The PLANETARY REPORT

Volume XIX Number 2 March/April 1999

Ices in the Solar System

On the Cover:

Not all ice is water. Not all water is on Earth. These are the first insights to come from studying the various ices in our solar system. Comets, such as Hale-Bopp (inset), are made primarily of water ice, but frozen carbon dioxide often makes up a substantial part of a comet nucleus. The Martian north polar cap (3D background image, exaggerated vertically to show detail) is primarily frozen water, but the southern cap on Mars is mostly frozen carbon dioxide. The largest of Jupiter's moons, Ganymede (full disk), is bigger than the planet Mercury. Still, in composition, it is roughly half water ice, making it a truly giant snowball in space.

Hale-Bopp image: Jerzy Giergielewicz
Mars: MSSS/NASA
Ganymede: JPL/NASA

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It's not often that a government official gets to lay out a vision for the future that goes beyond the next election cycle. But Wes Huntress, who recently stepped down as NASA's Associate Administrator for Space Science, did just that in a speech accepting the Carl Sagan Medal of the American Astronomical Society. Wes' text was far-ranging and detailed, and we had space in the printed magazine for only highlights of his talk. But the beauty of digital media is that you can squeeze a lot of text into a little space. The full text is available at the Planetary Society's World Wide Web site.

8 "Ices" Throughout the Solar System: A Tour of Condensable Species

Water is abundant throughout our solar system and probably in other solar systems as well. Most of it is in the form of ice. However, the word *ice* does not necessarily denote frozen water. Frozen carbon dioxide, frozen methane, and frozen nitrogen coat some of the small worlds of the outer solar system. To get a true feel for the planetary system we live in, we have to understand a bit about ices and how they behave. Wendy Calvin of the United States Geological Survey takes us on a tour through a garden of alien ices.

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NASA has made a major commitment to exploring that most Earth-like of nearby worlds, Mars. Every two years, the US space agency will launch two spacecraft to the Red Planet. The European and Japanese space agencies are also reaching out for Mars. In an effort to coordinate all this energy and activity, NASA recently formed a Mars Architecture group. Their charge is to study and suggest ways to get the most out of robotic exploration—perhaps leading to a human presence on Mars. Charles Elachi, Director for Space and Earth Science Programs at the Jet Propulsion Laboratory, leads the group. Lou Friedman, Planetary Society Executive Director, also serves on the panel. Here they summarize their findings for Society members.

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From The Editor

It's very hard to explore planets. The distances between worlds are nearly impossible for humans to comprehend, used as we are to this small, solid world. Space beyond our protective atmosphere is a hostile place, a near vacuum through which huge blasts of radiation—deadly to humans and their robotic surrogates—regularly flow.

Many, many of our robot explorers have crashed, blown up, or simply disappeared while attempting to complete their missions. *Mars Observer* seems to have blown up while maneuvering into Mars orbit. *Galileo*, exploring the Jupiter system, carries on despite being crippled. *Nozomi*, on its way to Mars, and the NEAR spacecraft, bound for Eros, have had to scramble to new trajectories. (You can read the details in Lou Friedman's World Watch on page 7.)

It's easy for people to cluck their tongues and ask, why can't those "rocket scientists" do it right? Planetary Society members know better. We know how great the challenges are. And we know how great the potential payoffs can be. So we'll cheer the resourceful engineers and scientists who find ways to overcome adversity and keep us on our journey outward. We choose the journey in part because it *is* hard—and worth the effort.

—*Charlene M. Anderson*

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Members' Dialogue

Space: Getting There From Here

My friend Neil Tyson is a worthy opponent; however, I put my money on Louis Friedman's side of the bet. I am sure Neil will forgive me! (See "Space: You Can't Get There From Here" in the January/February 1999 *Planetary Report.*) I look back on my days at Cape Canaveral (1957 to 1960) and realize that things I never dreamt possible have happened over four decades.

For example, Arthur C. Clarke's geosynchronous-orbital communications satellite was denied a patent in 1946 because the United States patent office claimed the theoretical orbital rocket to test his hypothesis did not then exist. Ten years later his patent was once again denied because he had published his works in the 1940s so the idea was "eminent domain."

Last week the international distress signal SOS was officially discontinued because satellite locator systems are so much superior that SOS is no longer needed.

In World War II, we built rockets, but Wernher von Braun was already envisioning what became the Saturn V.

In 1958, we tested an Atlas ICBM in low Earth orbit that later became the vehicle for John Glenn's first junket! However, when Glenn, Alan Shepard, and the others on *Mercury* and *Gemini* took off, we didn't yet have satellites to carry our television pictures to the world's TV networks. The film was carried to Orlando, Florida by motorcycle messengers for developing and transmission to television.

On the other hand, we went to the Moon with Newtonian gravitational theory and only failed in that we did not remain there and build a base when we had the chance. We may be days or months away from some basic discovery, on par with the discovery that the world is round instead of flat.

We should reach for the inner planets as soon as possible, and necessity will be the mother of invention to bring the technology to go to outer space.
—JAMES F. PINKHAM,
Hudson, New York

I just finished reading "Space: You Can't Get There From Here." What an outstanding article! It should be required reading for every appropriations officer in our government. Thank you, Neil, for verbalizing what I and others have known for years: that most of space beyond Mars is indeed science fiction. Stories from *Star Trek* and *Star Wars* sound exciting to those of us plugging along in our earthly lives, but there are more important (and realistic) projects here on Earth to spend our precious billions on.
—BRIAN SULLIVAN,
Springfield, Virginia

Given the cost and complexity of traditional human Mars mission planning, which really didn't change much from Wernher von Braun's *Collier's* magazine articles in the 1950s through the ill-fated Space Exploration Initiative of the late 1980s, I would probably side with Tyson. Unfortunately, his estimates of the price tag are woefully behind the curve of the current thinking in human Mars mission planning.

Thanks to the work of Robert Zubrin and the NASA Committee for Manned Exploration, it is now clear that the cost of a human Mars program need not be anything like the $100 billion quoted in Tyson's essay. New mission designs do not require bases on the Moon, huge orbital construction facilities, or any costly breakthroughs in propulsion technology. By manufacture of propellant and other consumables from the gases in the Martian atmosphere, the cost and complexity of human Mars exploration could be brought down to a level that could be funded within a fraction of the current NASA budget spread out over about a decade.

Participation by other spacefaring nations, private industry, universities, and nonprofit organizations would make the enterprise even more affordable. Furthermore, unlike the *Apollo* project, these new architectures lend themselves to long-duration, wide-ranging surface exploration instead of barebones, flag and footprints missions.
—PAUL CONTURSI,
Brooklyn, New York

Ice on the Moon

Another perceptive individual, besides Arthur C. Clarke and Bruce Murray, proposed the existence of ice on the Moon (see the January/February issue of *The Planetary Report*, page 10). Although I no longer possess V. A. Firsoff's *Surface of the Moon* (published in 1961, I believe), I recall my astonishment at his suggestion of ice being a possibility on the Moon.
—WILLIAM REYNOLDS,
San Rafael, California

Errata

The image caption on page 5 of the January/February 1999 issue of *The Planetary Report* is missing a few zeroes. The galaxy NGC 1232 is not 100,000, but rather 100,000,000 light-years away.

On page 22, the naming of asteroid Ida was mistakenly attributed to the astronomer Galileo. Ida was named by Moritz von Kuffner, co-discoverer of the asteroid with J. Palisa in 1884.

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Grand Challenges

by Wesley T. Huntress, Jr.

Last November, after stepping down as NASA Associate Administrator for Space Science, Wes Huntress received the second annual Carl Sagan Award from the American Astronomical Society at their annual meeting, held last year in Houston, Texas. Bruce Murray, who succeeded Carl Sagan as president of the Planetary Society, received the first Sagan award, given a year after Carl's death.

In his acceptance speech, Wes set forth a bold vision of humanity's future in space. Rather than focusing on a specific target for exploration, he described a steadily extending reach for human and robotic explorers, with each step accomplished by technology that points toward the next, more ambitious goal. The speech is excerpted here; for the full text, visit the Planetary Society site on the World Wide Web at **http://planetary.org.**

—Charlene M. Anderson, Associate Director

It is my intent here to be provocative in a sense that Carl Sagan would have understood; that is, my intent is to provoke thinking. Carl got you to think by gentle provocation. It was the way he got the public to think about science and the excitement of exploration. The particulars of what I will present in this article are not in themselves important. What is important is that it provokes thinking about the goals and strategy for space exploration in the next century.

In the late spring of 1998, the board of directors of the Space Science Enterprise, NASA's space science organization, established a set of Grand Challenges for Space Exploration, anticipating the new millennium. These Grand Challenges were

1. Read the history and destiny of the solar system;
2. Look for evidence of life elsewhere in the solar system—at Mars, Europa, wherever there has been a history of liquid water;
3. Image and study planets around other stars, and, ultimately, find Earth-like planets in other planetary systems;
4. Send a spacecraft to a nearby star; and
5. Conduct a progressive and systematic program of human exploration beyond Earth orbit.

Let's examine how each of these challenges might be addressed.

Grand Challenges 1 and 2

The first two challenges are about exploring the solar system, which contains a variety of planetary bodies requiring different levels of effort to reach. Let's take a look at the potential objects of exploration, beginning with the easiest missions and moving toward the hardest.

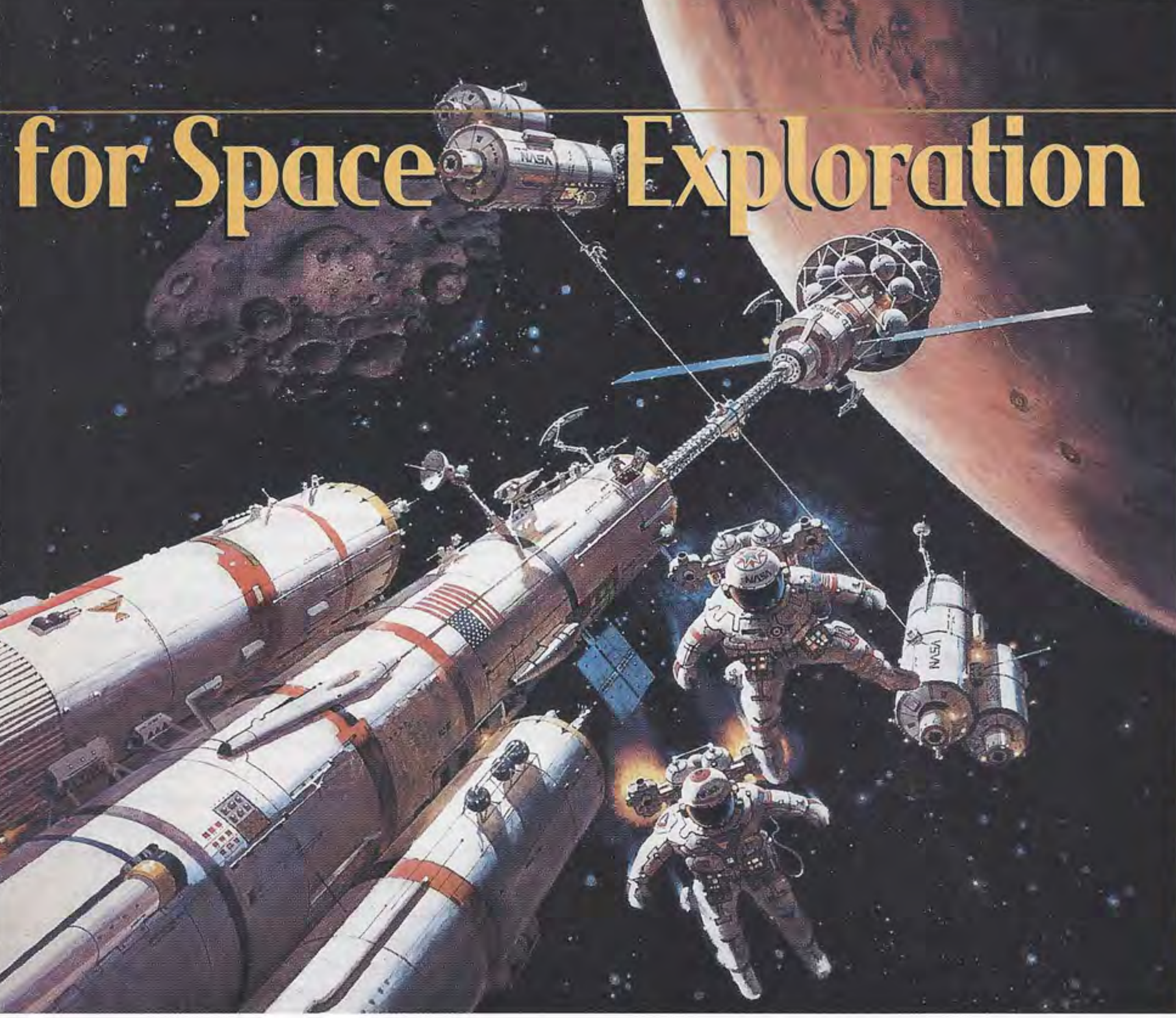
Near-Earth Objects. Near-Earth objects (NEOs), such as asteroids and comets, are the easiest to get to in terms of the energy required. A fleet of microspacecraft can explore a large number of these small objects. This kind of exploration will help us understand how to respond should any NEOs present a danger to Earth in the future. Meanwhile, we will also improve our understanding of their role in the formation of planets and their potential for supplying resources either for future space exploration or for export to Earth.

The Moon. There are many reasons to go back to the Moon, among the most important being to learn more about the history of the Earth/Moon system. By exploring the cratering record on the Moon, we can determine the frequency and size distribution of asteroid impacts on the early Earth. Age-dating of lunar soil and rock layers will teach us about the history of the Sun and its future evolution.

Mars. More difficult than lunar exploration is exploration of Mars. The most significant reason to go to Mars is to search for evidence of past or present life. Should any evidence for early or extant life be found by robots, there is no doubt that human fieldwork on Mars will be required. Other reasons to explore Mars include understanding how the planets evolved and evaluating resources that might be useful for future exploration.

