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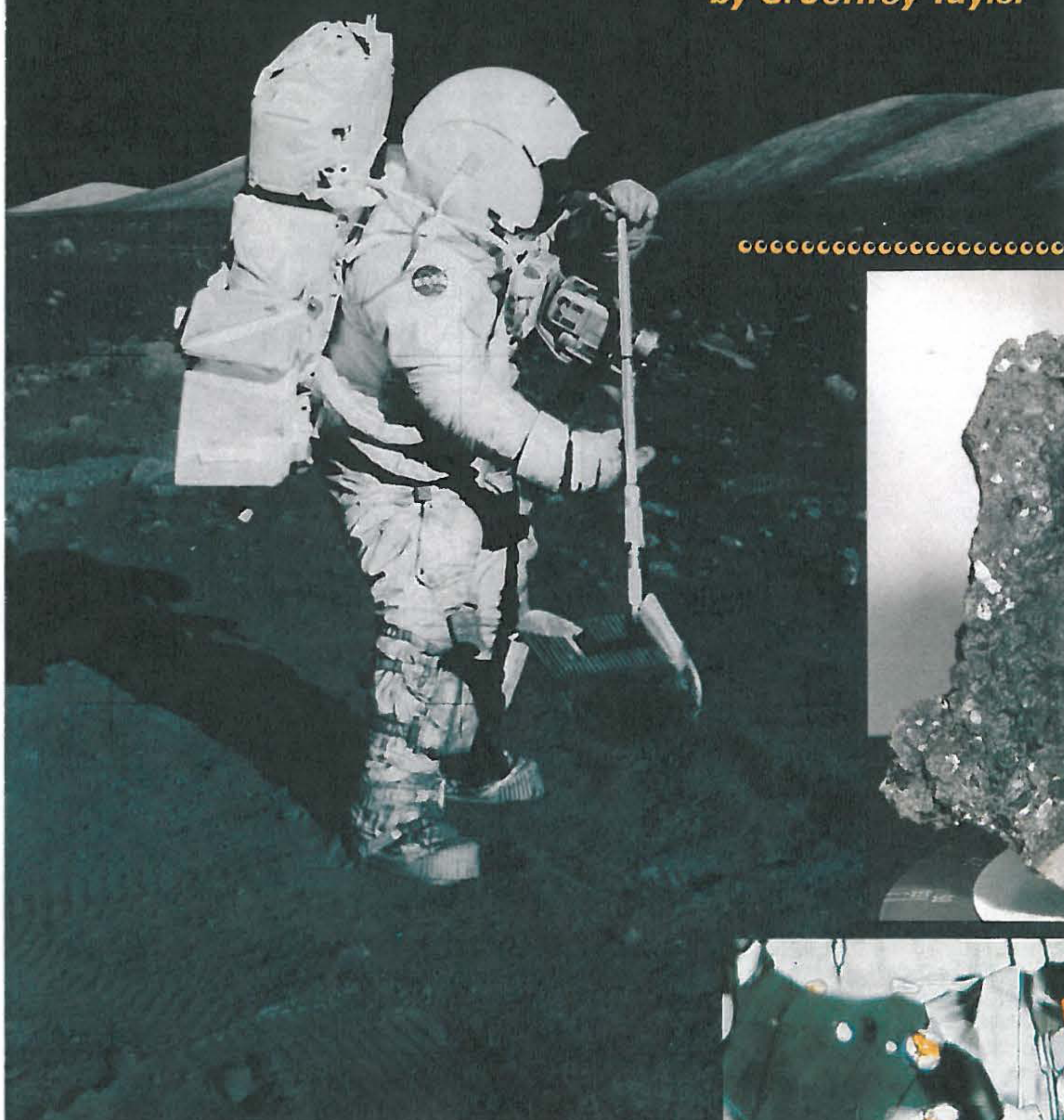
Samples from Space

MOON ROCKS

STILL NEW QUESTIONS ABOUT AN OLD MOON

by G. Jeffrey Taylor

The Moon has not changed in the 15 years since Neil Armstrong stepped off a ladder onto its du surface, but our ideas about it ha undergone a revolution. The Moon rocks, the tangible achievement of a dream fulfilled in 1969, have become far more than anyone, scientist or astronaut, could then have imagined. From the *Apollo* landings and Soviet automated sample returns, Earthlings obtained 381 kilograms (kg) of lunar rocks and soil to heft, examine, analyze and admire. And from these materials have come a host of revelations on the forces that shaped the early solar system, the early history of an Earthlike planet, and the histories



ABOVE: Scientist-astronaut Harrison H. Schmitt collects lunar rake samples at the Taurus-Littrow landing site during the Apollo 17 mission. His lunar rake collected discrete samples of rocks and rock chips ranging in size from one-half inch (1.3 cm) to one inch (2.5 cm).

ABOVE: This microscopic view (1.5 millimeters across) of a mare basalt was made by shining polarized light through a wafer of rock 30 micrometers thick. The shapes and sizes of the minerals indicate that the rock crystallized in a lava flow. Pyroxene appears as orange and blue, the gray is feldspar.

of the Sun and stars.

One reason for studying the Moon is learn the early history of Earth. The Moon is the only large body that we can readily study to find out what happened during and soon after the planets' formation, 4.6 billion years ago. On Earth, the record of our first 700 million years has been destroyed by our world's own geological activity. The less-active Moon still contains that record, cryptically preserved in its ancient rocks.

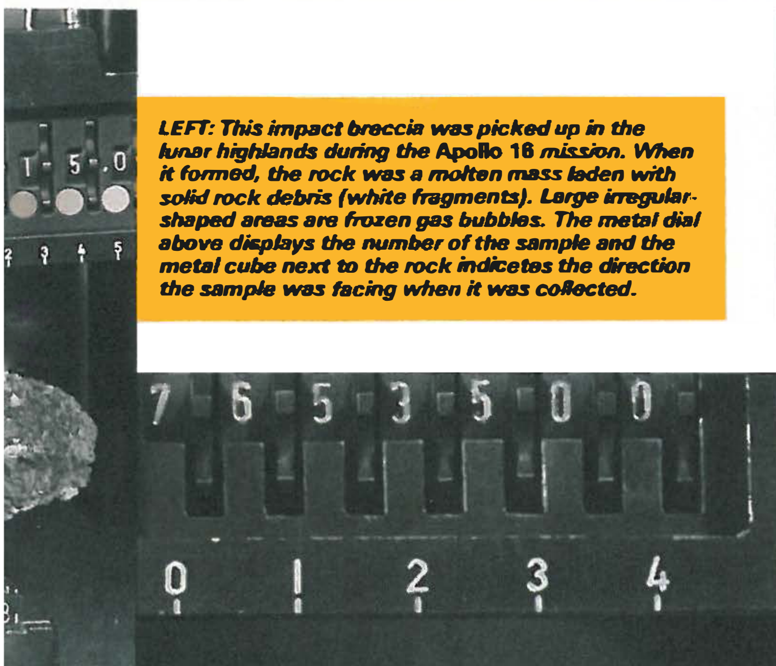
Differing Chemistries

There are fundamental chemical differences between Earth and the Moon. Some of the first discoveries made from the *Apollo 11* lunar samples were that Moon rocks have absolutely no water and no organic materials, and they contain much smaller amounts of other easily evaporated volatile elements such as sodium, than do Earth rocks.

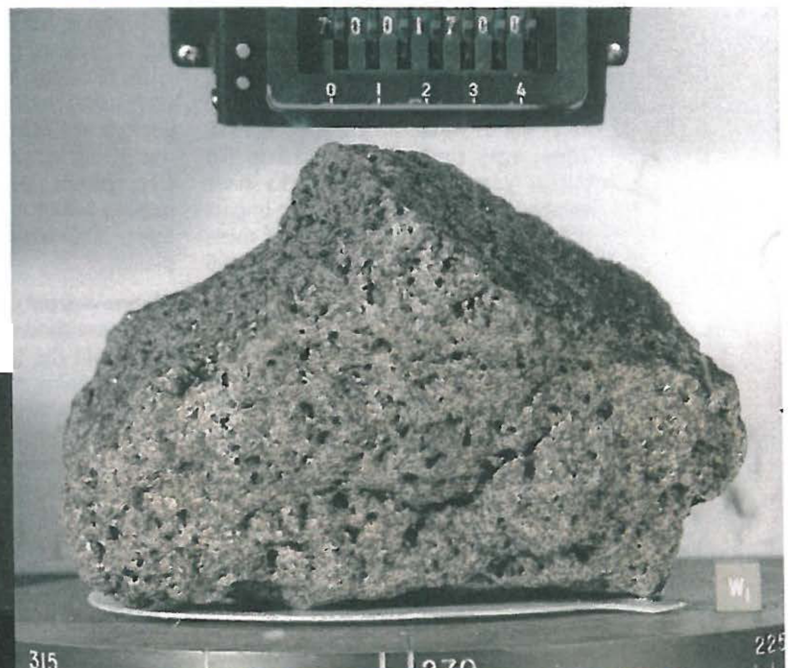
There are two different landscapes on the Moon. The *highlands* are higher, lighter in color, more rugged, and older than the *maria,* which are darker, smoother and younger. The highlands owe their rugged nature to the countless craters formed when large meteorites struck the Moon early in its history. Some of these craters are the size of Texas and were made by objects the size of Rhode Island. The younger maria also have craters, but not as many, because the rate at which meteorites hit the Moon has decreased with time.

The rocks of the highlands reflect the fierce battering that the early Moon received. Most of them, called *breccias,* are composed of broken fragments of other rocks. Many breccias contain rock fragments that are themselves breccias, some with still other breccias inside them. These complex rocks clearly show the important role that continuous meteorite impact played in shaping the ancient lunar surface.

Almost all the minerals found in Moon rocks were already known from Earth rocks. The exceptions are three



LEFT: This impact breccia was picked up in the lunar highlands during the Apollo 16 mission. When it formed, the rock was a molten mass laden with solid rock debris (white fragments). Large irregular-shaped areas are frozen gas bubbles. The metal dial above displays the number of the sample and the metal cube next to the rock indicetes the direction the sample was facing when it was collected.



ABOVE: Astronauts collected this sample of mare basalt during the Apollo 17 mission. It contains brownish pyroxene and ilmenite, and white feldspar. The holes are frozen gas bubbles called vesicles.

LEFT: This magnificent specimen, collected by the Apollo 17 astronauts, is one of the few rocks from the lunar highlands to have escaped the intense bombardment the Moon suffered early in its history. It consists of feldspar (white to light gray) and olivine (yellow brown). The rock's age of 4.5 billion years indicates that it was one of the first rocks to crystallize in the lunar crust.

PHOTOS: JOHNSON SPACE CENTER/NASA

minerals that could form only under the waterless, low-oxygen conditions that prevailed on the Moon. One of them, an oxide of iron and titanium, was named *armalcolite* for the crew of *Apollo 11* (*Arm*strong, *Al*drin and *Col*lins).

Highland rocks are rich in the white mineral feldspar, a silicate of calcium and aluminum. Some rocks are composed almost entirely of feldspar. Others contain less feldspar and more of such minerals as olivine and pyroxene, which are silicates of iron and magnesium. Some unique highland rocks contain significantly more potassium (chemical symbol *K*), rare-earth elements (abbreviated *REE*) and phosphorus (*P*) than do other lunar samples. This characteristic has earned them the nickname "KREEP."

We can determine the ages of lunar rocks by measuring the abundances of certain radioactive elements. The original ages of most highland rocks have been reset by the shock and heating produced by huge meteorite impacts, and the numbers we obtain from these rocks tell us when the impact occurred. These ages cluster around 3.9 to 4.0 billion years ago. Some rocks have escaped the ravages of meteorite impact and preserve older ages; a few of these rocks are as old as the Moon itself, 4.6 billion years.

The rocks of the lunar maria are quite different from those in the highlands; they are volcanic lavas rich in olivine, pyroxene and iron-titanium oxide minerals. Called *mare basalts*, they formed when molten rock from the Moon's interior came to the surface and flowed across it for great distances.

The Moon's History

The history of the Moon, partly revealed by the lunar rocks, goes back to the beginning of the solar system. When the Moon formed, 4.6 billion years ago, its outer several hundred kilometers was extensively melted, either by the energy released by smaller bodies crashing into the growing Moon or by the heat generated by short-lived radioactive elements such as aluminum-26. As this ocean of molten rock (*magma*) crystallized, the feldspar crystals, which were lighter, floated to the top, forming the feldspar-rich highlands. Denser minerals containing iron and magnesium tended to sink to the bottom. This stage of lunar history was completed 4.4 billion years ago.

