mars 59, 60
- Mercury 59, 60, 188
- Moon 59, 60, 186
- Saturn 38, 41, 60, 83, 198
- Venus 59, 60, 189
- magnetosphere
 - Earth 80ff, 206
 - Jupiter 83, 196
 - Mercury 83
 - Saturn 83, 198
- magnetospheric physics 206
- magnetotail
 - Earth 80ff, 206, 207
 - Jupiter 30, 196
- maria, lunar 16
- Mariner* spacecraft 205
 - Mariner 2* 79, 189
 - Mariner 4* 191
 - Mariner 6* 191
 - Mariner 7* 191
 - Mariner 9* 191
 - Mariner 10* 18, 19, 54, 120, 190
- Mars 20ff, 191ff
 - aerosol dust 190, 192
 - atmosphere 21, 22, 60, 61, 191, 193
 - bombardment 21, 59
 - channels 21, 191
 - chemical composition 191ff
 - climatic changes 62
 - clouds 191, 192
 - craters 21, 191
 - Argyre 21
 - dry ice 191
 - dust or sand storms 61, 192
 - environment for life 156
 - fog 192
 - ice ages 21, 192
 - lava flows 58, 191, 192
 - life 22, 192, 216
 - magnetic field 59, 60
 - moons 192, 193
 - polar caps 21, 191ff
 - prebiotic synthesis 150
 - red color 22
 - rifting 22
 - rocks 22, 23, 192
 - sample return mission 164
 - sediments 22
 - sky color 192
 - soil 22, 23, 150, 155, 156, 192, 216
 - surface pressure 192
 - temperature 192
 - Utopia region 22, 23
 - valleys 191
 - Vallis Marineris 191
 - volcanoes 21, 58, 191
 - Olympus Mons 21
 - water 192, 193
 - winds 192
- Mars 3* 191
- mascons, lunar 185
- Maunder Minimum 85
- medical benefits of space
 - research 142
- memory repatterning 133
- Mercury 18, 19, 188
 - atmosphere 188
 - Caloris Basin 188
 - craters 18, 19, 188
 - flybys 18, 188
 - lava flows 58
 - magnetic field 59, 60, 188
 - rotation period 188
 - scarps 19, 188
 - shape 188
 - temperature 19
- Mercury* project 127, 128, 214
- Mercury-Redstone 2* flight 127
- Meteor Crater, Arizona 59
- meteorites 50ff, 202
 - Allende 202
 - amino acids 53, 202, 216
 - cooling rates 202
 - environmental exposure
 - ages 202
 - formation ages 202
 - ion production in
 - atmosphere 207
 - isotopes 202
 - lava 202
 - mineral inclusions 202
 - Murchison 153
 - parent bodies 202
 - trapped gases 202
- microfossils 156, 216
- microorganisms 156
- microwave background
 - radiation 8, 90, 117, 119, 120, 210, 213
- Milky Way galaxy 5, 108, 209
 - corona 113, 212, 213
 - motion 213
- Moon 15ff, 184ff
 - chemical composition 185
 - far side 184
 - formation 185
 - fossil magnetism 60, 186
 - magnetic field 59, 60, 188
 - minerals 186
 - mining 167, 177
 - polar orbiting spacecraft 166
 - search for life 150, 185, 216
 - shape 185
 - Taurus-Littrow site 123
 - unanswered questions 166
- moonquakes 186
- Moon rocks 16, 17, 59, 60, 185, 186
- motion sickness 133, 214
- muons 209
- muscle atrophy, in space 130, 214
- nebulae 90, 95
 - Crab Nebula 100ff, 211
 - eta Carinae 90, 91
 - Orion Nebula 95
 - planetary 105
- Neptune 48
 - cloud patterns 201
- neutron stars 93, 97, 100ff, 109, 116, 121, 209, 211
- nuclear reactions, stellar 97
- nucleic acid polymers, synthesis
 - of 216
- oceans, primordial 154, 155
- Olson, Roger H. 84
- Open Universe theory 212
- Orbiting Astronomical Observatories*
 - OA0-2 54, 202
 - OA0-3 (*Copernicus*) 202, 212, 213
- Orbiting Geophysical Observatories*
 - OGO-31 202
- Orbiting Solar Observatories* 204
 - OSO-7 76, 205
 - OSO-8 4, 205
- organic molecules
 - comets 147, 152, 203, 216
 - Earth 149, 152
 - interstellar 146, 152
 - Mars 150
 - meteorites 147, 152, 153, 202
 - Moon 150
 - outer planets 216
- Orion Nebula 95
- ozone layer 84
- Parker, Eugene 76
- Pegasus 1* 203
- photosphere, solar 70, 72
- Pioneer 10* 3, 12, 46, 83, 92, 105, 194, 196, 197, 201, 203, 206
- Pioneer 11* 105, 194, 196, 197, 203
- Pioneer Saturn* 35, 38, 198, 199
- Pioneer Venus* 25, 26, 163, 190
 - entry probes 25, 190
- Pioneer Venus Orbiter* 25, 27
- planetary atmospheres 60, 61
- planetary exploration 188ff
 - future steps 62
- planetary nebulae 105
- planetes (Greek) 5
- planetesimals 43
- planetology, comparative 58ff
- planets
 - occurrence in space 146, 178
 - search for 178
- Pluto 49, 201
 - moon, Charon 49, 201
 - orbit 49
 - surface methane 49, 201
- prebiotic synthesis 152
 - Earth 149
 - gas giant planets 152
 - Mars 150
- primitive atmosphere
 - Earth 149, 152, 216
 - Titan 44