Outer Solar System. The outer solar system will be the exclusive realm of robotic explorers for the foreseeable future. Among the intriguing targets of this region are Europa, with its potential for a subsurface ocean; Titan, which may have hydrocarbon fluids and organic snows on its surface; and cometary objects, which may contain the most primitive of solar system materials, including prebiotic organic compounds.

for Space Exploration



A transportation depot in Mars orbit is not a piece of "space infrastructure" we are likely to see in the next couple of decades. However, farther into the foreseeable future, such a portal to another planet is a decided possibility.

Painting courtesy of NASA

Robotic Colonies. To carry out advanced exploration in our solar system, a concept to consider is the robotic colony —a remote scientific-research station operated autonomously by robots. Robot colonies would be permanent and self-sustaining, requiring occasional resupply. They could be deployed as expandable, intelligent stations in space or on the Moon, Mars, or elsewhere. They could conduct on-site planetary studies or remote astrophysical observations, and they could set the stage for later human activity.

Grand Challenge 3

In the first half of the next century, humankind will be treated to the first image of an Earth-like planet around another star. That image will have an even larger effect on human consciousness than did the first global image of Earth taken from space by *Apollo 8* in 1968. We already know what technology we will use to obtain that image—space interferometry, in which an array of space-based telescopes act together as a single observing instrument. And while we can foresee this technology, we have difficulty imagining the scope of its application.

Grand Challenge 4

Once an Earth-like planet is found orbiting another star, the desire to send spacecraft to nearby stars will become acute. This challenge is even more daunting than producing an image of an extra-solar planet. We can identify the technology required for the latter, but we cannot yet identify the propulsion technology necessary to send even a micro-spacecraft to a nearby star.

Designing the spacecraft for such a mission will require breakthroughs in technologies such as onboard intelligence, robotics, control, repair, navigation, and communication. However, each successive stage in technology development will take us farther, as we explore first the heliosphere and the Kuiper belt, then the Oort cloud, and then the interstellar medium and, finally, send out a spacecraft for a flyby of Alpha Centauri.

Grand Challenge 5

As a goal for human explorers, the ultimate destination remains Mars. The capability for human missions to Mars can be developed over time along a path of technological evolution. Developed in this stepwise way, the program would not be a "Mars or Bust" effort but a steady, progressive, strategic approach, encompassing more than Mars exploration and getting us there with much less risk and more robust capabilities than we would have with an all-out assault on Mars.

This plan assumes the International Space Station is in place as the key space-borne logistical element at Earth. To illustrate the plan, let's start again with the easiest and earliest missions.

Space Telescope at L1 or L2. If cost trade-off studies show that human missions are better than robotic for construction and service of space telescopes and interferometers, then an appropriate initial step for human exploration beyond Earth orbit would be to build a deep-space shuttle capable of ferrying humans and material from the International Space Station in Earth orbit out to L1 or L2 (two of the five Lagrangian points, where the gravitational pulls of Earth and the Sun are in balance).

This Station to Deep Space Shuttle (SDSS) would need the capability of escaping from Earth orbit, traveling the 1.5 million kilometers (about 900,000 miles) to L1 or L2 and back, and supporting humans on construction or service missions for a stay-time of days to months. The energy requirement would be minimal, less than for one of the *Apollo* lunar landing missions. The first SDSS would be a step in the evolutionary development of a later vehicle that would shuttle back and forth between Earth orbit and Mars orbit.

Lunar Surface Exploration. The next step, in terms of energy and hardware requirements, would be the capability to drop into the lunar gravity well and climb back out. In a lunar application, the SDSS would shuttle from the International Space Station in Earth orbit to lunar orbit and would carry a heavier payload than on space-telescope missions to L1 or L2. Lunar missions would require two new pieces of hardware: 1) a lunar shuttle, which would ferry crew and equipment between the SDSS in lunar orbit and the lunar surface, and 2) a lunar habitat, a module to support human expeditions on the surface of the Moon.

Asteroid Exploration. The energy requirements for human missions to NEOs are lower than for lunar surface exploration, but the distances are greater and trip times longer. The SDSS would need new capabilities for these longer trip times and for rendezvous with asteroids and station keeping (that is, keeping pace with the asteroid at nearly constant distance to support surface operations). It would also have to support an asteroid surface explorer, a module similar to the lunar habitat.

Phobos (or Deimos) Observatory. The goal at Mars should be human exploration and eventual colonization. The first step toward that goal ought to be a space station in Mars orbit to support operations to and from the surface. Fortunately, there are two station platforms already in close orbit of Mars—Phobos and Deimos—ready to accept habitats for human beings.

A station on Phobos or Deimos would initially be human-tended but not continuously occupied and would evolve into a permanent, rotated-crew facility. The observatory would track changes on the Martian surface, monitor the planet's weather, and operate surface stations. Robotic surface probes would be launched from the station to perform scientific studies and to emplace supplies.

Mars Surface Exploration. With all the necessary systems in place on a Martian moon to support a human outpost on the surface of Mars, the SDSS would bring two new vehicles to the Phobos station, a Mars Orbit to Surface Shuttle (MOSS) and a Mars habitat. The first missions for the MOSS would be robotic, as it emplaced the Mars habitat and all supporting hardware and supplies on the surface for a Mars outpost. Next, the MOSS would be piloted from Phobos to the Martian surface by the first human explorers. During their stay, the MOSS would stand ready to take them back for rotation with the next crew.

Beyond Mars? Mars is as far as this vision of human exploration goes. But there are destinations beyond Mars that may beckon as we explore space in the next century. If our robotic missions find an ocean below the ice on Europa, and if our aquabots find things swimming in the Europan ocean, then the temptation to send humans will be unbearable. Right now we know of no way to shield humans from a swift death in the radiation environment of Europa, even inside a spacecraft, but there may be a way—perhaps a magnetically shielded cocoon of some kind could enclose our explorers until they were well underneath the natural protection of Europa's ice.

Who can predict what we will find as we proceed over the next years to investigate our solar system and the stars beyond? Who could have predicted in 1990 all that we have learned since then about water on Mars, potential early life on Mars, oceans beneath the ice of Europa, planets around other stars, and the robustness and early origin of life on Earth? So in the coming years, as my 17-year-old son would put it, other stuff might happen. When it does, let's be ready.

Wesley T. Huntress Jr. is Director of the Geophysical Laboratory of the Carnegie Institution of Washington and former Associate Administrator for Space Science at NASA Headquarters.

Mars' larger moon, Phobos, would make a convenient way station to Mars. With its slight gravity, Phobos would be relatively easy to land on and explore. It could serve as a natural platform for a space base to house humans, who might send robot surrogates to investigate the surface of the nearby planet.

Painting courtesy of NASA

World Watch

by Louis D. Friedman

In an eerie coincidence, two interplanetary spacecraft had propulsion failures on the same day and had to be redirected to encounter their targets. On December 20, 1998, the US Near-Earth Asteroid Rendezvous (NEAR) and the Japanese *Nozomi* spacecraft experienced major problems in the midst of maneuvers in deep space.

Never before has an interplanetary spacecraft failed a propulsive maneuver and then been recovered, enabling the mission to resume with a delayed arrival date. Now it has happened twice on the same day.

NEAR was scheduled to rendezvous with asteroid Eros in January 1999. (Planetary Society members are invited to submit names for craters and other features that will be discovered on Eros; see the January/February 1998 *Planetary Report*, page 22.) The new rendezvous date, appropriately enough, is Valentine's Day —February 14, 2000.

The mishap on NEAR occurred when larger than expected acceleration caused the spacecraft to terminate automatically its final large firing. Then, for reasons still not determined, the spacecraft began to drift and lost communications-lock with Earth. It also began to lose solar orientation and power. With only a few hours left before the spacecraft would shut down, the mission team at the Johns Hopkins University Applied Physics Laboratory regained control.

However, 30 kilograms of hydrazine fuel (about 65 pounds) were lost during the time the spacecraft was out of control. That left insufficient fuel to carry out the January 1999 rendezvous. Mission designers came up with a set of new trajectories for encounters later in 1999 or 2000. To conserve fuel for the final approach, they selected the February 14, 2000 arrival.

Nozomi was scheduled to reach Mars in October 1999 but now is on a trajectory to arrive in December 2003. The spacecraft, while leaving Earth orbit, had fired

Although it missed its planned meeting with Eros, the Near-Earth Asteroid Rendezvous spacecraft did manage to take some quick snapshots as it flew by. From images such as this, taken December 23, 1998, scientists have created a model of the asteroid's shape. They will gather more data when NEAR returns to Eros on February 14, 2000.

Image: The Johns Hopkins University Applied Physics Laboratory/NASA

its rocket less than planned, so a corrective maneuver was required. The December 20 correction was successful but for unknown reasons used too much fuel. There was not enough left to accomplish the planned orbit insertion.

Scientists at the Institute of Space and Astronautical Science (ISAS), looking for alternative ways to continue the mission, came up with a new trajectory that includes two Earth flybys for gravitational assist. The first will occur in December 2002, the other in mid-2003. The spacecraft will then be on target for Mars orbit insertion with less velocity and a reduced requirement for fuel.

These adversities remind us that spaceflight is difficult. We can take nothing for granted, not even ingenious saves by mission designers who, time and again, find ways to keep our spacecraft flying.

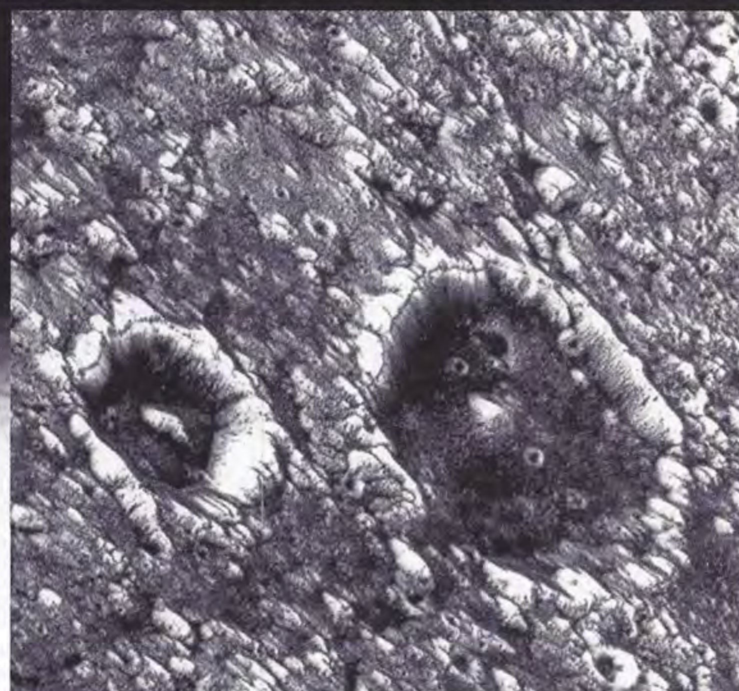
Washington, DC—The possibility of flying an aircraft on Mars on the 100th anniversary of the Wright Brothers' 1903 flight is the highlight of the NASA budget proposed by the Clinton administration for fiscal year 2000. The Mars airplane (which may be either a real airplane or a glider) is one of two new Mars initiatives added to the robotic program. The other is a start-up of a Mars communication network, building up the infrastructure for missions of the emerging Mars architecture (see "Building Toward Mars," page 14 in this issue). Both of these missions will be of the "micromission" class —very small payloads added to already scheduled launches of the Ariane 5.

Space science and exploration plans now under way received full funding in the budget proposal, including Discovery missions like *Genesis* (a solar-wind sample return) and *Contour* (a multiple-comet flyby), deep-space missions like the Europa orbiter and Pluto/Kuiper Belt flyby, and a number of Earth-orbiting astronomy and space-physics satellites. Even advanced technology development of solar sails was included, which in some future century might lead us to the stars.

Overall, the proposed NASA budget is slightly lower than current spending but higher than projected by the White House a year ago. Space-station funding is up slightly as the program suffered another delay in its estimated completion, with the next launch now scheduled for September 1999. The budget must now be considered by the US Congress.

Louis D. Friedman is Executive Director of the Planetary Society.

"ICES" Throughout the Solar System: A Tour of Condensable Species



by Wendy M. Calvin

When we think of ice, we tend to imagine those chunks of frozen water in ice-cube trays in the fridge, sometimes fuzzy with surface frost if they've been left in there too long. Or we may think of snowflakes and hailstones, both of which also involve water ice. In the context of solar system exploration, "ice" can mean a variety of condensed materials—materials that we on Earth usually think of as gases.

Carbon dioxide, nitrogen, methane, and other compounds, in addition to regular old H_2O, occur as ices in our solar system. These icy compounds and their distribution are important to us in several ways. For example, ices in the outermost reaches of the solar system and in comets may have condensed in the earliest stages of solar-system formation and may thus hold clues to the origins of planets and of life. In the future, some of these ices may be resources for space exploration. Our focus in this article will be on ices on the solid surfaces of planets and their moons (rather than those that can occur as ice clouds in atmospheres). Let's start with a look at the elements and compounds from which ices are made, called volatiles.