Soon after the crust solidified, new magmas, formed by melting inside the Moon, invaded the crust. These crystallized to form younger highland rocks that contain less feldspar than do the older, feldspar-rich rocks. At the same time, the KREEP rocks formed by melting inside the Moon, and much of the molten material erupted in lava flows. This period ended about 4.0 billion years ago.

At the same time, huge meteorites bombarded the Moon, melting, mixing and demolishing the original bedrock and reducing the outer several kilometers of the Moon to a cratered rubble pile. The period of intense bombardment lasted until 3.9 billion years ago; then the impact rate decreased rapidly. The enormous circular basins on the Moon were excavated near the end of the intense bombardment.

Finally, the deep interior of the Moon began to melt from the heat produced by such radioactive elements as uranium and thorium. The regions at depths between 100 and 500 kilometers partially melted, producing new magmas. These reached the surface and flowed into the great impact basins. There the rocks crystallized, forming the dark lavas that make up the lunar maria. This period lasted from 3.9 to about 3.0 billion years ago.

By then, the Moon's heat was apparently exhausted. Since then, it has been geologically quiet and nearly inert. Not much has happened on its lonely surface, except for occasional meteorite impacts and a few recent visits by creatures and machines from a nearby planet.

Unanswered Questions

The most fundamental unsolved problem about the Moon is how it formed. Before *Apollo*, there were three theories: formation with the Earth as a double-planet system, fission from Earth, and formation elsewhere followed by capture by Earth. All three theories are still alive and well, but studies of lunar samples have placed limits on some of them. For example, if the Moon spun off from Earth, it could have done so only when Earth formed 4.6 billion years ago and not more recently. However, the Moon's origin remains unsolved, and before we can solve it, we must fill up some gaping voids in our knowledge about our natural satellite.

Although the outline of lunar history described above seems generally correct, it is still not detailed enough. We need additional research to discover the full range of lunar rock types and to understand the physics and chemistry of the huge ocean of molten rock that existed on the ancient Moon.

The Moon is asymmetric. Almost all the dark maria are on the Earth-facing side of the Moon, and the KREEP rocks are much more abundant on the western half of the Earth-facing side than elsewhere. Why? Do these surface differences reflect lateral or vertical variations in the Moon's crust, or are they caused by deeper variations in the Moon, at depths below about 60 kilometers? Have the enormous impacts produced some of the differences, or have they simply blurred even more pronounced, primordial variations? Answering these questions requires continued study of Moon rocks, including the mare lavas, which originated deep in the Moon.

Filling the Gaps

Can we make progress on problems by studying the 281 kilograms of Moon rocks and soil carefully preserved in Houston? Can we really learn more from the same rocks after 15 years of intense study? Without a doubt! Each year several new rock types are discovered by painstaking examination of the complex highland breccias and lunar soils, which contain thousands of individual rock fragments, patiently waiting for us.

The work goes forward, and it is slow, careful and exciting. Recently my colleague, Dr. Cyrena Goodrich, and I went to NASA's Planetary Materials Laboratory in Houston, where the lunar samples are stored in dry nitrogen gas in special cabinets to protect them from contamination by Earth's oxygen-rich, wet and dusty atmosphere (see *The Planetary Report*, July/August 1982). The laboratory air smells strange because there is nothing in it; it is dry and carefully filtered to remove all dust. The laboratory personnel look like a surgical team, wearing special nylon "bunny suits," hats and gloves.

We had been there several times before to look at lunar rocks. This trip was to examine a freshly-cut slab of a complex highland breccia returned by *Apollo 14* in 1971. Decked out in our bunny suits, Cyrena and I peered through the windows of the stainless steel cabinet at a 10-by-20 centimeter slab of lunar rock. Hundreds of small rock fragments were visible on its surface, varying from white to charcoal gray in color and from less than a millimeter to several centimeters in size. Reaching into the cabinet with special built-in gloves, we moved the slab enough to see that one fragment was a granite, an abundant rock on Earth, but a curiously rare one on the Moon. During the next two weeks, carefully looking and chipping, we separated about 30 bits of different rock types from the parent breccia. It will be a year before the chemical and mineralogical analyses are completed. Only then will we be able to tell where this new information fits into the overall picture of lunar history.

G. Jeffrey Taylor is a research scientist at the University of New Mexico's Institute of Meteoritics. He has written numerous papers about lunar rocks and is also co-author of a science-fiction novel, Impact *(Leisure Books, 1979).*

METEORITES: Little Rocks with Lots of History

by Harry Y. McSween, Jr.

A rock in the hand is worth 2,000 in the sky. As we found from insights made possible by the returned lunar samples, there is no substitute for the detailed study of actual rock samples of other worlds.

For samples from beyond the Moon, we must turn to meteorites. The records preserved in these migratory chunks of matter that have somehow come to Earth are difficult to read, but recent studies of them have revolutionized our understanding of the origin and early evolution of the solar system. Meteoritics (the study of meteorites) is very much an interdisciplinary effort, requiring the skills of scientists trained in geology, chemistry, physics and astronomy. What follows is a summary of some of the most exciting recent discoveries and unsolved problems in meteorite research.

Many people tend to think of meteorites as chunks of metal, but most meteorites observed to fall are rocks. *Iron meteorites* are easily recognized and are thus probably over-represented in museum collections. The more common *stony meteorites* can be divided into two main groups, the *chondrites* (from a Greek word meaning "seeds," an allusion to their being made up of many small, round objects called chondrules) and *achondrites* ("without chondrules," actually igneous rocks that have crystallized from molten lavas).

Chondrites are especially important because they provide the best estimates for the age of the solar system. The time of chondrite formation was about 4.6 billion years ago, as determined from measurements of radioactive isotopes with known rates of decay. Chondrites also contain evidence of other now-extinct radioactive isotopes that decayed very rapidly, suggesting that the time between the solar system's beginning and the formation of chondrites was very short (in the geological sense), possibly only a few tens of millions of years.

One particularly exciting discovery is that many of these isotopic signatures could only have been produced during the massive explosion of a star. These short-lived isotopes could have been incorporated into chondrites only if the explosion was nearby, a fact that has led some scientists to argue that a nearby star-blast triggered the formation of our solar system. They suggest that the shock wave from the explosion compressed interstellar gas and dust to the point where continued collapse due to gravity could occur, eventually forming the central Sun and the planets around it.

Chondrites' chemical compositions closely match that of the Sun, except for gases such as hydrogen and helium. Because almost all of the mass of the solar system is in the Sun, we say that chondrites have an average solar system composition, not altered appreciably since they formed, in contrast to planetary samples whose compositions change each time they undergo melting or other kinds of geological processing. Thus chondrites can be thought of as leftover original planetary building blocks.

Many chondrites do appear to have suffered some alteration by heating, but some have not. These provide an unparalleled record of early solar system processes. White inclusions contained in some of them consist of minerals that could have formed only at high temperatures in the original solar nebula, the cloud of gas and dust surrounding the early Sun. Scientists are now debating whether these white inclusions condensed from hot vapors or whether they are residues from evaporation as the nebula was heated up during its collapse into the Sun. In either case, the white inclusions are probably the oldest bits of solid matter remaining in the solar system. These objects, together with the other components of chondrites such as metal grains, are telling us how various groups of elements separated as the solar system formed, and why the planets' compositions vary.

Some chondrites even contain organic molecules (mostly long chains or rings of carbon atoms connected to hydrogen and oxygen), as well as complex amino acids. Most of the organic units that make up DNA and RNA (the carriers of genetic information in living organisms) have now been found in chondrites. Although these compounds

***ABOVE:* This piece of the Allende meteorite, which fell in Mexico only three months before the Apollo 11 samples came back from the Moon, contains white inclusions that may be among the first bits of solid matter to form in the original solar nebula.**

***LEFT:* A young Mexican meets extraterrestrial visitors — some large pieces of the Allende meteorite, which fell in 1969.**

PHOTOS: BRIAN MASON/ SMITHSONIAN INSTITUTION were not formed by living things, their occurrence in meteorites suggests that the raw materials for life were present throughout the early solar system. Indeed, part of the carbon in chondrites may have formed outside the solar system as interstellar dust.

Many chondrites are *breccias*, rocks composed of angular fragments of other rocks. Such breccias were formed when colliding meteorites crushed and mixed together the various rocks on the surfaces of the meteorite parent bodies. In some cases these breccias formed a kind of rubble on the surface of their parent planets. Similar breccias found on the Moon preserve a record of the ancient solar wind and solar flares in the form of trapped gases from the Sun. The lunar and meteorite breccias are somewhat similar, but the meteorite breccias are older, thus extending the historical record of the Sun back to the earliest days of the solar system. The magnetic properties of the chondrites also provide evidence for an early strong magnetic field in the solar system that has since disappeared.

The achondrites are very different from chondrites. Instead of accreting from small, cold objects, they crystallized from melts, like lavas on Earth. However, the mineral composition of achondrites indicates that most of them could have formed if a chondrite parent body was melted. Their ages are also about 4.6 billion years, indicating that this melting occurred very soon after the chondrite parent bodies formed.

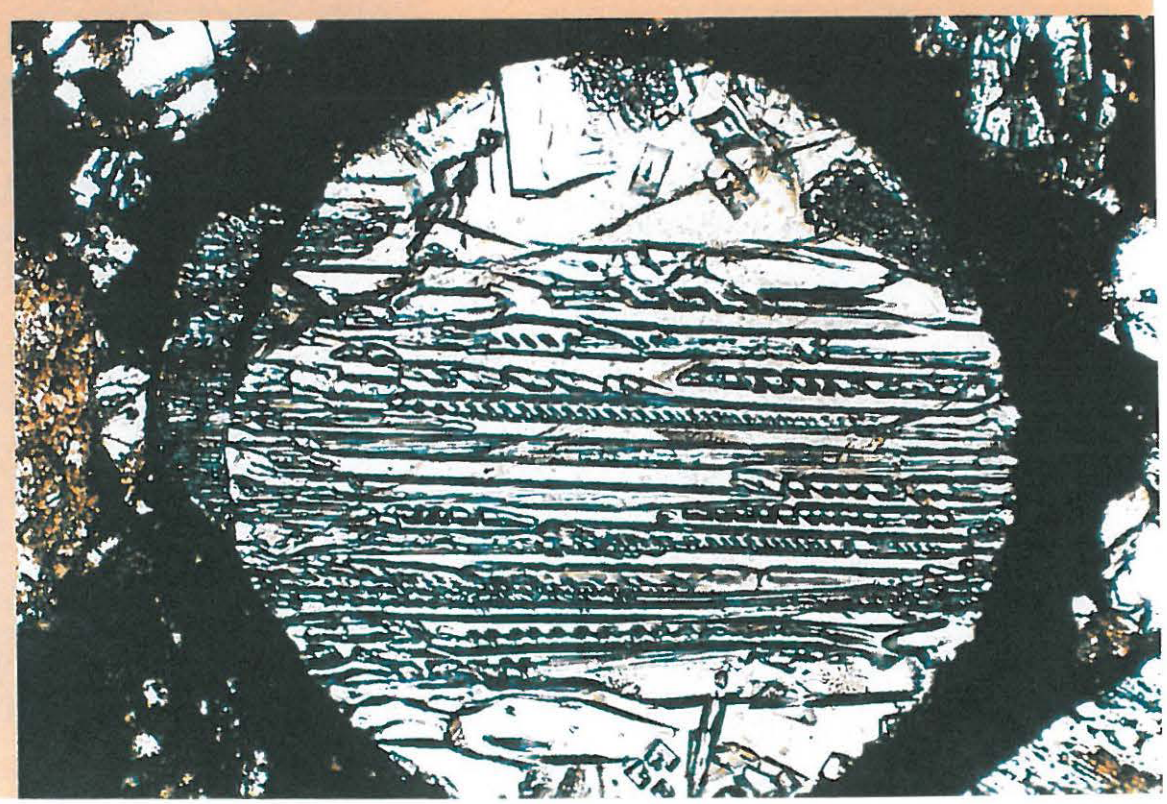
Iron meteorites look quite unlike other meteorite types, but they are probably related to achondrites. Most of them have ages of about 4.6 billion years, although a few are a little younger. We have determined the rates at which iron meteorites cooled and so can estimate the depths at which they formed within their parent bodies. Most iron meteorites have fairly rapid cooling rates, suggesting that they formed as cores within very small parent bodies or as metal accumulations dispersed throughout the bodies. These concentrations of metal may have melted and collected during episodes of partial melting.