- prokaryotes 216
 protosolar cloud 12, 13
 pulsars 100ff, 116, 211, 212
 binary pulsar 212
 CP 1919 211
 Crab pulsar 211, 212
 drifting subpulses 212
 gamma rays 211, 212
 giant pulses 212
 nulling 212
 optical pulses 212
 Vela pulsar 102, 212
 X-rays 211, 212
 pyroxferroite (mineral) 185

 quasars 114ff, 210, 211, 213
 BL Lacertae objects 116
 gamma rays 211
 infrared radiation 210
 OX 169 211
 redshifts 210, 211
 3C 273 114ff, 210, 211
 X-ray images 119
 X-rays 210, 211

 radio telescopes 178ff
 Ranger 7 184
 Ranger 8 184
 Ranger 9 184
 red dwarf stars 95, 121
 red giant stars 95, 97, 121
 Red Planet, see Mars
 Red Spot, see Jupiter
 rifting
 Mars 22
 Tethys 43, 44
 Venus 26, 27
 Rigel (star) 97
 rings
 Jupiter 31, 197
 Saturn 34ff, 198ff
 Uranus 201
 Roberts, Walter Orr 84

Salyut (USSR) 130, 134, 214
 Saturn 34ff, 198ff
 ammonia haze 35, 38, 198
 atmosphere 61, 198
 aurorae 198
 chemical composition 198
 circulation patterns 198
 clouds 35, 36, 38, 198
 energy source 38, 198
 interior 198
 jet streams 38, 198
 lightning 199
 magnetic field 38, 41, 60, 83, 198
 magnetosphere 83
 moons 35ff, 199, 200
 bombardment 43
 composition 200
 Dione 35, 38, 43ff, 199, 200
 Enceladus 43ff
 Iapetus 44, 199, 200
 Mimas 43ff, 200
 Nos. 10-14 199
 No. 15 200
 Rhea 35, 43ff, 199, 200
 shepherd moons 40, 43, 199
 Tethys 38, 43ff, 200
 tidal forces 44
 Titan 13, 35, 44, 45, 199, 200, 216
 radiation belts 38, 198
 red oval 38, 198
 rings 34ff, 198ff
 A-ring 38, 199, 200
 B-ring 35, 38, 199
 braided 38, 199
 C-ring 35
 Cassini Division 35, 38, 199
 elliptical 38
 F-ring 38, 40, 43, 199
 G-ring 199
 particles 38, 41, 198, 199
 ringlets 199
 spokes 38, 41, 43, 199
 theories 43, 199
 temperature 38, 198
 winds 198
 Saturn Orbiter 164
 scarps 19, 188
 Schirra, Walter M. 128
 Schmitt, Harrison 15
 Schweickart, Rusty 133
 Scott, David 131
 sensory changes in space 215
 Seyfert, Carl 108
 Seyfert-type galaxies 108, 114, 116
 Shepard, Jr., Alan B. 126
 Sirius (star) 95, 106, 121
 Skylab 54, 65, 75ff, 128, 130, 133ff, 177, 205, 214, 215
 Skylab Workshop 129
 Small Astronomy Satellites
 SAS-2 212
 solar constant 85, 205
 Solar Electric Propulsion System (SEPS) 166
 solar flares 66, 70, 73, 76, 204ff
 Solar Maximum Mission 205
 solar system 12ff
 age 43, 51
 formation 12, 51, 53
 motion 119
 solar-terrestrial physics 204ff
 solar wind 54, 60, 73, 76, 79ff, 187, 189, 202, 205, 206, 210
 Soyuz (USSR) 214
 space colonies 139ff
 space food 134, 135
 space medicine 124ff
 space sickness 133
 space suits 142
 Space Telescope 120, 172ff, 178
 space walk 125
 spiders, in space 136, 138
 Sputnik 1 4, 5, 7
 Spacelab 86, 177
 Spacelab Infra-Red Telescope Facility (SIRTF) 120
 SS 433 99
 stars
 diameters 121
 masses 121
 normal 95, 97
 rotation 99
 spot cycles 73
 winds 97, 99, 103, 105, 106
 Sun 65ff, 204ff
 active regions 204
 arcades 75, 205
 as a star 72, 73, 121
 balance of forces 95
 chemical composition 68, 70
 corona 72, 73, 75ff, 204ff
 coronal holes 75, 79, 169, 205
 coronal transients 76, 77, 205
 diameter 70, 121
 flares (see solar flares)
 gamma rays 204
 magnetic field 67, 72, 75, 79, 205, 206
 magnetic loops 75, 76, 205
 Maunder Minimum 85
 M-regions 76, 79
 nuclear reactions 70, 73, 204
 oscillations 204
 photosphere 70, 71
 polar regions 169
 prominences 65, 73, 76, 77, 205
 radiation 70, 71, 204
 radio bursts 204
 spicules 205
 structure 68ff
 supergranulation 204
 temperatures 70, 72
 weather effects 84, 85
 X-ray bright points 76, 205
 X-ray bursts 204
 X-ray photographs 74, 75
 Sun-Earth interactions 170
 sunspot cycle 68, 73, 85, 86, 207, 210
 sunspots 68, 76
 supergiant stars 95, 97, 99, 102, 121
 supernova 100ff, 202
 remnants 89, 100ff, 109, 209
 solar system formation 52, 53
Surveyor
 Surveyor 1 184
 Surveyor 3 187
 Surveyor 5 184
 Surveyor 7 184