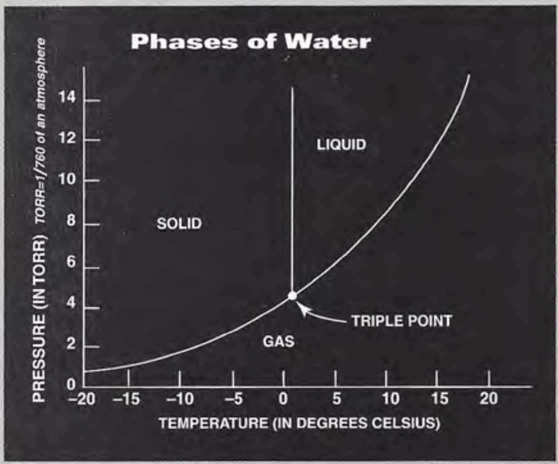
Volatile Review

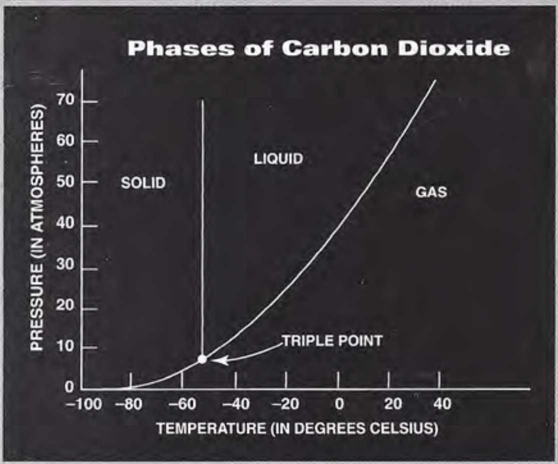
A volatile, in planetary lingo, refers to anything that is pretty easily evaporated or otherwise lost from a planet. Volatiles are light elements or compounds, typically made of hydrogen, carbon, nitrogen, and oxygen. They would be among the last

Top: Could volcanoes exist on an ice world? Our exploratory spacecraft have discovered that in the frigid outer solar system, ice can behave like magma. In this view of Ganymede, the central feature is most likely an icy volcanic lava flow. The lobate depression with scalloped walls and internal terraces is about 55 kilometers long and 17 to 20 kilometers wide (roughly, 34 by 11 miles).

Middle: Impact craters on Earth and on its Moon were blasted deep into a rocky crust. On the large moons of the outer solar system, they were blasted into ice. These two structures on Ganymede display the typical features of impact craters: steep walls, flat floors, and central peaks. The crater Chrysor (left) is about 6 kilometers in diameter (4 miles); Aleyn is about 12 kilometers across (7 miles).

Right: Of all the icy worlds in our solar system, Uranus' moon Miranda may be the most bizarre. This surface has been fractured, grooved, cratered, and marked in ways not seen elsewhere, pointing to a long and complex history for this little body. Images: JPL/NASA





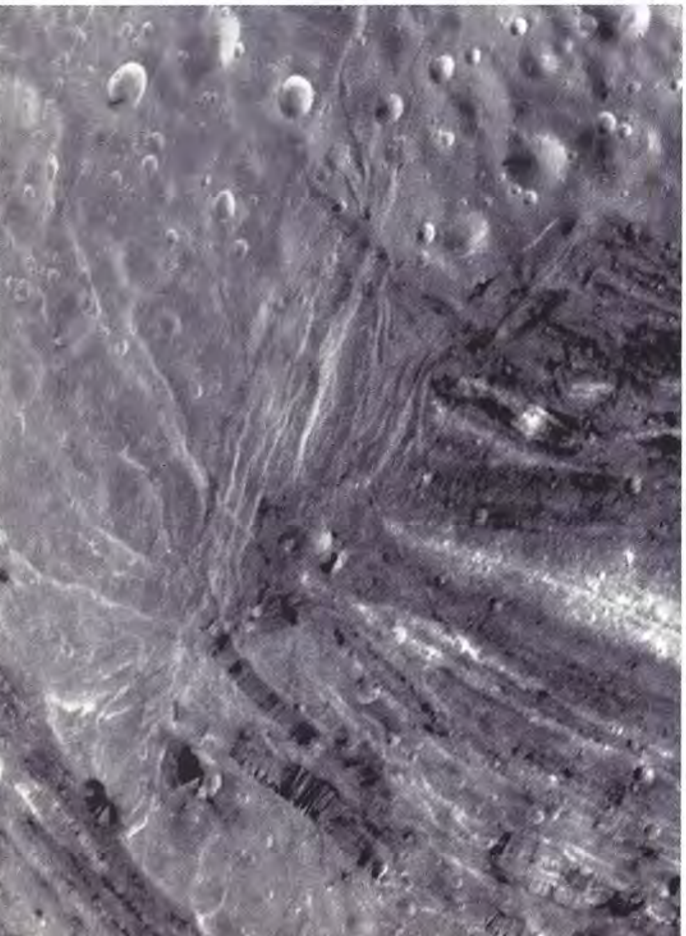
It's Liquid, It's Gas, It's Phase Equilibrium

Every material has a specific temperature at which it changes from solid to liquid or from liquid to gas. This temperature varies with pressure. In the accompanying graph about water, you can find temperature and pressure combinations at which H_2O is stable as a solid, as a liquid, or as a gas. The lines that separate these phases show temperature and pressure conditions in which two phases of a single material can exist in equilibrium. The temperature and pressure at which all three phases can coexist is called the triple point.

If pressure and temperature do not stay exactly on the equilibrium line, then the material will undergo a phase change. For example, if pressure and temperature are such that liquid is the stable phase, then a solid will begin melting.

At temperatures and pressures below the triple point, the liquid phase is not stable at all, and the material proceeds directly from solid to gas, a process known as sublimation. As an example, consider carbon dioxide ice, often called "dry ice." The triple point of CO_2 is 5.2 atmospheres and −57 degrees Celsius (5.2 times the air pressure at sea level and −71 degrees Fahrenheit). Under natural conditions of pressure and temperature on Earth, CO_2 is always a gas. To create carbon dioxide ice, one has to get the CO_2 very cold. When a block of dry ice is exposed to normal temperatures, the CO_2 begins to sublimate, producing the vapor used for eerie effects on stage and screen.

The case for water is very different. The triple point of H_2O is 0.006 atmospheres and 0.01 degrees Celsius (32.02 degrees Fahrenheit). At normal Earth atmospheric pressure, the phase of water is controlled by temperature, and, depending on the temperture, the phase can be solid, liquid, or gas. On Mars, where the atmospheric pressure is 0.006 atmospheres and temperatures are usually −20 degrees Celsius or lower, water can only move between solid and gas states, much as CO_2 does on Earth. At low enough temperatures, even CO_2 will condense from the thin Mars atmosphere as "snow," creating a winter cap of CO_2 ice at the north and south poles. —*WMC*



things to condense from a cooling solar nebula (a cloud of dust and gas from which planets form). Because they are light, volatiles or their constituent elements are often lost from a planet in the course of its evolution. The elements that remain on a planet depend on the strength of its gravitational pull, the presence or absence of a magnetic field (to stave off the solar wind, which can strip away volatiles), and, in the case of Earth, the abundance of organisms that consume certain compounds and produce others.

On the inner planets, gaseous molecules tend to hop around until they land somewhere that has the appropriate temperature and pressure to freeze them. On Mercury, which has no atmosphere to speak of, volatiles are probably trapped near the poles. On Venus, Earth, and Mars, volatiles exist in equilibrium between gas and solid states (that is, we find volatiles in the atmosphere and on the surface). At the orbit of Jupiter and beyond, volatile molecules probably condensed directly from the solar nebula, coalescing into planetary objects such as satellites and comets.

Table 1 (see page 11) outlines the volatiles that we know exist in condensed phases (liquid or solid) on surfaces in the solar system. The table shows the temperature that would be required to freeze the substance on Earth's surface. However, many planets and moons have a thin atmosphere or none at all, and at lower atmospheric pressure, the freezing temperature for a substance also is lower. Therefore, the freezing point given for a substance in table 1 should be considered an upper limit for condensing it into an ice (see accompanying

How Spectroscopy Works

The technique most commonly used for identifying a material that we can't put under a microscope or bring into the lab is to break down its light (reflected or emitted) into constituent wavelengths.

All bodies in the solar system reflect the Sun's rays, and all ices and minerals absorb and reflect different wavelengths of light. In the same way that the colors of a red and blue shirt are different because they reflect different wavelengths to the eye, the glorious colors of Jupiter's atmospheric belts are caused by differences in the materials of the clouds (methane, ammonia, and water), which reflect the Sun's rays differently. Most ices are very white and bright at visible wavelengths but at infrared wavelengths exhibit strong differences, which allow us to tell one kind of ice from another.

Ices (and all other materials) absorb light, not just at one wavelength but over a range of adjacent wavelengths, called an absorption band. Different ices can be identified by their characteristic absorption bands.

We use a prism or a grating to break down light into wavelengths. An instrument called a spectrometer measures the intensity of the light as a function of wavelength. In this way, a spectrometer attached to a telescope or mounted on a spacecraft allows us to survey objects in the solar system and determine their compositions based on observed absorption bands. We can identify gases in atmospheres and minerals and ices on planetary surfaces using this technique. —*WMC*

story on equilibrium phase-curves at the top of page 9).

In most cases we identify extraterrestrial volatile ices by reflectance spectroscopy. In this technique, the light from a moon or other sunlight-reflecting object is gathered in a telescope and broken into a spectrum of wavelengths (by a grating or prism, for example). This spectrum contains a pattern of intensity variations. Wavelengths where the intensity is weaker are called absorption bands, revealing which wavelengths were absorbed rather than reflected by the target body. Every ice has its characteristic signature of absorption bands. To identify all the various kinds of ices, we observe in wavelengths from ultraviolet to the infrared. In the case of comets, we identify certain ices by their fluorescence—that is, they *emit* light in response to solar X-rays.

The Universal Ice, H_2O

With the exception of Venus and the asteroids, water ice is found on or has been suggested for most objects in the solar system. Water ice occurs on satellites of all the outer planets (table 2) and is the most abundant ice in comets. Our Moon and Mercury may have water ice cached in permanently shadowed regions. Water ice is also found on grains in interstellar molecular clouds, so it truly is the universal ice.

Our planet Earth is the only place in the solar system where water occurs in equilibrium with all three phases: solid, liquid, and gas. On Mars, water is either a solid or a gas. On Europa, it occurs as a solid and perhaps as a liquid, if recent evidence of an ocean beneath the moon's icy crust is borne out. However, Europa has virtually no atmosphere and thus no water vapor.

On Earth, water acts as a solvent for a variety of salts and other compounds; by analogy, some of the icy satellites of the outer solar system may have oceans with salts and other minerals entrained in icy crusts.

The Dry Ice, CO_2

Dry ice gets its name from the fact that when it "melts" on Earth there is no liquid. Carbon dioxide (CO_2) proceeds directly from the solid to the gas phase, a process known as sublimation. In the solar system, dry ice occurs on Mars, Triton, comets, and perhaps Callisto.

The Martian atmosphere is composed mostly of CO_2 gas. In winter on Mars, the surface temperature at the poles gets so cold (140 kelvins, or –207 degrees Fahrenheit) that the CO_2 atmosphere condenses straight onto the ground. Thus, overlying its two permanent polar caps, Mars also has seasonal polar caps of almost pure CO_2 ice that come and go with winter and summer.

Io: Hot Spots and SO_2

Home of the only known active volcanoes beyond Earth, Io is indeed a world of "fire and ice." Until recently, Io also had the distinction of being the only location sporting sulfur dioxide (SO_2) frost. Observations in the ultraviolet have since revealed SO_2 on two other Jovian moons, Europa and Callisto, where its occurrence may be caused by energetic sulfur ions from Io being transported along magnetic field lines to impact the surfaces of the other moons, combining with the water ice there.

SO_2 gas is commonly emitted from volcanoes. The volcanic plumes on Io can create temporary and localized "atmospheres," and as material moves away from the volcanic hot spots, it cools rapidly and eventually SO_2 "snows" out, creating a fine, fluffy frost on the surface. We think that with time and repeated deposition, the SO_2 grains merge into thicker ice-deposits below in a process similar to what we observe in terrestrial snowpacks. While we assume other sulfur-bearing volatile ices occur on Io, so far the direct evidence for materials like hydrogen sulfide or sulfur trioxide is equivocal.

The Far Reaches: N_2, CH_4, CO, NH_3

Far out in the solar system, the amount of sunlight hitting the surfaces of planets dwindles and temperatures plummet. Neptune lies six times further from the Sun than Jupiter, which itself is five times further from the Sun than Earth. The sunlight hitting the Neptune system is lower than on Earth by a factor of 900. Surface temperatures on Neptune's moon Triton hover around 40 kelvins (–387 degrees Fahrenheit). At these distances from the Sun, even the most "stubborn" of gases can turn into ice. Nitrogen (N_2) and methane (CH_4) were among the first ices identified on Triton, and more recent work has identified carbon monoxide (CO) and CO_2 as well.

Nitrogen ice on Triton's surface is in equilibrium with a thin nitrogen atmosphere, which means condensation and sublimation can transfer nitrogen back and forth in response to varying solar input. At Triton's low atmospheric pressures, small changes in surface temperature, on the order of one or two degrees, can lead to dramatic and rapid fluctuations—perhaps revealed in *Voyager 2*'s observation of dark streaks associated with geyser-like plumes. One interpretation of these plumes is that the Sun heats near-surface layers in the nitrogen ice, which then generate sufficient gas and pressure to erupt, streaking the moon's surface with the fallout.

On the ninth planet, Pluto, we see volatile ices similar to Triton's, but on its moon Charon only water ice has been definitively identified. Further out, in the Kuiper belt, astronomers have discovered a number of small bodies, and if these are related to Pluto and Triton, then we might expect exotic volatiles to be the norm out there as well.

Comets, messengers from the extreme edges of the solar system, may have a number of unusual ices, such as methyl hydroxide (CH_3OH), hydrogen carbonyl (H_2CO), and hydrogen sulfide (H_2S), and many other complex compounds in small amounts. Comets have the distinction of being the only bodies where ammonia (NH_3) occurs as an ice—at least we think it does. No one has directly identified NH_3 ice on any object as yet, but we do see breakdown products such as NH_2 in comet comae.