All of this information about meteorites raises an obvious question—where do they come from? Some types of chondrites may be the nuclei of burned-out comets. However, most meteorites were probably once parts of asteroids orbiting between Mars and Jupiter. We have determined the orbits of several meteorites before Earth impact; they are elliptical, and the most distant orbital points lie in the asteroid belt. Certain meteorite types can even be assigned to individual asteroids. The spectrum of sunlight reflected from an asteroidal surface can be compared with the spectrum obtained in the laboratory from powdered meteorites. Close matches allow certain asteroids to be recognized as possible parent bodies for chondrites, achondrites and iron meteorites. (See *The Planetary Report*, July/August, 1983.)

Knowing the chemistry of meteorites is also important for interpreting geological events on Earth. For many years geologists have debated the causes of the simultaneous extinction of many animal species at certain times in the past. The most well-known of these events is extinction of dinosaurs at the end of the Cretaceous period, about 65 million years ago, but mass extinctions have also occurred at other times. Recently, scientists have found, at widely separated places on Earth, high concentrations of noble metals such as gold and iridium in sediments deposited at the end of the Cretaceous period. Chondrites have much higher amounts of these elements than terrestrial crustal rocks, so the implication is that a large meteorite struck Earth at that time. The impact might have thrown enough pulverized rock into the atmosphere to alter the environment and cause the extinction. However, similar concentrations of noble metals found at other stratigraphic intervals suggest that other impacts occurred without causing extinctions.

Much of the information gained from meteorites cannot be presently obtained from any other source. Meteoritics attempts to answer major questions about the age and origin of the solar system, the chemical composition and evolution of the Sun and planets, the presence of ancient magnetic fields and heating events, and the internal and surface processes on planets and asteroids. The scientific value of meteorites is vast in relation to their limited quantity, and the secrets contained in these extraterrestrial gifts have only begun to be unraveled.

Harry Y. McSween is a Professor of Geological Sciences at the University of Tennessee and a long-time worker on achondrite meteorites, especially the possible Martian ones.



A single chondrule from the Chainpur meteorite, only a tenth of a millimeter across, displays a network of crystals and glass that formed during the earliest moments of the solar system.

PHOTO: LAUREL WILKENING/ UNIVERSITY OF ARIZONA

COSMIC DUST

The smallest pieces of the solar system begin to tell their stories

by Donald E. Brownlee

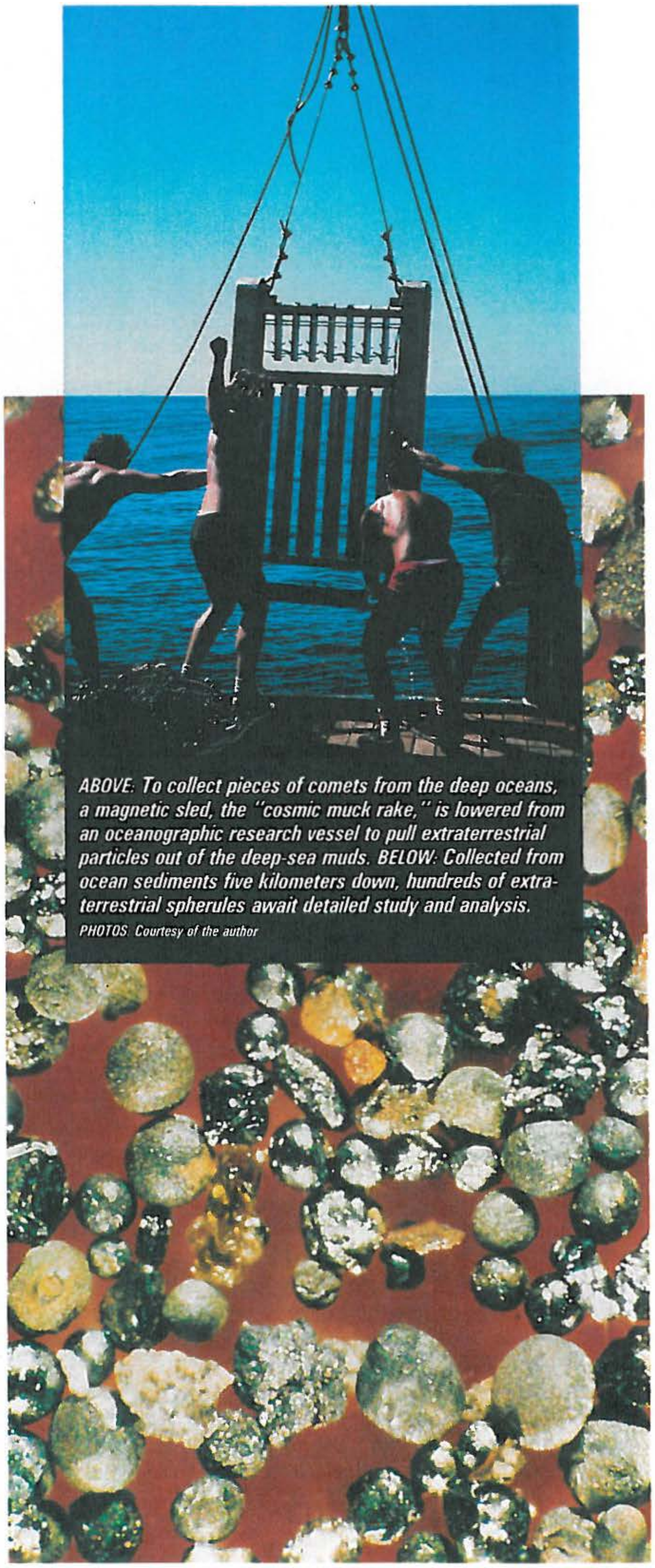
In a truly dark night sky one can actually see the faint glow of sunlight reflected off a thin cloud of dust that fills the space between the planets. This glow, called the *zodiacal light*, appears as a cone of light around the Sun, and it extends upwards from the eastern horizon before dawn and above the western horizon after sunset.

Study of the zodiacal light in the early part of this century provided the first evidence that the space between the planets was not a complete void. There are only a few dust particles in each cubic kilometer of space, but Earth sweeps up nearly 10,000 tons of this material each year as it swings around the Sun. Spacefaring humans regard this dust in two ways. On one hand, it is a minor hazard to spacecraft. On the other, it is a highly sought-after sample of well-preserved material from the early solar system — perhaps even from interstellar space.

None of this dust has been around for very long. Even sunlight can exert enough force on a microscopic dust particle to cause it to spiral into the Sun in less than a million years. Collisions in space destroy many particles even faster. So here is a paradox: Individual dust particles are short-lived, and yet the zodiacal dust cloud seems to have existed for most of the age of the solar system. The solution: The dust cloud must be replenished by fairly continuous supplies of fresh dust. Where does it come from? The most likely sources are the small bodies of the solar system, asteroids and comets. Some of the dust might come from interstellar space.

Comets are obvious suppliers of dust; they develop huge visible dust tails when they get close to the Sun. (They also release the millimeter-sized and larger particles that produce the annual meteor showers.) Comets are composed of ices and dust; when they approach the Sun, the ices vaporize, and the dust particles are released and pushed outward by the escaping gas. Asteroids should also produce dust particles when they collide with each other, but there is no direct evidence yet for any dust in the asteroid belt.

Both comets and asteroids are thought to be relatively unchanged objects left over when the larger planets formed, and dust from these objects should contain preserved clues about the origin of the solar system. Cometary dust is of particular interest because comets must have formed in the outermost fringes of the original solar nebula, where temperatures were low enough for ices to form and survive. In these distant regions, it is even possible that some of the interstellar dust particles that helped form the solar system were trapped and preserved in the icy comets.



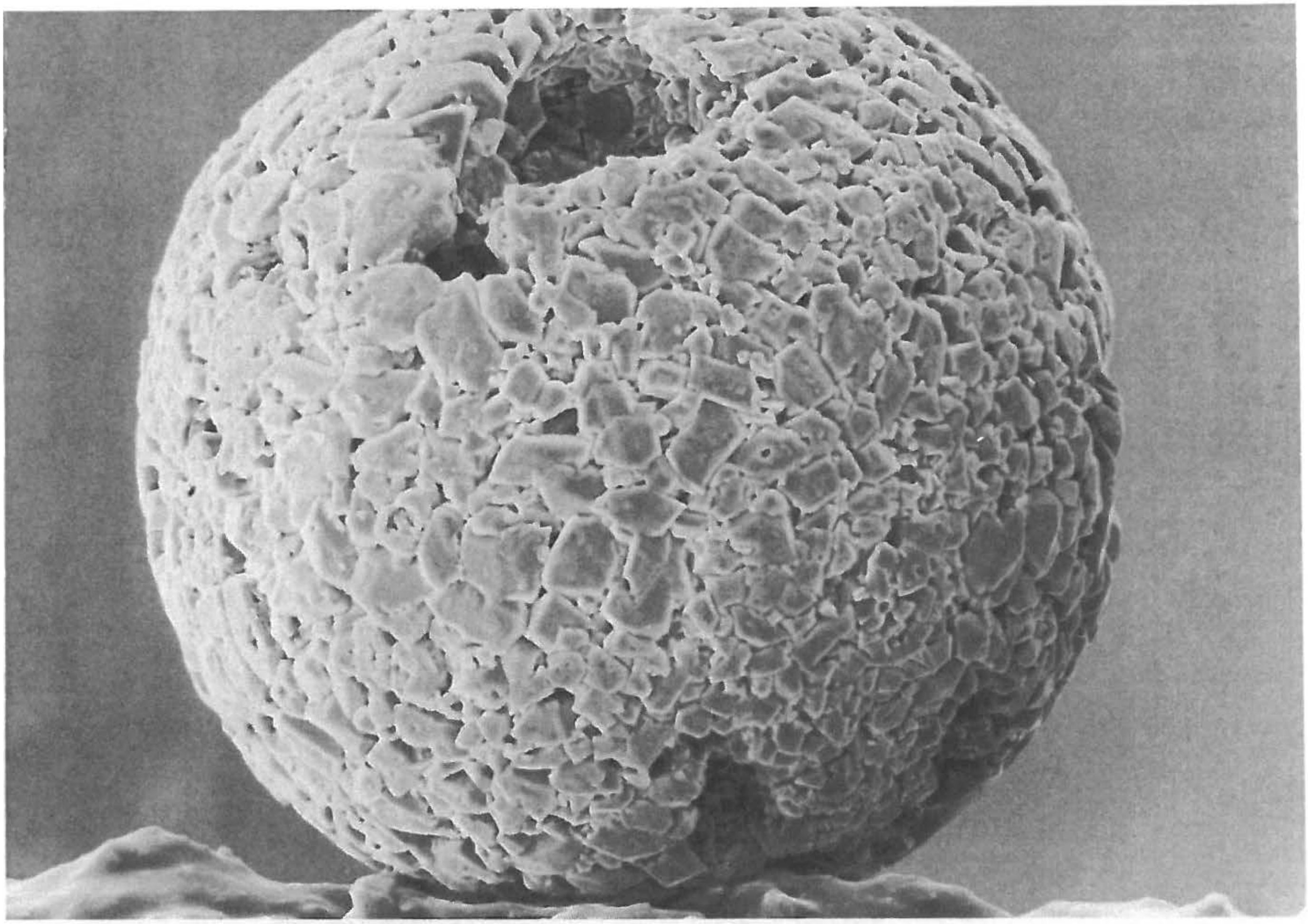
ABOVE: To collect pieces of comets from the deep oceans, a magnetic sled, the "cosmic muck rake," is lowered from an oceanographic research vessel to pull extraterrestrial particles out of the deep-sea muds. BELOW: Collected from ocean sediments five kilometers down, hundreds of extraterrestrial spherules await detailed study and analysis.

PHOTOS: Courtesy of the author

Many of the early studies of cosmic dust were spurred by fear as well as by curiosity. When the first measurements of cosmic dust in space were begun, shortly after World War II, many were concerned that such dust, striking satellites with typical impact velocities of 15 kilometers per second (km/sec) would be a serious threat, and many early spacecraft carried devices to detect and measure dust impacts. The fears that satellites would be hopelessly sandblasted after only a few years in orbit were quickly dispelled by the survival of the first satellites themselves, but assessment of the dust hazard is still going on.