 temperature in space 92
 terrestrial planets 12, 13, 15ff, 60
 tidal heating 32
 Titov, Gherman 133
 tranquillityite (mineral) 185
 trapped radiation
 Earth 33

- Jupiter 33
- troposphere 84
- Tsiolkovsky (lunar crater) 3
- Tunguska event 59
- Uhuru* 208
- universe 117ff
 - Big Bang 7, 8, 90, 94, 108, 117, 213
 - closed 94
 - expansion 117, 212
 - extent 92
 - gas density 117
 - homogeneity and isotropy 213
 - origin 117, 213
- Uranus 46ff
 - axis 46
 - rings 46, 201
 - Voyager 2* flyby 12, 46, 48
- urinary changes in space 214
- Van Allen, James 80
- Van Allen belts 33, 38, 80, 81, 206
- variable stars 97
- Vega (star) 95
- Vela* satellites 208
- Venera* (USSR)
 - Venera 7* 189, 190
 - Venera 9* 190
 - Venera 10* 190
 - Venera 11* 190
 - Venera 12* 190
- Venera* landers 26, 189, 190
- photographs 26
- Venus 24ff, 189, 190
 - aerosols 26, 62, 190
 - atmosphere 24, 25, 60, 61, 190, 198
 - chemical analysis 26, 189
 - circulation patterns 24, 25, 189, 190
 - clouds 25, 61, 189, 190
 - craters 27, 190
 - lightning 190
 - magnetic field 59, 60, 189
 - plateaus 26, 27, 190
 - Ishtar Terra 26
 - radar mapping 26, 27, 164, 190
 - rifts 26, 27
 - rocks 26, 190
 - rotation 25, 60, 189
 - surface 190
 - surface pressure 189
 - temperature 25, 189
 - volcanic landforms 58, 190
 - Beta Regio 26
 - winds 190
- Venus Orbiting Imaging Radar (VOIR)* 164
- Very Large Array (VLA) 120
- vestibular apparatus 133
- Viking* landers 21, 22, 192
 - experiments 150, 151, 153, 155, 156, 192, 216
 - labeled release experiment 155
- Viking 1*, photographs 20, 21
- volcanism 58, 60
 - and origin of like 144ff
 - asteroidal 58, 202
 - Earth 85, 144
 - Io 58, 197
 - lunar 58
 - Martian 22, 58
 - Mercury 58
 - Venus 58
- volcanoes
 - ancient asteroidal 51
 - Enceladus 44
 - Io 32, 33, 44, 58, 197
 - Mars 21, 58, 191
 - Venus 26, 58, 190
- Voskhod* (USSR) 214
- Vostok* (USSR) 126, 214
 - Vostok 2* 133
- Voyager 1* 13, 35, 38, 105, 106, 170, 194ff, 200
 - Jupiter flyby 194
 - Saturn flyby 35, 43, 199
 - Titan flyby 44
 - photographs 11, 30ff, 35, 39ff
- Voyager 2* 12, 13, 102, 169, 194ff
 - Jupiter flyby 194
 - photographs 29ff
 - Saturn flyby 163
 - Uranus flyby 12, 46, 48, 163
- water, on planets 13
- weather, planetary 61, 62
- weight loss in space 134, 214
- weightlessness 124, 126ff, 138, 177, 214
- White, Edward H. 125
- white dwarf stars 97, 100, 106, 121, 213
- X-ray background 114ff, 213
- X-ray binary stars 103
- X-ray observatories 114
- X-ray pulsars 103
- X-ray sources 208
- X-ray telescopes 116
- X-rays, soft 116
- X-rays, stellar 99
- zodiacal light 57, 203