Table 1: Condensed Volatiles on Surfaces in the Solar System

Element or Compound		***Normal Freezing Temperature (at 1 atmosphere of pressure)***	***Where Is It Found?***
H_2O	water	273 K (0° C or 32° F)	Earth, Mars, satellites of outer planets (see table 2), comets, and maybe Mercury and our Moon
CO_2	carbon dioxide	215 K (–58° C or –72° F)	Mars, Triton, comets, perhaps Callisto
SO_2	sulfur dioxide	200 K (–73° C or –99° F)	Io, Europa, Callisto
NH_3	ammonia	195 K (–78° C or –108° F)	Comets; also predicted on icy satellites but not yet observed there
CH_4	methane	91 K (–182° C or –296° F)	Triton, Pluto, comets, Kuiper belt objects
O_3	ozone	80 K (–193° C or –315° F)	Ganymede, Rhea, Dione
CO	carbon monoxide	68 K (–205° C or –337° F)	Triton, Pluto, comets
N_2	nitrogen	63 K (–210° C or –346° F)	Triton, Pluto, comets
O_2	oxygen	55 K (–218° C or –361° F)	Ganymede

Note: K = kelvins

For comparison, the coldest recorded temperature on Earth was –89 degrees Celsius (–129 degrees Fahrenheit), measured on July 21, 1983 at Vostok, Antarctica.

Table 2: Icy Moons of the Outer Planets

	Large Moons (>1,000 km radius)	***Mid-size Moons (200 to 1,000 km radius)***	***Small Moons (often irregular in shape, < 200 km semi-major axis)***
Jupiter	Io, *Europa, Ganymede, Callisto*		Metis, Adrastea, Amalthea, Thebe, Leda, Himalia, Lysithea, Elara, Ananke, Carme, Pasiphae, Sinope
Saturn	*Titan**	*Mimas, Enceladus, Tethys, Dione, Rhea, Iapetus*	Pan, Atlas, Prometheus, Pandora, Epimetheus, Janus, Telesto, Calypso, Helene, *Hyperion,* Phoebe
Uranus		*Miranda, Ariel, Umbriel, Titania, Oberon*	Cordelia, Ophelia, Bianca, Cressida, Desdemona, Juliet, Portia, Rosalind, Belinda, Puck
Neptune	*Triton*	Larissa, Proteus, Nereid	Naiad, Thalassa, Despina, Galatea
Pluto		*Charon*	

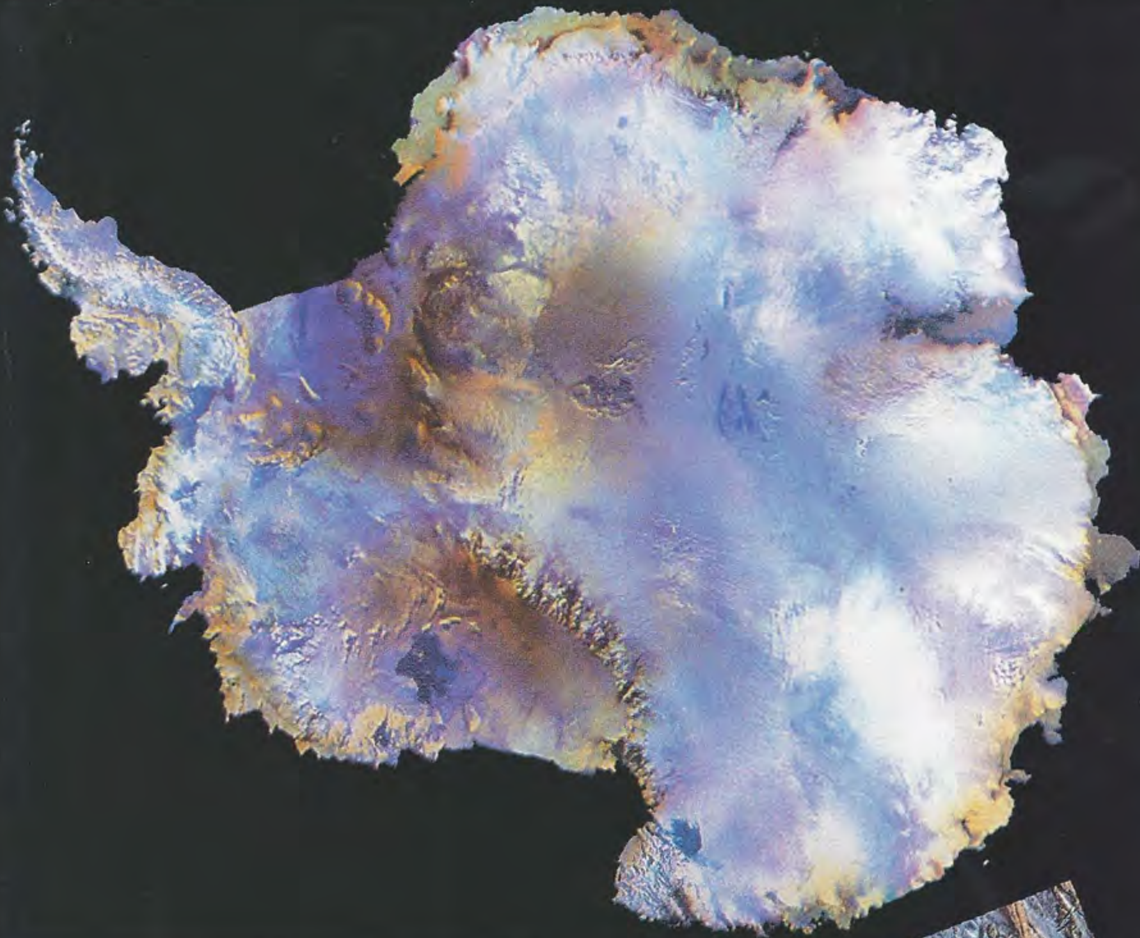
In each column, satellites are listed in order of their distance from their parent planet. Those satellites known to have H_2O ice on their surfaces are in italics. Other satellites may also be icy, but reflectance spectra that would reveal the composition have not yet been obtained. Many small moons are dark in color, suggesting that there is little water ice on the surface.

**The large moon Titan is the only moon in our solar system with a substantial atmosphere. Its atmosphere is rich in nitrogen and methane, making the surface difficult to observe through the thick orange haze. Infrared "windows" in the atmosphere allow views of the surface at certain wavelengths, and recent observations suggest there is water ice in at least some places.*

The Odd Oxygen: O_2 and O_3

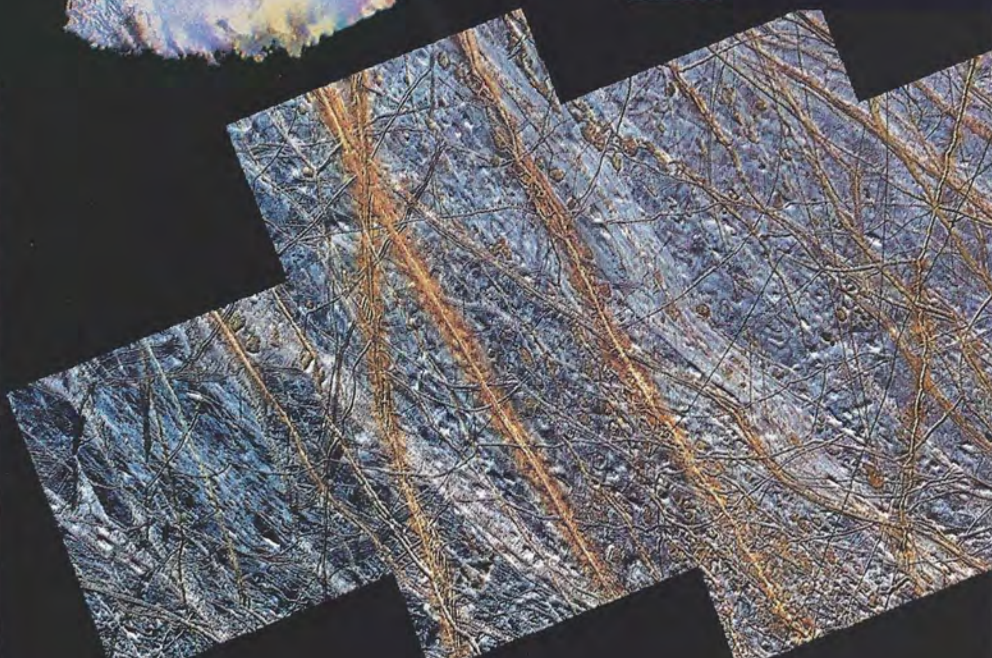
At the bottom of the list in table 1 is the substance we all breathe, oxygen. Under normal atmospheric pressures on Earth, it should require a temperature near 55 kelvins (–361 degrees Fahrenheit) before oxygen turns into an ice! Therefore, it is odd indeed that oxygen occurs in a condensed phase not on some rock at the edge of the solar system but on a moon that is relatively close to us, Jupiter's Ganymede. Normal surface temperatures on Ganymede are low compared to Earth's but still too high to turn oxygen even into liquid, much less into ice. And Ganymede has hardly any atmosphere, so we are hard pressed to understand how oxygen can exist there at all. Nevertheless, condensed oxygen has a characteristic signature (two absorption bands with an unusual asymmetry), and we see it on Ganymede.

One line of thinking about Ganymede's condensed oxygen begins with Jupiter's strong magnetic field, which constantly bombards the Jovian moons with high-energy particles and ionized elements. The impacts of these particles would damage water-ice crystals on Ganymede's surface and break water ice apart into its component elements, hydrogen and oxygen. In these conditions, the single oxygen molecules could then recombine into molecular oxygen (O_2) and ozone (O_3) with the addition of a little solar energy. We believe that the oxygen created by the bombardment migrates into the damaged crystal sites and collects there—droplets of liquid or solid oxygen in a water-ice matrix. So we are seeing the O_2 and O_3 suspended within the matrix, like the color in a cat's eye marble, because water ice is very transparent at wavelengths for observing oxygen. Laboratory studies of comets have shown that "guest molecules" can remain trapped in an amorphous water-ice matrix well above their normal sublimation temperatures. Similar processes may be



Above: Some of the most beautiful ice features in the solar system are very close to home. This mosaic of satellite data shows the ice-covered continent on Earth's south pole.

Image: National Oceanic and Atmospheric Administration



Right: The Antarctic ice sits over both continental rock and ocean water. The ice of Europa may be sitting over a global ocean of liquid water. The blue regions of Europa, observed spectrographically by Galileo, *look remarkably similar to blue regions observed by the spacecraft while flying over Antarctica. The dark-brownish features may be colored by mineral salts.*

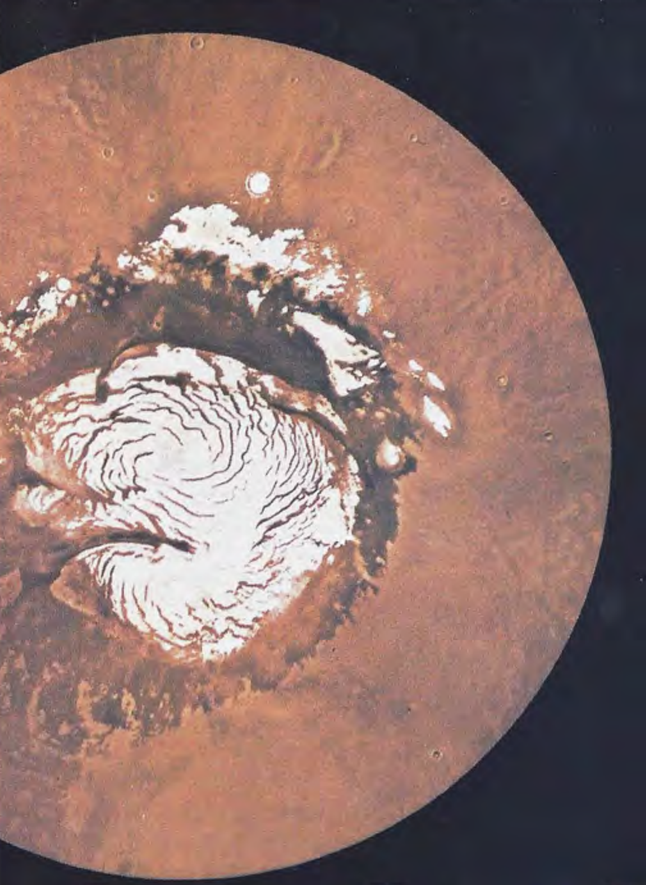
Image: JPL/NASA

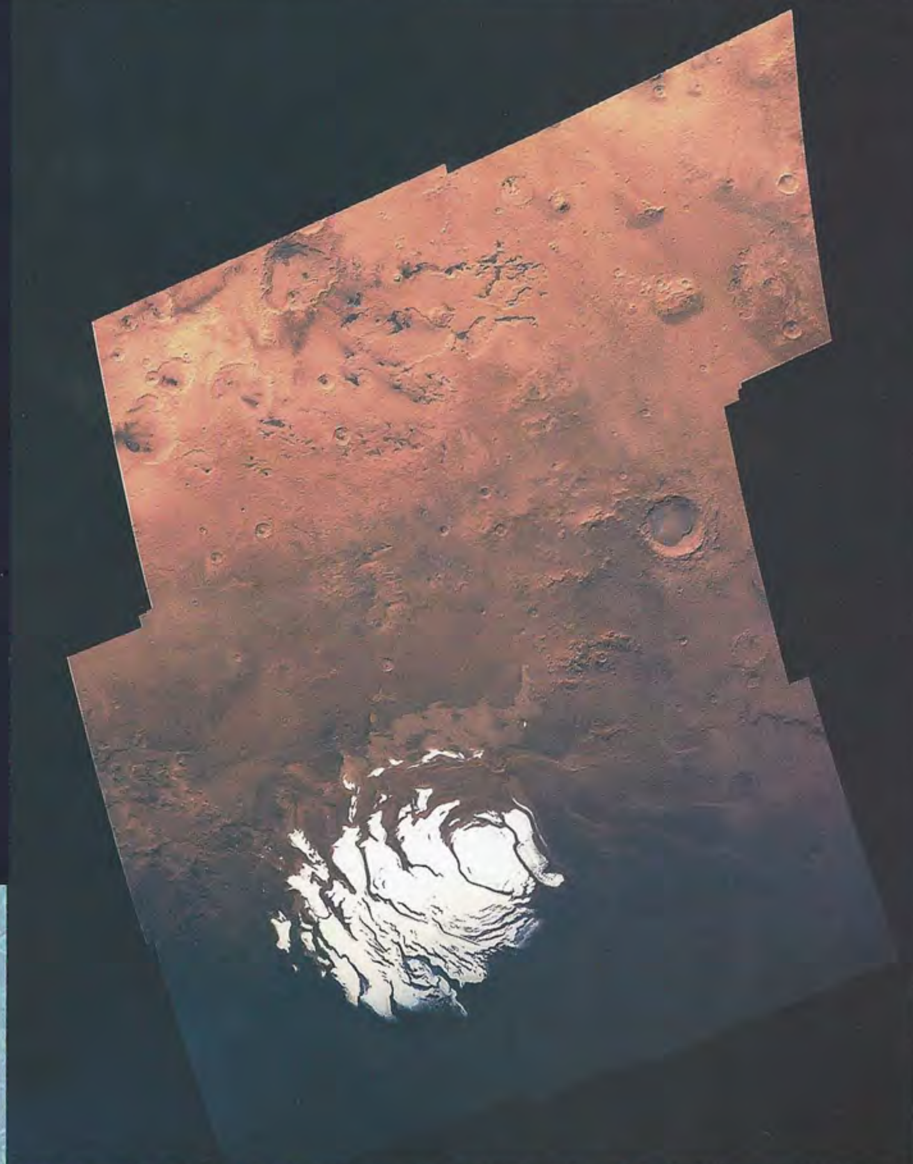
at work with molecular oxygen and ozone on Jupiter's satellites. This is an area of active research.