This hazard, although small, is not negligible, especially for large spacecraft or long missions. Both our Space Shuttle and the Soviet *Salyut* space station recently had to replace windows hit by dust particles large enough to produce visible craters. On July 27, 1983, the *Salyut 7* cosmonauts actually heard a loud crack as an impact pit several millimeters across suddenly appeared in their spacecraft window. The cosmonauts described the impact — with considerable understatement — as "an unpleasant surprise." The most serious dust hazard is near a comet, where the dust density is high. Both the Soviet VEGA and the European *Giotto* spacecraft will run considerable risks during their high-speed flybys past Halley's Comet in March, 1986. Although *Giotto* carries a massive shield, it still may have only a 50-50 chance of surviving, even at the presently proposed flyby distance of 500 km.

More recently, spacecraft have taken good measurements of cosmic dust, especially by the *Pioneer* spacecraft, and better dust detectors will be included on such future planetary missions as the *Galileo* Jupiter mission and the European Solar Polar Mission. Several different kinds of dust measurements are planned for the European *Giotto* and Soviet VEGA missions to Halley's Comet, thus collecting unique information about cosmic dust directly at one of



A melted spherule of extraterrestrial matter, collected from the deep ocean floor, shows a beautiful arrangement of crystals when seen by an electron microscope. Most of the crystals are the minerals olivine and magnetite.

PHOTOS: Courtesy of the author

its best-known sources.

An alternative approach is to collect interplanetary dust in space and bring it back to a terrestrial laboratory for detailed examination. The obvious way to collect cosmic dust is to put a dust-catcher in space, leave it there awhile, and then return it to the laboratory. This turns out to be a very difficult experiment. Unless the catcher is very large or is exposed for a very long time, it will collect only a few particles, and these particles would strike the catcher at such high velocities (10 to 50 km/sec) that they would vaporize and make tiny craters. Early experiments of this type were flown on the US manned *Mercury* and *Gemini* spacecraft, and the first genuine particle impact craters were collected on *Gemini 12*. Some new and improved experiments of this type will be flown on the Long Duration Exposure Facility (LDEF), a rack of experiments which will be launched from the Space Shuttle in April, 1984, and recovered from space a year later.

PIECES OF COMET

Oddly enough, we can collect unaltered, unmelted comet particles even closer to home, simply by collecting them *after* they enter Earth's atmosphere. These particles enter the atmosphere at high velocities, in excess of 11 km/sec, and they are slowed down by collisions with air molecules, becoming heated by friction in the process. Particles smaller than 0.1 millimeter (mm) in diameter. slow down at altitudes above 80 km, where the air is very thin. As a result, the frictional heat builds up slowly, and the small particles can radiate the heat without melting. (Larger particles penetrate deeper into the atmosphere before slowing down and usually melt, forming droplets called *meteor ablation spherules*.) The smaller, unmelted particles (called *micrometeorites*) are rare (only about one in 1000 cubic meters of air), but they are abundant enough to be collected directly from the atmosphere before they fall to the ground.

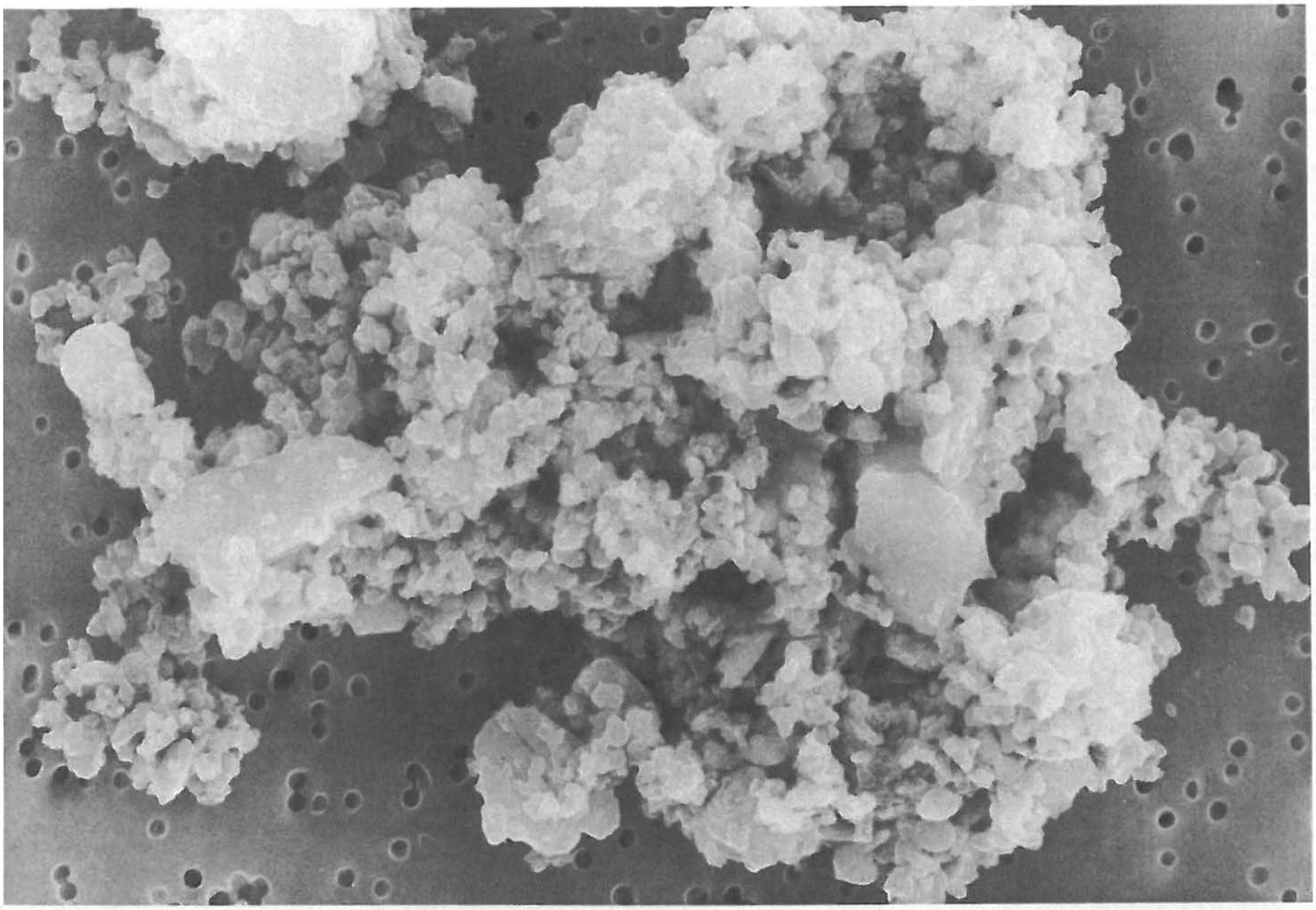
The first real micrometeorites were collected in 1970 using a large air sampling collector flown on a balloon at an altitude of 34 km. Since 1974, the NASA Ames Research Center in California has routinely collected cosmic dust with a U-2 aircraft, which can carry several sticky plastic plates into the clean air at altitudes of about 20 km. Since 1974, U-2's and other high-altitude aircraft have collected over 500 extraterrestrial particles. Recently, NASA's Johnson Space Center developed a special laboratory for preserving these particles and distributing them to scientific investigators all over the world.

DEEP OCEAN COLLECTING

Extraterrestrial particles larger than 0.1 mm are too rare to be collected in the atmosphere, but they can be conveniently collected from the deep ocean floor. The melted particles are magnetic, and the particles can thus be easily separated from the sediment with a magnet, an experiment done over a century ago on the first sediments ever recovered from the deep ocean floor. More recent collectors use a magnetic sled that is towed across the ocean floor at a depth of 5 km by an oceanographic research vessel. More than 100,000 cosmic spherules have been collected in this way; they range in size from 0.1 mm to 3 mm in diameter.

These particles are important, even though they have melted in the atmosphere and then been altered on the sea floor, because they are probably a representative sample of the millimeter-sized particles in space, a population that produces meteors or "shooting stars" in the atmosphere. Extensive studies have shown that most of the millimeter-sized particles that produce meteors are pieces of comets.

Because the tiny stratospheric particles (micrometeorites) are less altered, scientists have studied them most extensively. We have applied to them nearly all laboratory analysis techniques that can be used on such small (0.01mm) particles, and in many cases the studies of dust have actually advanced the state-of-the-art of the analytical methods. The most common micrometeorites have



Collected by a high-flying U-2 aircraft, this tiny particle of extraterrestrial dust, only a few hundredths of a millimeter across displays an aggregate of even tinier crystals.

the same relative abundances of the chemical elements that are found in the Sun and in primitive meteorites. In descending order of abundance, they are oxygen, iron, magnesium, silicon, carbon, sulfur, nickel, aluminum, calcium and sodium. The less abundant elements in micrometeorites also adhere to this "solar" pattern, which is the composition expected for primitive materials that formed in the early solar nebula and which have not been subjected to later chemical processes.

TINY CRYSTALS

Many dust particles appear as black, porous aggregates of very tiny crystals. Their chemistry closely resembles that of the primitive carbonaceous chondrite meteorites, but their structure and mineral composition are different from all other known extraterrestrial materials. Some of these particles are so porous that they are extremely fragile, totally unlike the solid meteorites we have long been used to.

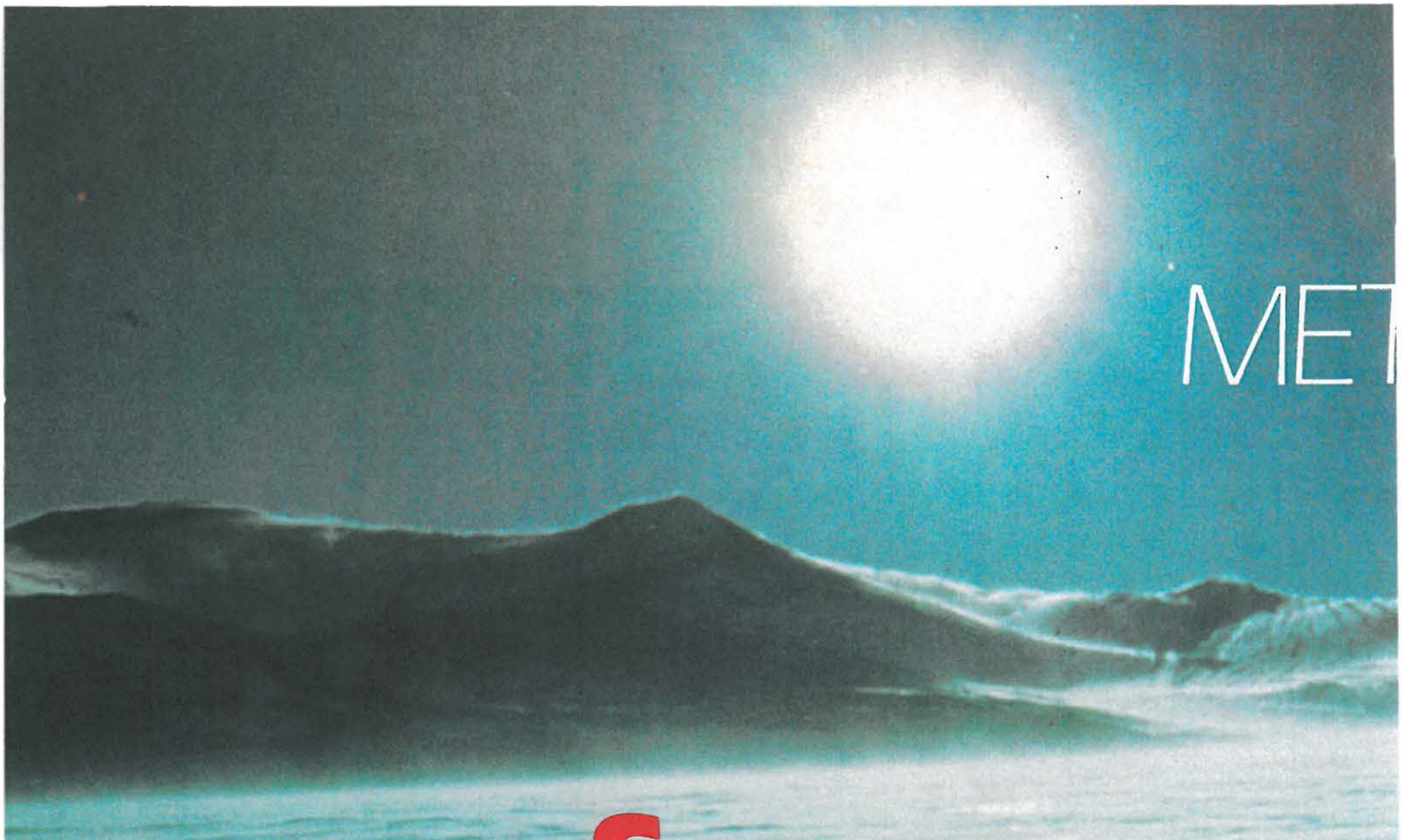
Current studies of micrometeorites concentrate on their origin and evolution. We have detected high levels of helium and other rare-gas elements derived from the Sun, indicating that most of the particles were truly microscopic objects in space and not just fine debris from larger objects that broke up in the atmosphere. Highly magnified views obtained with electron microscopes have revealed tiny crystals of silicate and carbide minerals in forms that have never before been seen in meteoritic materials. Some of these crystals resemble material formed directly by solidification from vapor, a process which may have occurred during the origin of the solar system or even earlier — in interstellar space. Some of the dust particles may in fact have an interstellar signature; recent measurements of their hydrogen show large enrichments in deuterium or "heavy hydrogen." Radio astronomers have detected similar enrichments in interstellar clouds.