The Odd Places: Mercury and the Moon

Let us return to our nearer neighbors. The case for the Moon and Mercury is a little different in that the first evidence for water ice was not from spectroscopic observations but rather from the strange reflection of radio waves. We obtain high or "bright" signatures when we bounce radar signals off icy satellites or off the polar caps of Mars, and so bright radar reflections have come to be associated with icy surfaces. When scientists using the Arecibo radio telescope found radar-bright poles on Mercury, it was suggested that the result was due to ice.

The difficulty with ice on either Mercury or the Moon is that although night-side temperatures are very low, daytime temperatures soar. Thus, at first glance, these planetary objects don't seem likely as places to find our familiar H_2O ice. On the heels of the Mercury radar observation, a study showed that permanently shadowed craters at the poles could be cold enough for long enough to allow any water to migrate there and remain for a long time. Such a mechanism was also feasible for the Moon. In 1994 the *Clementine* mission's bistatic radar obtained readings that suggested ice, but ground-based





Above left: The north polar cap of Mars may be one of the most Earth-like features on the planet—and yet it is a very singular place. Here we see the residual cap of water ice that permanently covers the polar region. Spiraling out from the pole in a counterclockwise direction are valleys and low escarpments (also seen on the magazine cover). The walls of these valleys show alternating layers of bright and dark material, most likely layers of ice and dust that may preserve a record of Mars' changing climate.

Above: Unlike Earth's polar caps and the northern Martian cap, the south pole of Mars is covered by a permanent layer of carbon dioxide ice. During the southern winter, the cap expands as carbon dioxide condenses out of the atmosphere and freezes onto the surface. In southern summer, the seasonal ice sublimates away but leaves behind a residual cap that covers the pole all year.

Images: JPL/NASA

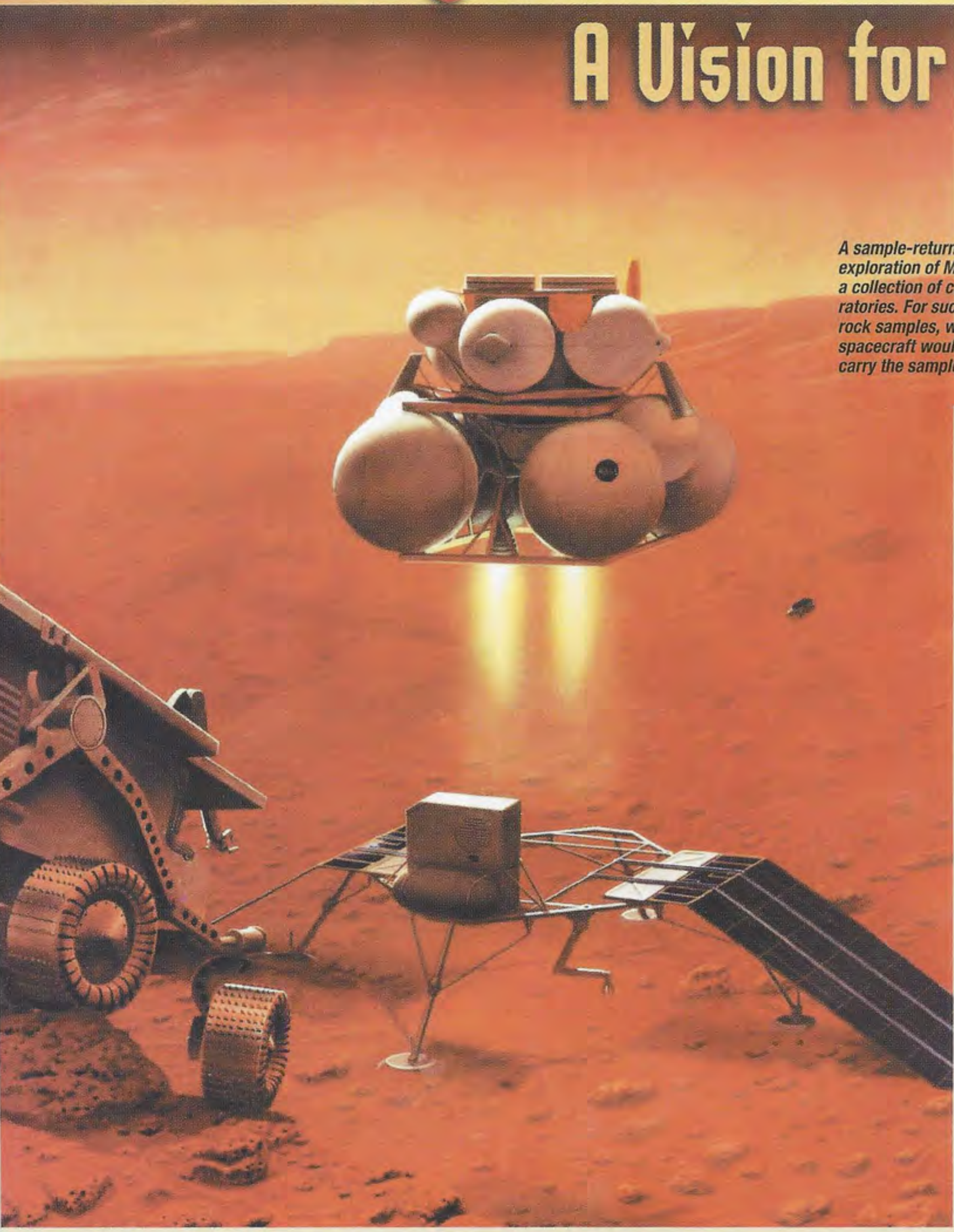
radio telescopes gave negative results.

The case for water ice on the Moon has been considerably strengthened by *Lunar Prospector*'s detection of substantial quantities of hydrogen at both poles (see the January/February 1999 *Planetary Report*, page 8). The hydrogen signature is not confined to permanently shadowed craters, so it appears that the lunar ice must be buried under an insulating layer of lunar soil. For Mercury, it has been suggested that the "ice" may in fact be sulfur.

We're learning more all the time about ices and their distribution in the solar system, and the next few years should turn up some interesting developments as *Cassini* visits Saturn and its icy moons and the *Stardust* and *Contour* missions visit comets. Later this year, *Mars Polar Lander* will give us a taste of Martian ice. So next time you plunk a chunk of that H_2O into your drink on a hot day, consider all its cousins from Mercury to Pluto and beyond.

Wendy Calvin is a geophysicist with the Astrogeology Team of the US Geological Survey. Her research centers on the identification and characterization of ices and minerals formed in association with water throughout the solar system. She was responsible for the identification of condensed oxygen on Ganymede.

Building Toward Mars: A Vision for the Future



A sample-return mission could be the most significant step in our near-term exploration of Mars. There is only so much science we can do without getting a collection of carefully selected samples into well equipped terrestrial laboratories. For such a mission, scientists would direct rovers to collect soils and rock samples, which would then be loaded into a small ascent vehicle. That spacecraft would rendezvous in Mars orbit with a mother ship, which would carry the samples back to Earth. Painting: Pat Rawlings, SAIC for NASA

by Charles Elachi and Louis D. Friedman

"Mars beckons," Carl Sagan used to say. The only known planet besides Earth with accessible oxygen and water, the only planet that has ever hinted (but not yet proved) it harbored extraterrestrial life, Mars beckons uniquely as a place for human exploration in the future. Mars as an exploratory goal is manifest in the extraordinary United States commitment (in a national space policy) to a "sustained robotic presence" on the planet, supported by two launches every two years for the foreseeable future.

Mars was warmer and wetter in the past, perhaps with conditions similar to Earth's when life first began here. Recent discoveries about terrestrial life persisting even in exotic and difficult environments suggest that life might have persisted on Mars—not on the surface, which seems surely sterile, but below the surface. In addition to the possibility of past life, Mars is the most likely (if not only) place for seeding future human life beyond Earth. This special role in the past and future of life is what drives us to Mars.

The United States is not alone in responding to Mars' intrigue —European countries, especially France, as well as Japan and Russia have made it a priority of space exploration. As you read this, there is an orbiter working at Mars, three spacecraft are on their way, four are in development for missions in 2001 and 2003, and there is an international commitment for the next decade or more to collecting samples of Martian rocks and soil and returning them to Earth for study. The political commitment by various nations to Mars exploration undoubtably reflects excitement about Mars among their people.

When *Mars Pathfinder* landed on July 4, 1997, tens of millions of people around the world looked on in awe as the little rover *Sojouner* went about its mission of exploring the landing site. Then the *Mars Global Surveyor* arrived and started its mission of imaging Mars from orbit at an unprecedented resolution.

Later this year, the *Mars Polar Lander,* equipped with a pair of penetrators called *Deep Space 2* (developed in the New Millennium technology program), will give us our first detailed views of the edge of the southern polar cap, while the *Mars Climate Orbiter* studies the global dynamics of Mars' atmosphere. In 2001, another orbiter and lander (with a rover—*Sojourner*'s twin sister, *Marie Curie*) will continue to expand our exploration of new sites on the Red Planet. Also in 2001, another Mars Surveyor orbiter will fly, completing the series of experiments planned for the *Mars Observer*, which failed to reach Mars orbit after its 1992 launch.

An Architecture for Mars Exploration

The 1996 to 2001 missions are only the first steps in a major international campaign undertaken by the United States, France, Italy, the European Space Agency, and possibly other countries to explore the Red Planet extensively and bring samples back to Earth for analysis. We believe that the missions of the early 21st century will lay the groundwork for permanent robotic outposts on Mars and for human exploration—detailed planning for which could begin soon.

Meanwhile, an ambitious general plan of exploration has been laid out by an international group of scientists, engineers, technologists, and educators—the Mars Architecture Team. This group conducted its work during the summer of 1998 and presented its recommendations to NASA, CNES (the French space agency), ASI (Italian Space Agency), ESA (European Space Agency), and numerous science advisory councils.

The plan recommended by the architecture team will further our understanding of the Martian environment as an abode of past and perhaps present life. The question of life is a prime driver in Martian exploration, and in seeking answers we set for ourselves a difficult task. It requires an understanding of the evolution of the Martian geologic and climatic environment. If life (past, present, or future) is the prime driver in the exploration of Mars, water is the road we must follow in our search.

As far as we know, water is a necessary condition to nurture life, and tracing the evolution of the planet's water will reveal its climate history and permit us to evaluate its resources. We will have to search for water below the surface. We will also have to examine multiple sites (imagine trying to learn about Earth from a single landing site or even a few) and conduct in-situ studies, using instrumentation on the planet, as well as sample returns from diverse surface and subsurface regions. The secrets of Mars may be buried underneath that oxidized dusty layer discovered by the *Viking* spacecraft more than 20 years ago.

Bringing Chunks of Mars to Earth

Sample return has been endorsed by the Academy of Sciences in the US and in Russia as the necessary next step in understanding Mars' geologic history and the possibility that Mars has been an abode for life. Sophisticated analytical tools in use on Earth are decades ahead of anything we can package and bring to Mars. As has been shown by the ultra-subtle analyses of Martian meteorites discovered in Antarctica, detecting and understanding the signature of life, even with advanced Earth-based laboratories, is very difficult and requires strong proof by independent techniques.

Much of the work for sample return will involve development of a safe containment system for Martian samples. We want to bring back pristine (unsterilized) samples so that we can look for signs of life. In case we find it, we will need to have a containment system that is totally reliable. Protection of Mars and any samples we bring back against contamination from Earth, and a corresponding protection of Earth against even the remote possibility of Mars contamination, must be the highest priority in the design of sample-return missions.

The campaign of exploration, as envisioned by the Mars Architecture Team, will start in 2003 with the launch of a US lander mission carrying a sophisticated rover that will acquire carefully selected samples from a one-square-kilometer region. Known as *Athena,* the 70-kilogram rover (compared to *Sojourner*'s 10 kilograms, or 22 pounds) will be developed by the Jet Propulsion Laboratory (JPL) under the leadership of Steve Squyres from Cornell University and his international science team. This rover will bring approximately half a kilogram of samples to the lander for loading onto a small rocket called a Mars Ascent Vehicle (MAV), which will use the lander as its launching pad. While the rover is roving, a lander-based drill, whose development is being studied by the Italian Space Agency, will acquire subsurface samples from a depth of one to three meters, perhaps reaching below the Martian surface-oxidation layer. After a few months of sample collection, the MAV will launch the samples cannister to orbit around Mars. This cannister will be tracked by the Mars Surveyor 2001 orbiter and the ESA *Mars Express* orbiter, both of which will already be in Martian orbit at that time.

Technology to Reduce Costs

The use of a simple, unguided MAV to deploy sample-bearing cannisters in Martian orbit for eventual pickup by an orbiter/Earth-return vehicle is one of the novel concepts adopted by the architecture team. The MAV will be a bare-bones solid-fuel rocket without a guidance system, capable

Whether or not Mars possesses easily accessible water will determine its future as a possible site for human settlement. Its now arid surface retains features that strongly suggest liquid water once flowed on Mars. This image of the wall and floor of an ancient impact crater, taken by Mars Global Surveyor, *contains some of the most intriguing evidence of water seen so far. The V-shaped depressions in the crater walls look as if they might have been formed by water seeping from an underground layer. The smooth, dark surface on the crater floor might be the remains of a Martian pond. There are other possible explanations for these features, pointing out the need for more exploration.*

Image: MSSS/NASA

only of roughly navigating to orbital altitude. The work of retrieving the cannister will be done by a more capable orbiter designed for that job.

In 2005, a similar US lander/rover/MAV and a French orbiter will be launched together on an Ariane 5. The major participation by France, making this a US-French joint sample-return plan, is a first in planetary exploration. The lander will explore a new site on Mars and put a second samples cannister in Martian orbit. The French orbiter will then rendezvous successively with the two cannisters, capture them, and put them in a US Earth-return vehicle, which will bring back the samples in 2008. The details of how the orbiter will carry out encounters with two objects in different orbits are still under study. The samples do not come back until 2008 because the interplanetary geometry of Mars and Earth requires a delay of approximately one year before conditions are favorable for the return journey. A round-trip to Mars from Earth takes two to three years.

One of the technological challenges for the 2005 mission is the use of atmospheric aerocapture to slow the French spacecraft and put it in orbit around Mars. Equipped with a heat shield, the orbiter will enter the atmosphere at a controlled altitude and attitude, using atmospheric drag rather than a retro rocket to allow its capture by Mars. This technique, which permits use of a vehicle with significantly less mass, is essential for future deployment of large robotic outposts and human missions.

The sample-return landers will have the potential to carry a number of additional scientific experiments and technology demonstrations for in-situ manufacture of propellant. Making propellant from resources in the Martian atmosphere or soil is a key technology for planning human exploration (see the January/February 1991 *Planetary Report,* page 8). Making propellant on-site eliminates the need to carry propellant from Earth for the return trip and thus significantly reduces launch-vehicle mass. Reducing vehicle mass reduces costs for future human missions, and one of the purposes of the program devised by the architecture team is to develop technologies for eventual human flight to Mars. Technology experiments that will be important for in-situ propellant production will fly aboard the Mars Surveyor 2001 mission, thanks to funding restored by Congress last year after a successful campaign of Planetary Society support.

Micromissions—An International Approach

While the international science community strongly supports Mars sample return, there are other important scientific and exploration studies to be done. Thus, a new class of missions —micromissions—has been devised to conduct special-purpose investigations at Mars at very low cost.

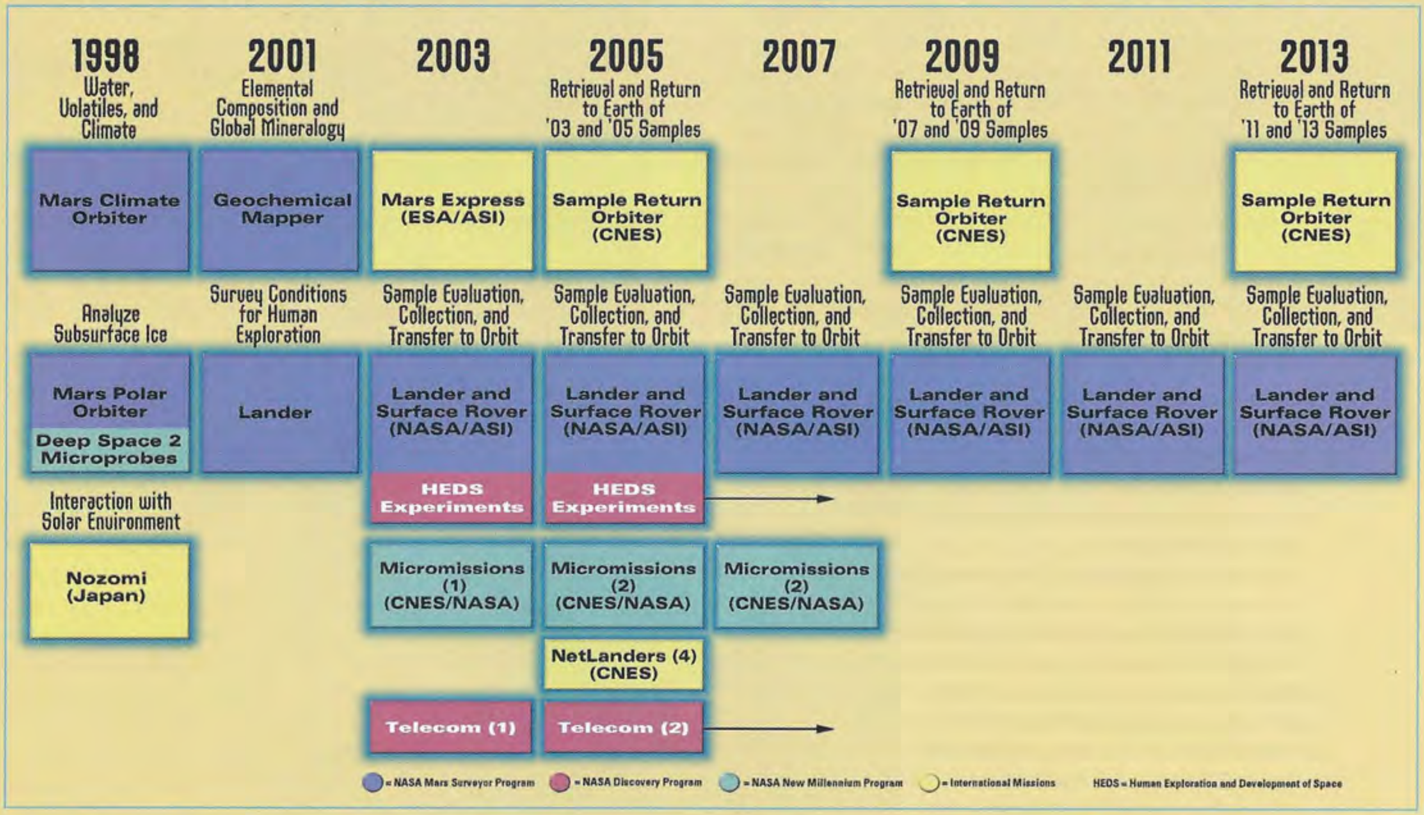
These micromissions will ride piggyback on Ariane 5 or US launchers carrying satellites to high Earth orbit. From there, using a small propulsion system and lunar flybys for gravity assist, a micromission vehicle can attain a Martian trajectory. A number of micromissions (with a spacecraft mass no greater than about 200 kilograms, or 440 pounds) are being considered for launch as early as 2003. One proposal calls for deployment of multiple penetrators (like those of *Deep Space 2*) to create a Mars lander network. Another idea is to send out balloons or gliders both as scouts for landers and as free-ranging vehicles for scientific investigations over a wide variety of sites. Another potential use for micromissions is the development of a Mars communications network.

France and other European countries want to establish a seismological and meteorological network on Mars. The launch capability of the Ariane 5 permits considering these probes as an add-on to the 2005 sample-return mission. French participation and availability of the heavy-lift Ariane 5 facilitate Mars exploration greatly, as can be said for international participation generally. Italy is assisting in development of a soil-sampling drill and in ensuring communications capability via the *Mars Express* orbiter after its basic 2003 mission is complete. *Mars Express*, an ESA mission, will include a US/Italian radar sounder, which will probe the top few Martian kilometers for signs of water, and

The Sun rises for the first humans to walk on Mars. The two explorers investigate a ridge above Noctis Labyrinthus, with the cloud-shrouded floor lying more than 6 kilometers below (4 miles). Side canyons such as this, part of the massive Valles Marineris, will be prime targets for human explorers. These deep gouges in the surface reveal layers of geologic history that could help us understand the Martian past.

Painting courtesy of NASA

Mars Exploration and Proposed Architecture



may include a lander being developed in Great Britain (if funding for the lander can be found).

Japan has no plans at present to follow up its *Nozomi* orbiter, now scheduled to reach Mars in December 2003. However, Japan does have an active planetary program, and much will depend on what we learn from *Nozomi* and *Lunar A*, scheduled for launch later this year. The Russians want to resurrect their planetary program with Mars missions. The Russian Academy of Sciences and Russian Space Agency recently approved a plan to study a Phobos sample return for the 2005 time period. Of course, Russian efforts in space will depend on recovery of their national economy and funding for science projects.

Communications: You Experience Mars

As proposed by the Mars Architecture Team, the 2003/2005 scenario for sample return could be repeated in 2007/2009, which means we would have samples from and detailed in-situ studies of four diverse Martian regions by 2012. In its report, the architecture team emphasized that we will need to know about multiple sites before we can sensibly decide where humans should explore.

Toward establishing a telecommunications and navigation network, the architecture team proposed deployment of a pair of Mars-stationary high-altitude satellites and a network of low-altitude, near-equatorial microsatellites. This combination will allow continuous communication from any station on Mars (rovers, landers, balloons, gliders, probes, etc.) to Earth at a rate of one megabit per second.

This information pipeline will connect to the Internet, or its 21st-century counterpart, making nearly real-time images (delay from Mars to Earth is about 10 minutes) accessible to everyone. In effect, we will be creating an Earth-Mars Internet, the first cell in an Interplanetary Internet.

The satellites we send to Mars will form a Martian counterpart of the Global Positioning System, pinpointing locations on and near the surface of Mars with accuracy down to a few meters or tens of meters. By the end of the next decade, we could have in place the core capability to visit and explore sites all over Mars and bring the "virtual reality" of these explorations to homes and schools all over Earth, even as we prepare for the next phase of Mars exploration.

The possibility of "virtual presence" on Mars leads to a key question: when will humans go? Will humans on Earth be satisfied with robotic exploration? Will it be enough, on the more capable Internet of the future, to have holograms of Mars that we can fly around in—or do we still want astronaut emissaries exploring the possibility of Mars colonies? We can anticipate this question being addressed in the near future.

Human Explorers—When?

Under the Mars Architecture Team plan, we will have visited nine or more Martian regions (counting the *Viking* sites) and brought back samples from four by the year 2012. With the telecom/navigation infrastructure in place and orbiters, rovers, and perhaps balloons or gliders exploring thousands of square kilometers at 1- to 2-meter resolution, we will have enough information to select sites for permanent outposts, which will function continuously as an "extended" arm of Earth research.

Some envision these outposts as bases for human explorers; others see the outposts as robotic precursors, carrying out such functions as deep drilling for subsurface water, site preparation, generation and storage of resources for human habitats, and so on. These outposts could be the robotic equivalents of Armstrong and the other lunar astronauts, Lewis and Clark, Columbus, Magellan, Marco Polo, and other explorers who expanded the horizons of people back home and prepared the way for future explorers.

Or the imperative for human exploration may move faster. After completion of the International Space Station (circa 2004), political and social forces may seek a new goal for space exploration, and Mars—holding the key to questions of past and future life in our solar system—is the obvious destination. Already there is considerable public interest in a human Mars mission, expressed in the media and in space-interest organizations. If a Mars mission were decided upon as the next human exploration initiative, then the Mars Architecture Team's plan offers a course for gathering the information we will need for such an adventure.

Human exploration of Mars undoubtedly will happen in the next century—whether it begins in the first 15 years or the second remains to be seen. A human mission will be difficult, requiring international resources that exceed today's space program commitments. It will require technology advances to lower costs and increase safety—technologies like in-situ resource utilization (for propulsion and power) and aerocapture. It will also require more knowledge about the surface of Mars—dust, radiation, wind, and soil toxicity are all hazards we must characterize. And perhaps most important, we need to know much more about the search for life on Mars—how and where to look and, if we are so lucky, how to handle it once we find it. The Mars Architecture Team plan is designed to meet these requirements.

Mars exploration will capture the imagination of humankind in the same way as did the first lunar landing and the travels of the *Pathfinder* rover. Exploration is the raison d'être for space programs, and Mars is the destination where we look for ourselves. The Mars architecture outlined here can guide this exploration, and along the way it will drive the development of engineering and technology advancements that may have significant payoffs for our way of life on Earth: electronic miniaturization, development of miniature biological sensors, autonomous robotics, high-speed communications, three-dimensional visualization, and high-efficiency deep-drilling techniques, to name a few.

The first decade of the new millennium will be truly the Decade of Planetary Exploration. In addition to establishing a permanent presence on Mars, we will be putting orbiters around Saturn and Europa, visiting Pluto, landing on a comet nucleus, and bringing samples back from asteroids and comets and possibly from Venus, Mercury, and the Jovian satellites. We will be establishing a permanent presence across the solar system and, as we extend humanity's reach to the planets, bringing the heavens to Earth.

Charles Elachi is the Director for Space and Earth Science Programs at JPL and the chair of the Mars Architecture Team. Louis D. Friedman is the Executive Director of the Planetary Society and a member of the Mars Architecture Team.

Planetary Society Contest Winner Names 2001 Rover

Apollo, Viking, Galileo, Pathfinder—these are names associated with space exploration, evoking dreams of accomplishment, adventure, and discovery. Spacecraft names, many of which have become household words, are usually chosen by space agencies. But in the spring of 1994, NASA and the Planetary Society initiated a new naming process—an international essay contest asking students of the world to submit their suggestions for the official name of the *Pathfinder* rover.

The Society received more than 3,000 essays. Participants from India, Israel, Poland, Russia, Japan, Mexico, and Canada joined students from the United States in this unprecedented opportunity. The contest rules were simple: choose a famous woman from history and explain why her name should be given to a future explorer of Mars. Some of the most popular names were aviator Amelia Earhart, the goddesses Athena and Artemis, teacher and astronaut Christa McAuliffe, and freedom fighter Harriet Tubman.