Studies of the larger deep-sea spherules have emphasized their chemical and isotopic composition. Measurements of the isotopes of strontium in individual spheres support the idea that the spheres are indeed extraterrestrial and that they have an age comparable to the age of the solar system, or about 4.6 billion years. Measurements of radioactive atoms produced by cosmic rays in space indicate that the spheres came from bodies that were themselves small and that had been exposed to cosmic rays in space for at least a million years. The chemical composition of the spheres shows that at least 80 percent of them came from material similar to primitive carbonaceous chondrite meteorites. These meteorites are rare in current meteorite collections, but are probably a very common type in space.

STUDYING THE DUST

Studies of interplanetary dust began over a century ago when the first particles were successfully collected from deep-sea sediments. Only 25 years ago, the field expanded further when the first satellites were launched into space. Now cosmic dust research is in a new ferment generated by new technology, expanded opportunities for space experiments, and new techniques for collecting dust particles from the stratosphere. At the same time, spacecraft studies of cosmic dust have taken on a new importance as we have come to realize how many different objects may contribute dust to interplanetary space — sources as diverse as the dust coma around a comet, the planetary rings around Jupiter, Saturn and Uranus, and the sulfur volcanoes of Io. The expanding collection and study of cosmic dust will provide a wide range of new vistas — the nature of comets, the formation of the solar system, and the nature and behavior of dust in the distant gulfs of interstellar space.

Donald E. Brownlee is a Professor of Astronomy at the University of Washington, Seattle. A pioneering and enthusiastic collector of cosmic dust, he has also been involved in studies of lunar samples and in the design of spacecraft experiments to collect cosmic dust in space.



MET

BY URSULA B. MARVIN

ABOVE: The author (left) and a colleague carefully collect Antarctic meteorites, using procedures developed for astronauts on the Moon to guard against damage, contamination or loss of important field data.

BACKGROUND: The midnight sun at Allan Hills turns the Antarctic icecap into a seemingly extraterrestrial landscape, a highly suitable place to search for rocks from other worlds. The normal temperature is about −20° Fahrenheit, and the wind never stops.

PHOTOS: Courtesy of the author

Strapped securely in our canvas seats, we listened through earphones as the pilot maneuvered the shuddering vehicle to a landing. Pushing open the door, we tumbled out in our clumsy, overstuffed suits and, crouching low to avoid the whirling rotor blades, scuttled across the windswept ice. We were not a party of astronauts landing on Mars or Ganymede; we were members of Project S-058 of the National Science Foundation's Division of Polar Programs, and we were searching for meteorites in Antarctica.

No expedition on Earth more closely simulates planetary exploration. The effort takes one to the white interior of the highest, coldest, windiest, driest and most remote of continents, the one that remained hidden from the most enterprising European explorers until 1820, and the only continent showing no traces of indigenous human habitation. Like the *Apollo* missions and flights of the Space Shuttle, Antarctic expeditions are meticulously coordinated so that teams of scientists can carry out field work as quickly and efficiently as possible and go home to analyze their data. And, like space missions, Antarctic expeditions stress safety first. Every United States field party makes daily radio contact with McMurdo Station to report its progress and state of well-being. Failure to do so for a 24-hour period prompts a rescue mission—no excuses are valid.

The comparison with a planetary mission is especially appropriate for Project S-058, whose purpose is to discover and collect samples that have fallen to the ice sheet from outer space. The search is not random. Within the past ten years we have learned that meteorites, which fall at different times and places on the vast polar icecap, are frozen in and carried seaward by the ice at a rate of 1 to 10 meters per year. As many as 95 percent of

EORITES **ON ICE**

the meteorites probably reach the edges of the continent and vanish out to sea in icebergs.

CARGOES OF METEORITES

If, however, the horizontal flow of the ice is stopped by a mountain barrier, the stagnating ice will push upward against it, bringing its cargo of meteorites to the surface where they sit, all types mixed together, like windfall apples waiting to be harvested. These astonishing concentrations of extraterrestrial materials may be spotted from low-flying helicopters, which can then land to allow their bundled-up passengers to jump out and determine whether the black dots on the blue ice are meteorites or terrestrial "trash" rocks. If they are meteorites, a tent camp will be set up nearby where the search party can live for weeks, photographing each specimen *in situ*, charting its location and collecting it with sterile procedures patterned after those used for lunar rocks by the *Apollo* astronauts.

The first meteorite concentration was discovered entirely by accident when a party of Japanese glacial geologists found nine meteorites on an expanse of bare ice inland from the Yamato Mountains. They sent the specimens home supposing they were all pieces of the same meteorite. But laboratory analyses revealed that the group included fragments of at least four different classes of meteorites! This totally unexpected observation, first reported in 1973, aroused great excitement internationally. Antarctica was clearly the place to look for meteorites. Nowhere else is there such a huge catchment area, a vast dome of ice that covers 12 million square kilometers (km) and has a maximum thickness of 4800 meters. Here both stony and metallic materials can be protected by a frigid climate from ordinary weathering and erosion and carried to concentration sites somewhat like the placer deposits of gold or precious stones created by mountain streams.

SEARCH FOR METEORITES

Japanese scientists returned to the Yamato Mountains icefields, specifically to search for meteorites, in the austral summer of 1973 and subsequent seasons. Beginning in 1976, members of Project S-058, led by William A. Cassidy of the University of Pittsburgh, have made annual trips to icefields along the interior flank of the Transantarctic Mountains within helicopter range of McMurdo Station. To date, more than 6000 meteorite specimens have been collected from these two areas 3000 km apart on opposite sides of the Antarctic continent and then shipped, still frozen, to curatorial facilities in the United States and Japan. The United States collections alone have supplied research samples to more than ninety laboratories in thirteen countries.

It will be a long time before we really know how many individual meteorites are represented by the thousands of fragments collected in Antarctica. Many of the meteorites undoubtedly exploded during passage through the atmosphere and fell in showers of small fragments. If, for example, each meteorite is represented by ten fragments, then the Antarctic program has already added about 600 new meteorites to the world's collections—which, in 1969, included some 2100 cataloged meteorites, accumulated over more than two centuries.

The actual numbers of meteorites are not nearly so important, however, as the fact that the Antarctic collections include new varieties of meteorites and new specimens of very rare ones. Still more spectacularly, one

(continued next page)

Antarctic meteorite has proved to be the first sample from the Moon ever found on Earth, and two Antarctic meteorites are strongly suspected to have come from Mars!

SOMETHING SPECIAL

From the moment specimen ALHA 81005 was spotted lying on a patch of ice thirty km from camp on the final, windy afternoon of the 1981-1982 field season, it was recognized as special. No other meteorites have large white clasts (fragments) embedded in a dark, glistening matrix; no others have so frothy a greenish-tan fusion crust. Analyses made early in 1983 led to an identification that was quick and positive: The rock is from the Moon. It closely resembles *Apollo 16* rocks in mineral, chemical and isotopic composition, and it differs from all other meteorites in these respects. It is a breccia in which fragments of several familiar lunar rock types, predominantly from the highlands but also including sparse pieces of mare basalts, are mixed with glassy spherules and embedded in a matrix of dark glass. The spherules and the wide variety of rock fragments earmark this unique meteorite as a sample of lithified lunar soil.

This lunar rock confounds numerous calculations, based on computer modeling and laboratory experiments. These data suggest that any lunar materials accelerated to escape velocity (2.4 km per second) would have to come from deep in the lunar crust and would be melted to glass. Somehow, this plum-sized, 31-gram sample of lunar soil was blasted off the Moon and landed on Earth with no more shock damage than many a rock the astronauts picked up and carried home.

A MARTIAN ROCK?

If lunar rocks are not expected to come to Earth intact, how about Martian rocks, which must be accelerated to 5 km per second to get off their own planet? Despite the horrendous theoretical difficulties, two Antarctic meteorites, and seven collected on other continents, appear to have come from Mars. The evidence is circumstantial but is becoming increasingly persuasive. These meteorites are coarsely-crystalline rocks called shergottites, nahklites, and chassignites (or SNC meteorites) which crystallized from molten lavas only 1.3 billion years ago. This great age is still remarkably youthful compared with the 4.6-billion-year age of other meteorites. Only a large, well-insulated planetary body—much larger than asteroids and even larger than our Moon, which ceased its volcanic activity more than 3 billion years ago—could have retained sufficient internal heat or generated enough radioactive heat to be volcanically active when the SNC meteorites formed. Which large body could it be? Mercury and Venus are poor prospects, as are the giant outer planets, so we are left with one prime suspect: Mars.

Mars lies close to the inner margin of the asteroid belt and its suface shows scars of heavy bombardment. But Mars also supports the largest volcano in the solar system, and the lava plains skirting Olympus Mons are only sparsely pocked with impact craters. Mars, then, has been volcanically active in comparatively recent times. How recent we cannot be certain, but 1.3 billion years before the present seems well within the realm of possibility.

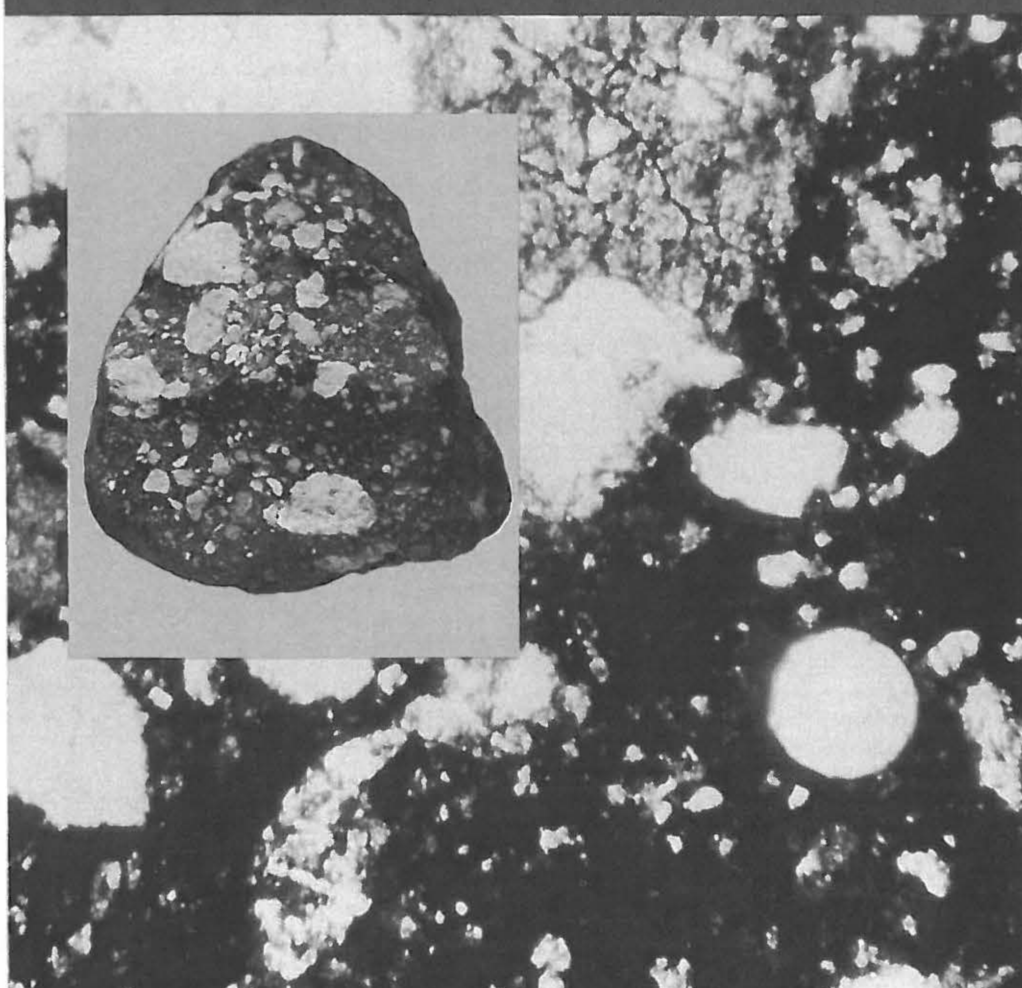
The case for a Martian origin has been strengthened by investigation of an Antarctic shergottite found in 1979. Unlike all of the other SNC meteorites, this specimen contains conspicuous pods of dark glass rich in trapped gases, including argon, krypton, xenon and nitrogen. These gases occur in relative abundances and have isotopic ratios similar to those measured in the Martian atmosphere by the *Viking* Landers. Was this partially shock-melted meteorite exposed to the Martian atmosphere just long enough to trap a sample of it during its lift-off to an Earth-crossing orbit? To date, all computer simulations have failed to show how any surface rocks could survive blast-off from Mars; if they do not, then they force us to find another planetary source for them—a large, warm body with a Martian-style atmosphere. Such an alternative would redouble the mystery.