The Society announced a winner, 13-year-old Valerie Ambroise, in June 1995, but the world had to wait two more years before being formally introduced to the amazing little rover named after abolitionist Sojourner Truth. As *Pathfinder* relayed images back to Earth, the Red Planet's first mobile trespasser, the six-wheeled *Sojourner*, joined the ranks of celebrated spacecraft exploring worlds beyond our own.

Now *Sojourner's* twin sister is getting ready to make her maiden voyage aboard the Mars Surveyor 2001 mission. The essay contest's second prize winner, Deepti Rohatgi, named this rover after the renowned scientist Marie Curie. Deepti's winning essay explains, "[The rover] Marie Curie would explore Mars with the unique and innovative fashion she conducted her life. She gave her life to researching new elements, and would have loved the opportunity to explore a new planet . . . although she would have to alter her techniques."

Marie Curie, born Marie Sklodowska, was one of the first woman scientists to win worldwide fame. In 1903, she won a Nobel Prize in physics, honoring her pioneering studies of radium and polonium, which contributed to the understanding of radioactivity. In 1911, Curie became the first person to win a second Nobel Prize—this one in chemistry, honoring her isolation of radium. Deepti Rohatgi concludes, "Although space exploration was never considered in [Marie Curie's] time, her research with these minerals would have made her a perfect candidate to help determine the composition of Martian rocks and soil."

What will the *Marie Curie* rover do after landing on the Red Planet in February 2002? It will definitely explore the rocks and soil near the landing site. It may uncover evidence that will help us better understand Mars' history. And it may even find something we have never seen before. One thing is for sure: this rover will bring the name Marie Curie to worldwide attention once again.

—Jennifer Vaughn, Assistant Editor

News and Reviews

by Clark R. Chapman

After *Mariner 10* took close-ups of one hemisphere of Mercury, I briefly served on a subcommittee charged with recommending names for the newly revealed craters and topographical features. But midway through its work, and long before the International Astronomical Union (IAU) formally adopted the names, I resigned from the subcommittee.

Nomenclature Junkets

Despite the virtues of international fraternity during the Cold War and the pleasures of sights and cuisines in exotic places, I decided that nomenclature meetings took time from research. The debates generated more heat than light. While it is easier, for example, to refer to a crater as "Haydn" than as "the big crater at lat/lon –27/72," the talents and expertise of scientists are largely wasted in traveling overseas to debate nomenclature. Issues were often petty: one scientist—a bird-watcher—wanted Mercury's craters named for bird species. Bickering erupted over such nonscientific issues as nationalism, political correctness, and history. Let others with time on their hands name the craters.

What about the latest controversy over demoting Pluto from being a planet to a mere asteroid or trans-Neptunian object (TNO)? When this contentious silliness first arose several years ago, I told a TV interviewer that "Pluto is Pluto." Instead of debating Pluto's categorization, I still believe our priorities should be to research Pluto and to fly a spacecraft out to study this fascinating double world on the periphery of the planetary system.

I'm skeptical of colleagues who justify raising such squabbles as a means to get more planetary science on the TV news. To be sure, schoolchildren may learn afresh about differences between planets and comets. But our popular culture is already one big talk show, and even Congress devotes itself to teapot tempests rather than the urgent issues of our times. The Pluto dispute shares in the nonscientific, value-laden aspects that mar nomenclature arguments. Are schoolchildren being confused by scientific arbitrariness? Is the memory of Clyde Tombaugh's contributions to astronomy being undercut by demeaning the planet he famously discovered? Who has the legitimate power to name, number, and classify celestial objects?

Pluto's Taxonomy

Still, the "Is Pluto a Planet?" issue has a scientific element lacking in most IAU nomenclature debates. After all, almost no one seriously proposes to change Pluto's name. The question concerns its *taxonomy*. Whether a cosmic object is a star, a brown dwarf, a planet, a comet, a TNO, an asteroid, a satellite, or a meteoroid may involve an arbitrary, subjective choice, but such classification also involves science. Taxonomy is an essential early phase of such fields as botany and zoology. Measuring the fundamental properties of things in the natural world, and recognizing their similarities and differences, can advance science by helping us to better understand natural processes.

A recent flurry of e-mail among my colleagues has drawn attention to fundamental issues about Pluto's nature, about the dozens of recently discovered TNOs (somewhat resembling Pluto but much smaller), and about whether other Plutos and even larger planets exist farther from the Sun.

Each of the eight other planets has its own special attributes, varying enormously in mass, composition, appearance, and possession (or not) of satellites and rings. Pluto's traits can be seen as the definition of its planetary identity or, instead, as evidence that it more nearly resembles cometary bodies that we don't call planets. Pluto is small, yet Mercury's planetary status has not been challenged by the larger sizes of Ganymede and Titan. As a double planet, Pluto-Charon resembles the Earth-Moon system. Yet we now know that "mere" asteroids can also have sizable satellites. Pluto has a "planetary" atmosphere, but so do some moons. Since discovery, Pluto's orbit has been known to be more elliptical than the orbits of other planets (for years before 1999, Pluto was closer to the Sun than Neptune); only recently has orbital eccentricity been raised as an argument against planetary status.

Were Pluto brought near the Sun, it would become a magnificent "comet," but so would other asteroids, satellites, and planets. As we discover the remarkable complexities of worlds like Triton, Titan, Europa, and Io, should these satellites be upgraded to planets? Should our evolving theories for the *origins* of Pluto and other bodies change their status, making Pluto a "protoplanet" or a "planetesimal" and Mercury a "planetary remnant"? Or, as one theorist has argued, should Pluto's minimal gravitational influence on other cosmic bodies decide against its planetary nature? Should a single body be placed into two different categories?

With their cocktail-party, parlor-room flavor, these debates rarely seem the stuff of serious science. So let's leave Pluto as a planet and get back to our research. Yet, in some subjective way, the Pluto debate may have changed some creative researcher's gestalt about the cosmic zoo, inspiring new research . . . and astronomy may, as a result, advance.

Clark R. Chapman is the 1999 recipient of the Carl Sagan Medal for Excellence in Public Communication of Planetary Science, awarded by the Division for Planetary Science of the American Astronomical Society.

Questions and Answers

What gives meteors the colors we sometimes see?
—Ingrid Baumgart,
El Segundo, California

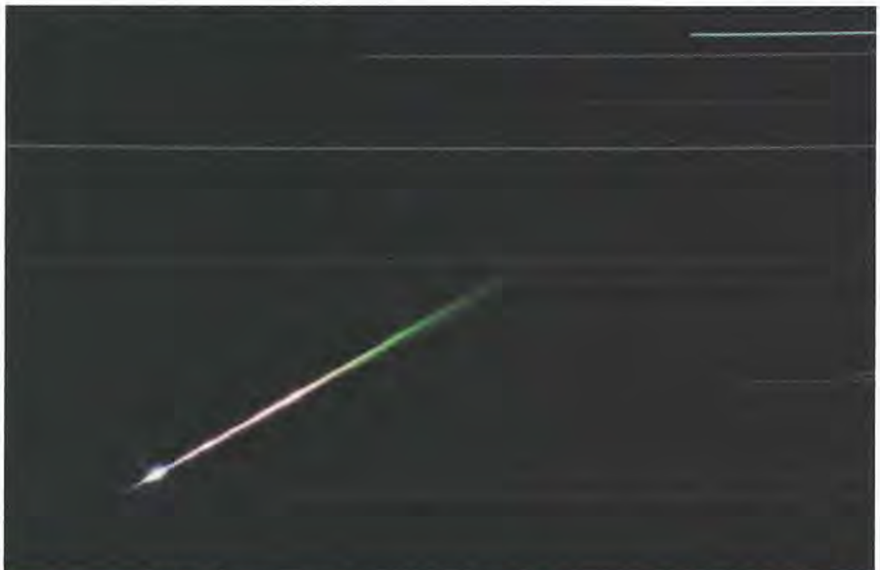
The color of a meteor—or its brighter counterpart, a fireball—depends on several factors, including our eyes' range of sensitivity to light and individual differences in color perception. The amount of atmosphere we are looking through and the meteoroid's speed through the atmosphere also have effects. And the chemical composition of a falling meteoroid may determine the colors generated.

Faintly illuminated objects are visible but show little or no color to the human eye (examine the pictures in *The Planetary Report* sometime under a full Moon). Thus, faint meteors appear as colorless flashes against the night sky. If a meteor or any object is bright enough, green will be the first color we perceive because that is the color to which our eyes are most sensitive. Interestingly, this color may be described by some viewers as blue, which points to the issue of individual color definition.

A meteor we see low on the horizon is distant, and we observe it through a lot of atmosphere. These conditions redden a sunset and can have the same effect on a meteor or fireball.

It is misleading to say a meteoroid "burns up" in Earth's atmosphere. Instead, frictional heating sublimates meteoroid particles directly from solid to gas. This change of state transforms large amounts of a particle's energy of motion so that its atoms become excited and generate light. Nearby atoms in the atmosphere may become excited and emit light as well. A slower collision with the atmosphere transforms less energy from motion to light and so affects a meteor's color.

Finally, the glow of an incoming particle's excited atoms may be tinged according to its ingredients. For example, iron can generate green, while sodium generates a bright gold (the color of some streetlights). Other elements in a meteoroid have their own characteristic colors.


A variety of factors can influence the colors seen by people lucky enough to observe a meteor. This photograph of a Leonid was taken on November 17, 1998. Photo: Steve Jackson

Observers commonly report bright fireballs to be green. People occasionally see other colors (I've seen a meteoroid in flashing pastels), and sometimes they observe yellow sparks coming off the main body. Thirty years ago, some Leonid meteors (so named because the constellation Leo serves as background for this annual shower) shone ruby red, and in 1998 color pictures of certain Leonids showed a transition from greenish to reddish.

Astronomers use spectrographs to record the atomic emissions of meteors. Detailed records from these instruments provide the only method of explaining scientifically why a meteor or fireball displays the colors it does. Individual perception cannot be quantified and so falls outside the bounds of a scientific explanation.
—STEPHEN EDBERG,
Jet Propulsion Laboratory

After reading the debate on whether the Mars rock ALH84001 contains evidence of early life on Mars (see the May/June 1998 issue of* The Planetary Report*), I'm left with a question. Did anyone investigate the Moon rocks with the same zeal? Are ALH 84001's organic compounds also found in Moon rocks?
—Jeffrey L. Yount,
Bourbannais, Illinois

A lot of work went into searching the lunar samples for organic materials. There is reduced carbon in the lunar regolith (surface layer), most of which comes from meteoritic sources and the solar wind, with a small amount being indigenous to the Moon's volcanic rocks. At one time, papers reported the presence of small quantities of complex organic compounds, particularly amino acids, in lunar samples. These compounds proved to be artifacts of the analytical techniques.

The interest in organic compounds on Mars is heightened by the evidence for liquid water there, at least early in the planet's history. There is no evidence for liquid water on the Moon at any time. The only hydrogen known on the Moon comes from the solar wind or meteoroids and comets. There may be water frozen in the cold traps at the lunar poles, but definitive evidence is not yet in hand.

Analytical techniques have improved significantly since the *Apollo* samples were studied, so smaller amounts of organic materials might be detectable now. However, the biological nature of any of these compounds in lunar materials would be very difficult to demonstrate because of the apparently nonbiological origin of most of the Moon's carbon.
—MIKE DUKE,
Johnson Space Center

What are the fastest-moving objects in the solar system?
—Mike Ashley,
Chatham, England

Comets are the solar system's fastest solid bodies. The speed of a comet depends upon the size of its orbit and proximity to the Sun. An object in space will reach its fastest orbital speed when it passes closest to the Sun (perihelion).

Among short-period comets and asteroids, asteroid 1995 CR and comet 96P/Machholz 1 are the fastest, reaching about 118 kilometers (73 miles) per second at perihelion. For comparison, comets Halley and Hale-Bopp reach more leisurely maximum speeds of 55 and 44 kilometers (34 and 27 miles) per second at their respective perihelia.

Earth attains a maximum orbital speed of just over 30 kilometers (about 19 miles) per second. But for downright breakneck speed, it would be tough to beat the cometary sungrazers —comets on highly elongated orbits that pass very near the Sun. For example, a sungrazing comet discovered by the SOHO spacecraft in 1996 (C/1996 S3 SOHO) achieved a maximum speed near the Sun of 1,088 kilometers (about 676 miles) per second. As for maximum possible speed, a sungrazing comet in a nearly parabolic orbit with its perihelion at the edge of the Sun's photosphere could reach 1,660 kilometers (about 1,030 miles) per second. At this rate, you would make the trip from Los Angeles to New York in just over 2 seconds.

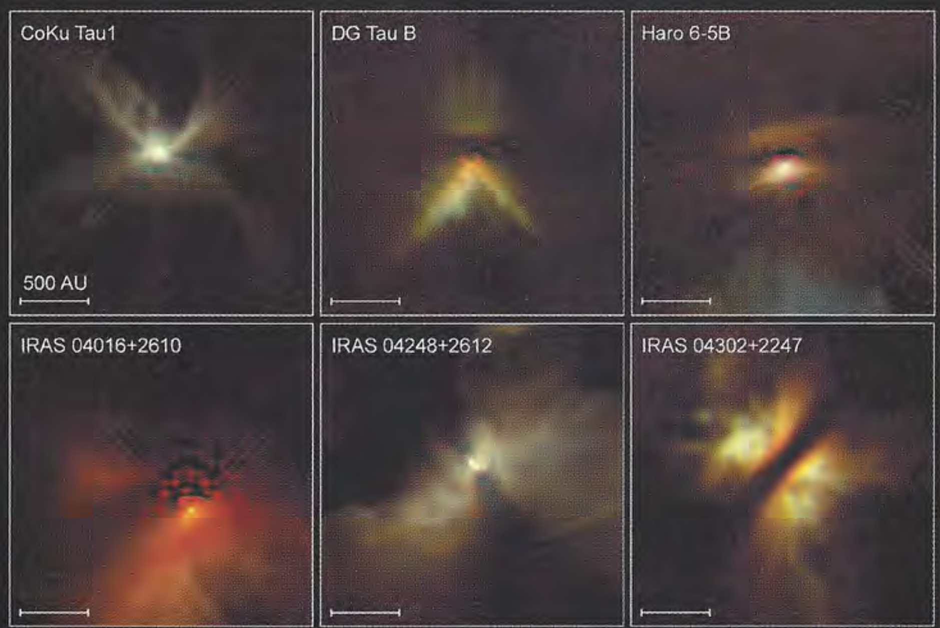
However, these super-swift sungrazers pay dearly for their reckless lifestyle. Eventually, in a final sunward plunge, almost all of them are consumed by the solar inferno.
—DONALD YEOMANS,
Jet Propulsion Laboratory

Factinos

New images of dust disks encircling young stars (below) are giving an assortment of science teams insight into what may be the early formative stages of planetary systems. Although planets are not visible in these pictures from the Hubble Space Telescope (HST), the edge-on disks provide the best view yet of planetary construction zones.

"While the existence of these disks has been known from prior infrared and radio observations, the Hubble images reveal important new details, such as a disk's size, shape, thickness, and orientation," said Deborah Padgett of the California Institute of Technology (Caltech) Infrared Processing and Analysis Center (IPAC) in Pasadena, California. Padgett's group used HST to peer through obscuring dust clouds surrounding six extremely young stars 450 light-years away in the constellation Taurus. The team found evidence for dusty disks in all six. The presumed disks have diameters 8 to 16 times that of Neptune's orbit.

John Krist of the Space Telescope Science Institute used HST to determine that the young star Haro 6-5B is actually a small nebula (cloud-like stage in a star's development) crossed by a large, dark band, or dust lane. And, with Hubble's help, Karl Stapelfeldt of the Jet Propulsion Laboratory (JPL) spotted the first example of a disk in a young double-star system. The disk, centered on the system's fainter star, has a diameter only 3.5 times that of Neptune's orbit.
—from the Space Telescope Science Institute



These eerie disks of dust encircling young stars are giving scientists unprecedented views into what may be the gestation of new solar systems. The abbreviation AU stands for astronomical unit, the mean distance between Earth and the Sun. Images: D. Padgett (IPAC/Caltech), W. Brandner (IPAC), K. Stapelfeldt (JPL), and NASA

American and European scientists have located the wellsprings of the solar wind. Using recent data from the Solar and Heliospheric Observatory (SOHO) spacecraft, the researchers found solar wind flowing from the edges of honeycomb-shaped patterns of magnetic fields on the Sun's surface. The findings appear in the February 5, 1999 issue of *Science*. "The search for the solar wind has been like the hunt for the source of the Nile," said Don Hassler of the Southwest Research Institute in Boulder, Colorado, main author of the *Science* paper.

As the solar wind streams past Earth, it changes, sometimes dramatically, the shape and structure of our planet's magnetic field. These changes can damage satellites and disrupt communications and power systems.

Scientists have long thought that the solar wind flows out of holes in the Sun's corona. The SOHO images pinpoint the outflows to specific patches at the edges of the honeycomb-shaped magnetic fields.
—from the Southwest Research Institute

Society News

Mars Microphone on Its Way to Martian Ice Cap

The Planetary Society's Mars Microphone is on its way to the Red Planet. Designed by a team at the University of California, Berkeley, the microphone is the first citizen-sponsored instrument to fly aboard a planetary mission. It is also the first US- Russian collaboration on a planetary instrument. Planetary Society members made this historic event possible.

The microphone is part of the Russian lidar instrument aboard the *Mars Polar Lander*, which launched on January 3, 1999. The lander arrives at Mars on December 3, 1999. On that day, the Planetary Society will open Planetfest '99, a celebration of a millennium of exploration, culminating in the current series of missions to Mars. Participants in the celebration will witness the *Mars Polar Lander*'s descent to Mars' south polar region, as the first images and the very first sounds of Mars are received at the Jet Propulsion Laboratory.
—Susan Lendroth,
Manager of Communications and Events

LEGO Challenge Puts Student Rover Project Closer to Mars

Thanks to members who responded to our special appeal for Red Rover Goes to Mars, an historic, collaborative opportunity for the next millenium. The conditions of the LEGO challenge were met, and LEGO is a full sponsor for the project. The Planetary Society is now working with science and engineering teams of the Mars Surveyor 2001 project on software and mission operations protocols that will permit the first-ever citizen participation in the operation and control of a planetary spacecraft.

If all goes well, the Planetary Society's education and outreach program for the mission will involve students around the world. Student scientist and astronaut teams will be selected on the basis of written entries (procedures for entering are still being worked out). The selected student team will work with mission engineers and scientists in devising and sending commands to the *Marie Curie* micro-rover and in teleoperating the lander arm that will collect soil and dust samples. High-school students will also have a chance to propose micro-experiments, at least one of which will fly on the 2001 mission.

In addition, the Society plans to engage students around the world with mission data as transmitted by the student team. Updates will be regularly broadcast via the Internet throughout the course of the mission. Stay tuned for important developments.
—Linda Hyder,
Manager of Program Development

Get Ready for Planetfest '99

Plans are well under way for Planetfest '99, a celebration that will coincide with the landing of the *Mars Polar Lander*. The event takes place December 3 to 5, 1999 at the Pasadena Convention Center in Pasadena, California. Following on our very successful Planetfest '97, which brought out tens of thousands to witness first-hand the historic landing of *Mars Pathfinder*, Planetfest '99 will celebrate a millennium of discovery with the theme "From Mars to the Stars."

As we celebrate humanity's discoveries and exploration over the last thousand years, we'll take a special look at Mars, as mission images come directly from the Jet Propulsion Laboratory to the convention center and the first sounds ever recorded on the Red Planet arrive from the Society-funded Mars Microphone.

Throughout Planetfest '99, the Discovery Symposium will bring together leading scientists, thinkers, and writers to discuss our path in space over the next millennium. A venue to excite young imaginations, A Child's Universe, will be full of hands-on activities. Current mission displays, information from a panoply of exhibitors, and special concerts and events will make this a weekend to remember. Prepare to join us for the historic landing of *Mars Polar Lander* as we cross into the next century.

For more information about Planetfest '99 and to get your tickets early, contact Society headquarters at 1-800-WOW-MARS, or visit our site on the World Wide Web at **http://planetary.org**.
—Cindy Jalife,
Director of Membership and Programs

More News

Mars Underground News
Rocky rovers and new propellant technologies are paving the way for efficient robotic exploration.

Bioastronomy News
Optical SETI scans the skies for light signals from other civilizations.

The NEO News
The Society announces recipients of the 1999 Gene Shoemaker NEO Grants.

For more information on the Planetary Society's special-interest newsletters, phone (626) 793-5100.

Also, visit our home page at *http://planetary.org*

Optical SETI Searches for Signs of Light

After more than a decade of sponsoring SETI searches that listen for radio signals, the Planetary Society, thanks to our member support, is turning eyes to the skies to scan for possible light signals from other worlds. Two optical SETI programs at the University of California, Berkeley and one at Harvard University are now operating with Society funding. One of the Berkeley projects will search for light pulses as brief as one-billionth of a second; the other will search for steady, extremely narrow bands or single-color light signals from stars similar to our Sun. The Harvard project will also search for light pulses, scanning collected data on 2,500 nearby Sun-like stars. *—SL*

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Winds of Mars and the Music of Johann Sebastian Bach ***NEW!***

This audio CD features digitally simulated sounds of the winds of Mars as interludes between 17 of Bach's finest compositions, performed on piano. The wind data were collected by an instrument on the *Mars Pathfinder* lander and translated into wind sounds through a Musical Instrument Digital Interface (MIDI). The CD includes extensive liner notes explaining the production of the Martian sounds and a general history of Mars exploration.

Mars Polar Lander is carrying the Planetary Society's Mars Microphone to record the first actual sounds from the Martian surface. It will be interesting to compare this simulation recording to the real thing—coming in December 1999!

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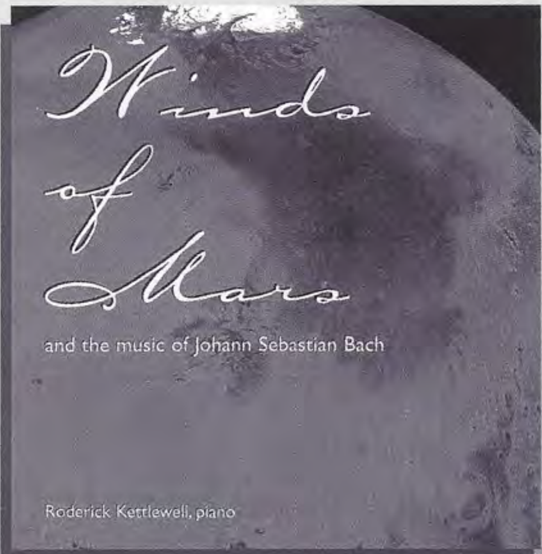

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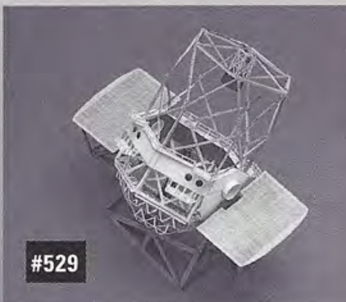

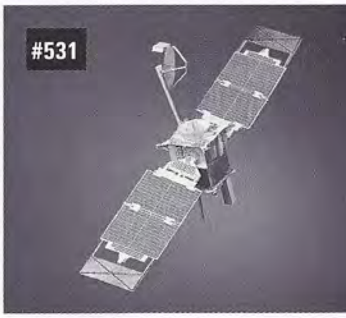

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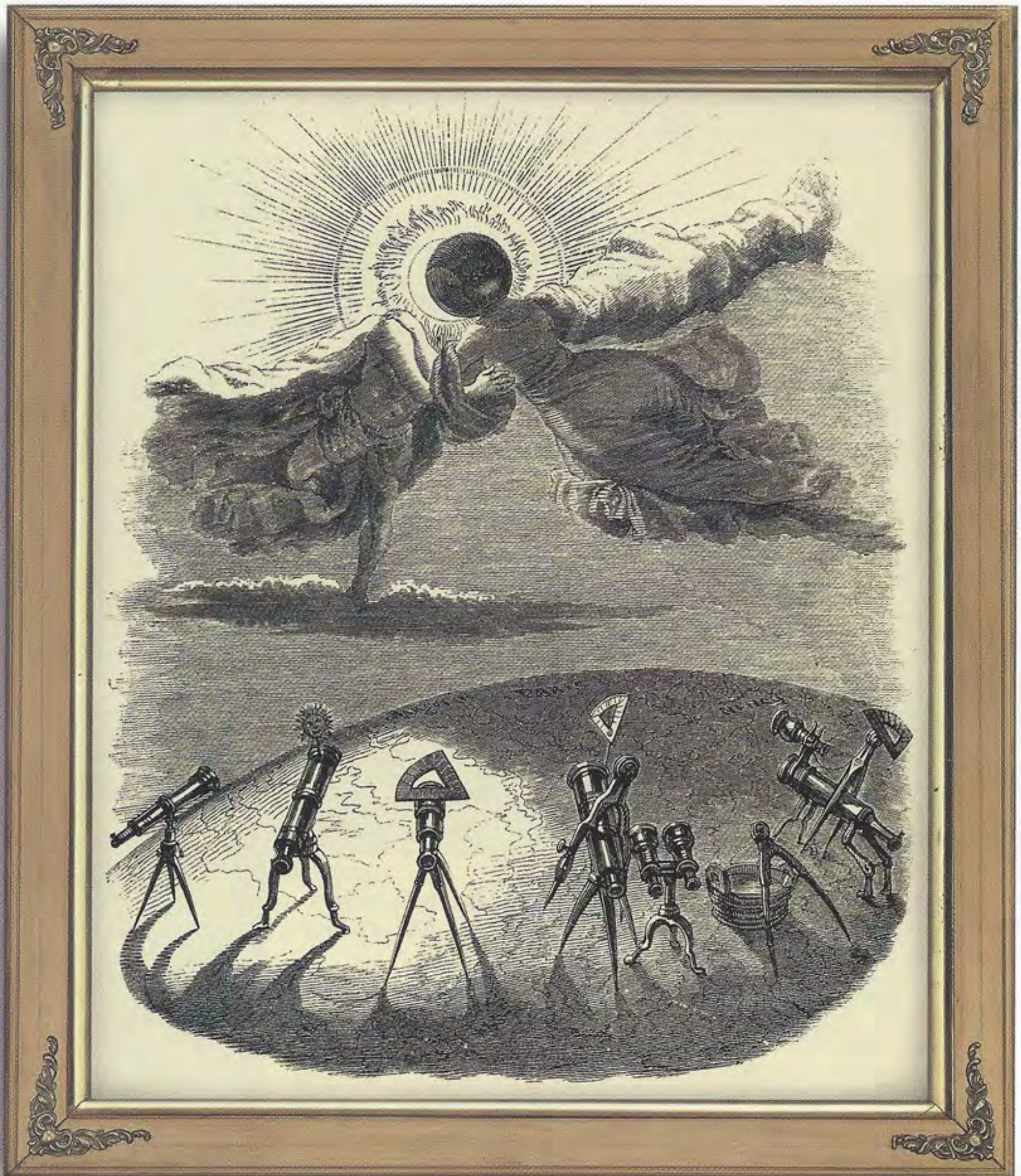

In this 19th century illustration by Jean Grandville, scientists on Earth, represented by their instruments, observe a solar eclipse—the Moon kissing the Sun.

Jean Grandville (1803-1847) was a French caricaturist and illustrator. He was on the staff of *La Caricature* and *Le Charivari* with a famous contemporary, Honoré Daumier. Grandville's most important work is *Un Autre Monde*, a series of fantastic compositions in which he abandoned the logic of the conscious mind to depict a dream world where perspective, viewpoint, shape, and size go through strange metamorphoses and distortions.

From *Fantastic Illustrations of Grandville*, Dover Publications, Inc., New York, 1974

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