YIELD OF TREASURE

The Antarctic treasure trove has yielded other new and precious types of meteorites. These include specimens of basaltic achondrites (meteorites with strong similarities to terrestrial and lunar basalts) of a compositional variety not found elsewhere; the world's second-known diamond-bearing iron meteorite; and more than 40 specimens of carbonaceous chondrites. These meteorites are of special interest because they contain hydrocarbon compounds, including amino acids, that were formed by inorganic processes either in the primeval solar nebula or in parent bodies that accreted at the birth of the solar system. These ancient hydrocarbons show us what types of molecules existed millions of years before life appeared on Earth.

To better understand the ice-flow regime and concentration mechanism, geophysical studies are underway at the most productive of the US collecting sites near the Allan Hills. Another on-going project involves attempts to determine how long ago the meteorites fell to the ice sheet. Most meteorites on other continents fell within the past few hundred to few thousand years. The Antarctic specimens dated so far have lain in the ice for 4,000 to 700,000 years! Thus, they provide us with significantly older interplanetary materials than we have examined before. Perhaps we will find Antarctic meteorites that fell more than a million years ago, but falls much older than that seem unlikely because, although ice has lain on parts of Antarctica for perhaps 20 million years, the continuous outward flow of the ice would have long ago carried older meteorites into the sea.

The Antarctic meteorite program is among the most exciting and fruitful new efforts in planetary science. It has forged a new link between planetary and Earth sciences. And it is a superb adventure. Few thrills can match racing in a snowmobile across an expanse of rippled blue ice and then skidding to a stop beside a black rock from the distant reaches of the solar system. Above all, our yearly trips to Antarctica are an elegant means of adding to the world's store of planetary samples while we wait for future collecting missions in space.



A slice of the Moon, this is how the lunar meteorite ALHA81005 (inset) looks under the microscope. It is a mixture of various lunar rock fragments and once-molten glass. PHOTOS NASA

Ursula B. Marvin is a researcher at the Harvard-Smithsonian Center for Astrophysics in Cambridge, Massachusetts. She has worked extensively on both lunar rocks and meteorites, and she recently visited the Antarctic with Project S-058 to collect meteorites on the spot.

by Clark R. Chapman

One of the most spectacular discoveries of the 1970's was that Jupiter's moon Io is the most geologically active body in the solar system. Until then, most scientists felt that all other planetary bodies were "dead" compared with our own planet. In early 1979, several separate approaches to studying the planets came together and revealed Io to be very much alive internally, spewing volcanic emanations into a mighty torus girdling Jupiter. Dynamical theorists Stanton Peale and his colleagues were the first to score when they published a model for Io's tidal interaction with Jupiter and the other Galilean moons. They predicted that Io's interior would be continually kneaded and heated so that active volcanos would be inevitable. At the same time, some especially peculiar Earth-based data on Io's infrared spectrum were published, extending a decade-long record of weird telescopic observations of that moon. Finally, *Voyager 1* flew by Io and the rest is history: The stunning close-ups of Io's tortured surface bore witness to the cumulative effects of erupting volcanos, whose immense plumes were seen silhouetted against the blackness of interplanetary space.

Voyager scientists Torrence Johnson and Laurence Soderblom have written an illuminating article about Io in the December, 1983 *Scientific American* that reports on our understanding of that unusual world after nearly five years of detailed research. The excitement of discovery in 1979 overshadowed the very complex problems raised by the reality of Io. For example, Io's volcanism is so active that even the tidal-wrenching processes predicted before the encounter may be inadequate to generate the full amount of heat required; but more work may reconcile theory with measurement. After years of hard research, scientists have reached an understanding of Io that transcends the "Oh, wow!" level of appreciation recorded in numerous popular articles following the discovery. Johnson and Soderblom's clear explanation of current ideas about a combination of sulfur- and silicate-driven volcanism is augmented by some stunning, specially-processed mosaics of Io's surface, prepared by computer processing at the United States Geological Survey. Just as the years of research have led to new understandings of Io, so the careful image-processing work has yielded pictures that are far clearer than the widely printed versions released during the *Voyager* encounters. (See the January/February 1984 *Planetary Report.*)

Voyager *Saturn Encounters*

Henry S. F. Cooper, Jr. is one of the most sober and skillful reporters about the space program. His illuminating articles in *The New Yorker* are always a pleasure to read and are sometimes collated into books. *Imaging Saturn* (Holt, Rinehart and Winston, 1983) is up to Cooper's usual standards. At the two *Voyager* encounters with Saturn, he witnessed the "instant science" that was being done during those two exciting periods. Unlike Mark Washburn's recent book, *Distant Encounters* [see page 22], which captures the excitement of encounter from the perspective of the daily press conferences, Cooper focuses directly on the scientists and what they were doing and thinking during the hours between the press conferences. His book concentrates on the members of the Imaging Team responsible for acquiring and interpreting the spacecraft pictures, and discusses the other *Voyager* experimenters only when the discoveries by other instruments affected the interpretation of pictures.

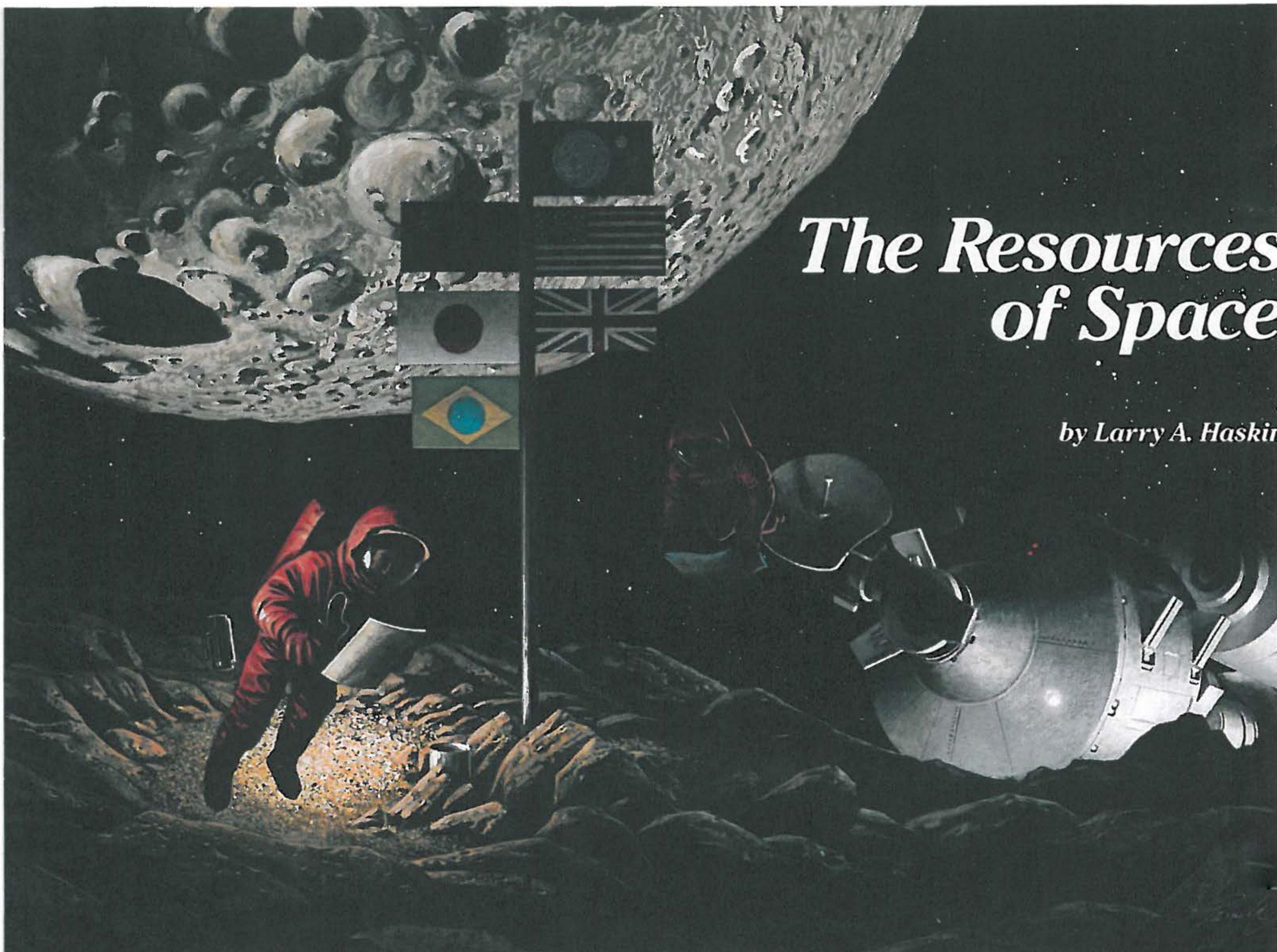
Cooper was privileged to sit in the JPL offices of the Imaging Team, to listen to off-the-cuff conversations and to witness regularly scheduled discussions of the Imaging Team and its various subgroups. He interviewed the scientists and recorded their changing ideas about Saturn in "realtime." Most science that reaches the layperson has been "digested" in one way or another. Professional scientific journals contain reports on the conclusions of scientific research, complete with well-buttressed logical arguments usually bearing no relationship to the intellectual and psychological processes that went on in the researchers' heads while the ideas were being formulated. Even the *Voyager* press conferences presented results that had been specifically selected by the scientists as being "ready" for the press. In contrast, Cooper has, in *Imaging Saturn,* captured the scientific mind at work.

Nuclear War: A Planetary Perspective

A special virtue of planetary science as an intellectual discipline is the uniquely global perspective it brings to other scientific disciplines which once treated only our Earth. Workers in geology, geophysics, meteorology and other sciences have, until recently, based their understanding on terrestrial data alone. Planetary scientists argued, during recent funding crunches, that there is much more to the "planetary perspective" than the emotions conjured up by pictures of our own blue, cloud-bedecked planet spinning in space.

A recent article on a very important topic—probably the most important topic of our times—highlights the significance of the planetary perspective. A seminal article in the December 23, 1984 issue of *Science,* by R. P. Turco, O. B. Toon, T. P. Ackerman, J. B. Pollack and Carl Sagan, reports the results of computer models of the climatological effects of nuclear war. What these scientists have discovered is that earlier studies of the consequences of World War III were far too optimistic. In our present understanding of how Earth works, it seems likely that a nuclear exchange would bring a sudden, months-long winter to the entire northern hemisphere and that effects on the southern hemisphere would be greater than previously thought. This conclusion about dangers to the southern hemisphere was derived in part by analogy with the behavior of dust storms on Mars. The results of this planetary perspective have been reported in popular fashion in *Parade* magazine and on network television, thanks to the efforts of Carl Sagan. In *Science,* they are presented in a drier, more technical way. But most Planetary Society members would find much to learn in this article on "nuclear winter" as well as in the follow-up article, by Paul Ehrlich and others, on the biological consequences of such a "winter."

Clark R. Chapman is a planetary scientist specializing in asteroids, comets and planetary surfaces. He lives in Tucson, Arizona.



The Resources of Space

by Larry A. Haskin

Materials mined from the asteroid and the Moon may someday be valuable resourc for space activitie In this painting, suited miners "sign in" on a double asteroid as scientists do at Earth's South Pole. They bring a Swedish flag to "fly" with those of other nations over this small, dark member of the solar system.

PAINTING BY PAMELA LEE

When our ancestors sought new surroundings, they took for granted the resources they would find—the water, game and plants to support life. We have carried into space the same urge to cross frontiers and to live off the land. Ideas of living on other worlds appear in human literature from traditional folk tales to science-fiction paperbacks. We have long imagined colonizing new worlds, meeting alien cultures, and finding new minerals and other riches.

Space exploration has evaporated many of these dreams. No gold and diamonds pave the Moon. No bison roam its silent plains. No jungles thrive in the tropics of Venus. Why, then, do so many of us still retain an optimistic vision of humanity's future in space, adjusting our battered dreams and still believing in them? It is because there are tangible resources in space that can enhance the wealth of all humanity. The process of using them has already begun, encouraged by governments that seek security and economic progress. Near-Earth space contributes to both. Surveillance satellites are a cornerstone of our defense system, and communications satellites are mainstays of our industrial growth. Commercial processing of pharmaceuticals and special alloys in space may soon follow.

In time, lunar and asteroidal materials will also become important. As we use more near-Earth space, we will need more material in space. It is costly to lift a payload from Earth into even a low-Earth orbit (LEO, about 300 kilometers up), mainly because of the energy required to overcome Earth's strong gravity. When the Space Shuttle leaves the launch pad, only about 1.5 percent of its weight is payload. Most of its weight is fuel—to lift the orbiter and its payload.

The High Cost of Lifting

Materials from the Moon or asteroids may help us beat this high cost of lifting. From such low-gravity bodies, more than 50 percent of the liftoff mass can be payload for a rocket-driven spacecraft, and more than 90 percent if electromagnetic mass drivers can be used. Furthermore, if the payload can be accelerated enough to reach Earth's gravity field, it can be guided into our atmosphere and slowed into orbit by aerobraking. Payloads of lunar or asteroidal material can be delivered to LEO for a small fraction of the energy needed to lift the same mass from the Kennedy Space Center. This saving of energy—and therefore of money—makes lunar material attractive for use in LEO, and even more interesting for use on the Moon or in geostationary orbit (GEO, 35,880 kilometers up), where a satellite circles Earth in 24 hours, remaining fixed above a specific area of Earth.

But why use lunar or asteroidal materials? Every kind of material we might want to use in space is abundant on Earth, and putting the necessary mining and processing facilities on the Moon or an asteroid would be a big, expensive project in itself. Nevertheless, the combined costs of plants, manufacturing and delivery to LEO may still make lunar or asteroidal material more economical in the long run. One example of a valuable extraterrestrial commodity is oxygen, a very common material on Earth, and needed in space by both human beings and rockets. Oxygen might be the first commercially important lunar material for use in space.

Extraterrestrial Demands

This possible demand for extraterrestrial oxygen stems from NASA's plans for launching communications satellites in the 1990's. Communications satellites, which must be put in GEO for best results, would be carried up in stages. First, the Space Shuttle would lift them to a space station in LEO, near the limit of the Shuttle's range. From there they would be carried to GEO by a second spacecraft, the Orbital Transfer Vehicle (OTV), powered by oxygen-hydrogen fuel supplied from Earth by the Space Shuttle.

By the year 2000, the estimated traffic between LEO and GEO—just for communications satellites—could require some 300 tons of liquid oxygen per year, a mass equivalent to more than ten Shuttle payloads. The liquid hydrogen needed would require a similar number of payloads. Preliminary estimates of the economics of oxygen use in space suggest that, if more than 300 tons per year is needed, it may be more economical to mine lunar oxygen and transport it to LEO than to lift it from Earth.

In terms of lifting costs, the jump from LEO to GEO is just short of that from LEO to the Moon's gravity, and the OTV would need little change in design to reach lunar orbit. A second OTV, fitted with landing legs, could lift lunar products from the Moon's surface to lunar orbit.

Providing stabilizing mass and shielding for space platforms could be other early uses for lunar or asteroidal materials. Stabilizing mass reduces unwanted motions of reaction. For example, when a sensor mounted on a space platform is turned to point in a new direction, that platform reacts by rotating in the opposite direction. If the platform can be made massive enough, its motion becomes negligible, its orientation in space does not change, and pointing is much easier. The necessary mass is simply provided, perhaps as sandbags filled with rubble from the lunar surface.

Radiation Shields

Humans and machines at GEO will also need shielding from harmful radiations produced by the Sun and cosmic rays. A thickness of at least a meter of lunar soil would probably be needed. The possible demands for shielding and stabilizing mass could reach thousands or tens of thousands of tons. It may prove cheaper to get such large amounts of simple bulk materials from the Moon or a near-Earth asteroid.

A major demand for material from the Moon or from a near-Earth asteroid will start an important sequence of activities. First, we will have to build the facilities, vehicles and infrastructure needed to obtain that material. As a result, other materials will become available, and new uses will appear for them. Experience in working with materials under low gravity and in space will trigger swarms of new ideas. We will begin to overcome our Earth-bound perspective that extraterrestrial environments are mainly obstacles to overcome rather than advantages to be used.

Given access to the Moon and near-Earth asteroids, what resources will our new planetary pioneers find? There will be no food and water. But for a technological civilization, available resources mean available chemical elements. The Moon and any sizeable asteroid contain immense amounts of every natural chemical element, although they may not be concentrated into convenient ores. We still do not know the full variety of materials available, but we do know important elements that are abundant. From the *Apollo* samples, we know that the common Moon rocks are made of oxygen, aluminum, iron, titanium, silicon, magnesium, calcium and sodium, bound together mainly as silicate and oxide minerals. From these rocks we can obtain oxygen for fuel and life support. We can produce glass for fibers, building materials and insulation. We can make ceramics for heat shields. We can extract metals for construction and electrical power transmission. We can use the available power from sunlight to process these materials. Furthermore, eons of meteorite impacts on the lunar surface have pulverized its rocks into a convenient powdery rubble; we can just shovel it up without having to blast or crush it.

Space Processing

We will have to develop new methods of processing the ores of outer space. On Earth we have it easy, with concentrated ores, fossil fuels to use for power and reducing agents, water for washing and cooling, and expendable chemicals for separations. On the Moon, we have only sunlight for power and rather ordinary rock, part of it powdered to very dry dust, for ores. But some encouraging preliminary experiments indicate that the mineral components of lunar soil can be separated electrostatically. Other experiments show that oxygen, iron, and alloys of titanium and silicon can be separated by electrolysis of molten rock. Still other studies show that acid dissolution and water separation can extract aluminum. This can probably be done in closed systems, with the liquid reagents recovered and re-used. All these results are encouraging, but much more laboratory work needs to be done—and soon—before we will know exactly how to proceed.

We need more exploration too. From the Moon rocks, we know that the Moon had no water when it formed. However, water brought in by colliding meteorites and comets may remain trapped as ice in permanently shadowed craters at the lunar poles. The proposed Lunar Geoscience Orbiter mission can detect such water and can also give us other valuable information about the Moon's surface composition. If there is water on the Moon, it will be as precious as in any other desert terrain. It would affect our extraction techniques, and it could be the source of both oxygen and hydrogen for fuel. If there is no lunar water, then most Earth-style ores could not have formed. However, there may be other types of ores. Analysis of lunar materials shows that elements such as sulfur, zinc, copper, uranium, barium, chromium and rare-earth metals are strongly enriched in certain minerals.

Mining the Moon

Because the Moon is close and relatively well-known, it will probably be mined before the asteroids. However, asteroids may supply materials that are scarce on the Moon. Near-Earth asteroids (whose orbits cross or approach Earth's) are being discovered at a rate of three or more per year; more than 60 with diameters of a kilometer or more have already been found, implying the existence of hundreds or thousands of smaller ones. We believe that the variety of asteroidal material is at least as great as that found in meteorites. We can expect to find abundant iron-nickel alloys, water and hydrocarbons, as well as iron and magnesium silicates. But some close-up exploration is essential. We cannot now tell which asteroids will yield which materials, nor do we know whether asteroid surfaces are covered with easily mineable rubble. The proposed Earth Approaching Asteroid Rendezvous mission would greatly increase our information.

The first use of lunar or asteroidal products will begin a permanent human presence in space, but the first established base will not suddenly create a new society. Neither did the settlements at Plymouth Rock or Jamestown. There will be agonizing about costs, about economic returns, about all the aspects of any new venture that concern both backers and detractors. The first Moon base, like the Roanoke Colony, may falter if its initial support is inadequate or its mission too narrow. But time will probably provide a different perspective. Could even King George III argue today that the country born from England's early ventures has been such an economic and social failure as not to be worth its intial cost?

During its early exploration and settlement, North America was regarded as a country well-endowed but not unusually rich in natural resources. Who could have imagined then how far beyond those recognized resources a modern society could go? Viewed in this light, our neighboring planets' lack of obvious food and shelter seems more of a stimulating challenge than an impossible barrier.

Larry A. Haskin is a Professor of Earth and Planetary Sciences and Chemistry, and a Fellow of the McDonnell Center for the Space Sciences, at Washington University in St. Louis.

THE LONG REACH

Machines may collect our next samples from other worlds

by Bevan M. French

"Good evening, ladies and gentlemen. I'm John Meredith, speaking to you live from NASA's Planetary Materials Laboratory in Houston, Texas. Only two days ago the sample container from the Mars Sample Return mission arrived here, and already the scientific excitement has reached a level unheard of since the Viking *landings on Mars a generation ago. The first briefing has just ended, but the scientists are still here, standing in the halls and the auditorium, talking and arguing. It's been an exciting day. Let me summarize some of the discoveries. The most unexpected result came from the Life Sciences Examination Team, which reported..."*

*Perhaps it is 1999, perhaps a few years into the 21st century. From this beginning, the scientific studies of the Mars samples expand, the once-sketchy picture of post-*Viking *Mars takes on depth and color, and the planet becomes familiar, almost as well-known as Earth and its Moon. Detailed chemical analyses of the returned rocks and soil specify the composition of Mars' outer crust, give insights into the nature of its underlying mantle, and even permit a few shrewd estimates about the size of the planet's central metal core. Age measurements, using radioactive elements in the rocks, pinpoint the times of great volcanic eruptions on Mars' surface. Studies of Mars' rusty, weathered soil begin to unravel the chemistry of the Martian atmosphere and the nature of Martian surface weathering. And in special laboratories, other scientists expand their search for life on the Red Planet.*

The collection of solid samples from other worlds, whether done by humans or by machines, is an essential part of exploring the solar system. Planetary exploration goes in stages. The early missions, flybys and orbiters, are planned to give us a global view of the planet and its geology, surface chemistry, and geophysics. Then robot landers and rovers, such as *Surveyors*, *Viking*, and *Lunokhods*, carry out more complex experiments on the surface. The next step, which has never been done for any world except the Moon, is the return of solid samples to Earth, where they can be examined with the full resources of Earth-based laboratories. Once back on Earth, the samples provide a wealth of new and otherwise unobtainable data, and they make it possible to understand better the data returned by earlier missions.

The great value of sample return missions is balanced by their difficulty. Such missions are complex, demanding and expensive. Even with a robot mission, two different spacecraft are needed—one to get to the target world, the other to bring the samples back. The spacecraft needs other things as well—manipulators to handle the samples, a protective container to store them in, and perhaps some visual or chemical instrumentation to help select the right samples. And all the complex and delicate operations must be managed from tens of millions of miles away on Earth.

Robot Missions

All these problems can be solved. In fact, robot sample return missions are not new. Between 1970 and 1976, the USSR landed three robot spacecraft (*Luna-16*, *-20* and *-24*) on the eastern side of the Moon. Each spacecraft used a robot arm to dig into the lunar soil, secure a sample, and return with between 100 and 300 grams of lunar material. *Luna-24* even used a flexible core drill to obtain a section of the powdery lunar surface layer down to a depth of two meters. These impressive feats were overshadowed by the *Apollo* missions and by the hundreds of kilograms of samples they returned, but the *Luna* samples, which came from regions that we could not reach with *Apollo*, provided important information about the chemistry and timing of volcanic activity in an entirely different part of the Moon.

We know a lot more about the solar system now than we did in the *Apollo* days. The *Voyager*, *Viking* and *Pioneer* Venus missions have shown us about two dozen solid planets and moons at close range. Which of these are the best targets for sample return missions in the near future? In deciding where to send the next sample return mission, we must consider several things about the target world:

☐ Can we reach it and get back with our available launch vehicles?

☐ Is there some kind of solid material (rocks, soil, ice) to be collected?

☐ Do we already know enough about it so that we can plan the mission, select the landing sites, and estimate what the science return will be?

☐ Are there still major unanswered questions about the world that only return samples can solve?

Putting all these questions together, Mars becomes one of the best targets for a sample return mission, and already a good deal of thinking has gone on about how and when we might go about it. We know Mars fairly well. Its surface has been thoroughly mapped by *Mariner* and *Viking* orbiters, and we have rough chemical data (for two sites, anyway) from the *Viking* Landers. We know that Mars has rocks and soil, and we know enough now about the planet to build a spacecraft that can go there and collect them.

Martian Questions

There are still major unanswered scientific questions about Mars. The rocks look like volcanic lavas, but we know little about their chemistry and nothing at all about their mineral composition, ages, origin, and how they fit into the evolution of the planet. The reactions between the atmosphere and the rocks, and the chemistry of Martian weathering, are unknown. Finally, there is the still-unanswered question about life on Mars, a question that may be finally settled only when returned samples can be studied, intensively and at leisure, in terrestrial laboratories.

Even for a planet as well known as Mars, many key decisions must still be made before we can put a sample return mission together. How much sample is needed, and what kinds of material? How much surface mobility should we have—just a few meters around the spacecraft or perhaps complex sampling rovers that could range for kilometers, collecting as they go? How much analysis, with TV or chemical sensors, must we do on-the-spot to identify the best samples? Should we sterilize the samples before return (to reduce the danger of possible infection to us) and thus perhaps destroy any evidence for Martian life? Do we return the sample directly to Earth or send it into Earth orbit to dock with a Space Shuttle or a possible space station? What kind of quarantine do we impose, and where—in a space station or on the surface of Earth?

Even a handful of Mars cannot tell us everything we need to

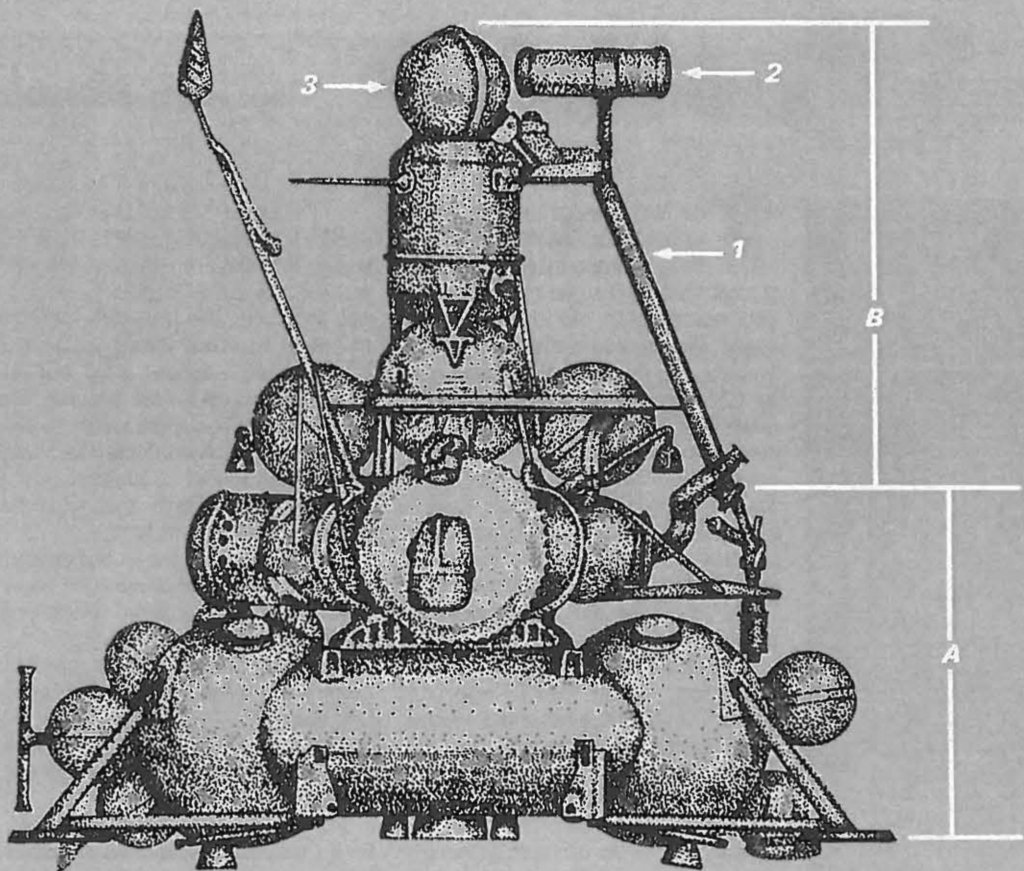


ILLUSTRATION: S. A. SMITH

All the essential equipment for a sample return mission is shown on this* Luna 16 *spacecraft, which made the first robot sample return from another world in 1970. The Soviet spacecraft contains a landing stage (A), a return stage (B), an arm to reach the surface (1), a sample scoop (2), and a sample return capsule (3), which carried the precious material down to the surface of Earth.

know about the solar system. Mars is an active, evolved planet; it will not reveal much about the origin and earliest history of the solar system 4.6 billion years ago. To probe into that ancient time, we need to find primitive, unaltered material, and we can probably find it in the small, relatively unchanged bodies of the solar system—asteroids and comets, especially comets.

Comets are entirely different from the other solid objects in the solar system. We have not yet even seen a comet close up, but we think they consist of low-temperature volatiles (water ice and other ices) mixed with silicate dust. We suspect that comets record the very earliest stages of planetary formation, the conditions in the cold, dark regions far from the central Sun, and perhaps also the nature of the interstellar material that came together to form the solar system. A sample of a comet would be a unique time probe into the very beginning of our surroundings, and no one can predict what it might tell us.

Sampling a Comet

We are still a long way from sampling a comet. The great scientific gains are offset by major uncertainties. For instance, just what should we plan to collect? We expect a mixture of dust and ice, but there might be liquids briefly formed as the comet passes close to the Sun. How do we collect, preserve and return such unstable materials as dust and ice without altering or contaminating them? There are problems with the mission as well. What is the nature of the surface of the solid central part of a comet? Is it something we can land on, or is it a swarm of small particles, hard to sample and dangerous to the spacecraft?

Some of the problems can be solved by Earth-based research, but others will require actual reconnaissance missions to comets. The challenges are great, but the scientific returns could be some of the most important in the history of space exploration.

Mars and comets may be the current front-runners in today's version of the sample-return sweepstakes, but several exotic and not-yet-understood worlds are not far behind. Asteroids have already told us much about the earliest days of the solar system by shedding (we think) the meteorites that fall to Earth. But we have never visited an asteroid, we have never positively identified a single asteroid as the source of a group of meteorites, we do not really know what asteroids are made of, and we do not know what their surfaces are like.

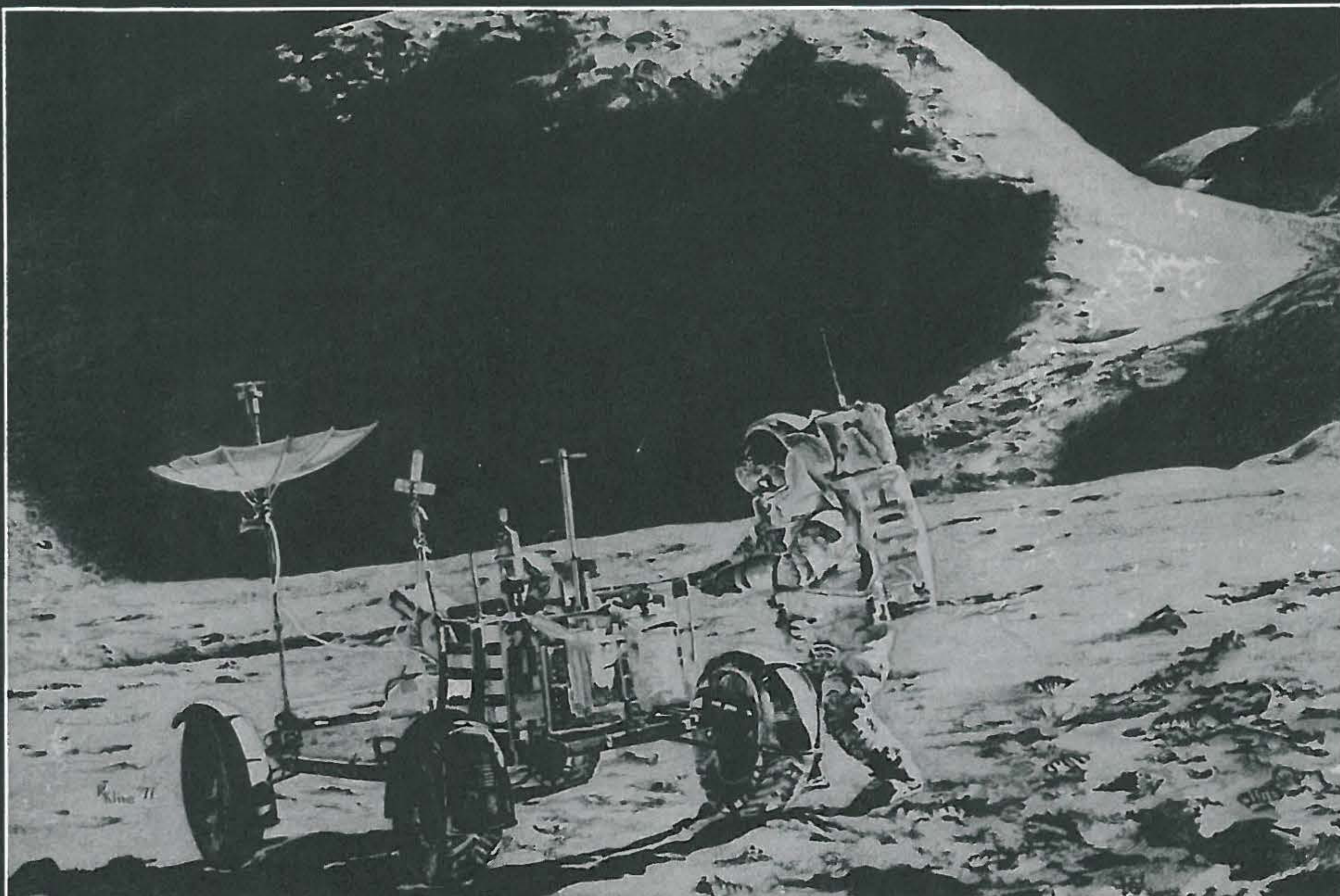
There are even stranger worlds in the solar system, many of which we have seen clearly only in the last few years. We have learned just enough about them to know that we can never understand them fully without sample returns. But they are so distant and strange that they lie beyond our present reach, and they remain as tantalizing challenges for the years beyond 2001.

☐ The blistered, altered surface of Venus, seen only by short-lived Soviet *Venera* spacecraft, bakes under a thick, corrosive atmosphere. Its surface material, and the bedrock from which it formed, are almost totally unknown.

☐ Mercury, the innermost planet, is a neglected Moon-like world lying so deep in the gravity well of the Sun that our present launch vehicles cannot carry the weight of a sample return mission to it.

☐ The weird moons of Jupiter and Saturn, including the spectacular volcanic landscapes of Io, lie far away, held by the gravity fields of their huge parent planets and surrounded by curtains of intense radiation dangerous to humans and machines alike. Sulfur, rock, ices—many of the strangest and least-known building materials of the solar system await collection here.

None of these worlds is barred from the long reach of our collecting missions. There are no challenges that cannot be met, and the rewards will be a series of unparalleled and often unexpected discoveries about the solar system and its worlds. Our space explorations have given us many things, but one of the greatest is confidence. We know we can build machines to go to other worlds and bring pieces of them back to Earth. We know that we can analyze them and extract from them the information that they have preserved for so long. Whatever the problems are, the final answer is clear. The rocks of the solar system, and the secrets they contain, are ready for us—whenever we want to go and get them. ☐



ASTRONAUT AT MOUNT HADLEY— With the introduction of the Lunar Rover on the Apollo 15 mission, astronauts were able to expand their sample collecting across wide areas of the Moon. In this drawing, astronaut David Scott returns rocks collected at the foot of Mount Hadley (background) to the Rover.

Robert Kline is a staff artist at the Griffith Observatory in Los Angeles where he works on museum displays and planetarium shows. He recently designed the logo of the International Association of Astronomical Artists.

We understand that some of our members did not receive the January/February 1984 issue of The Planetary Report because the labels failed to adhere to the magazine. If you did not receive your issue, please send a postcard to: Mailing Section, P.O. Box 5406, Carson, CA 90749-5406, and we will send you a replacement.

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