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THE FUTURE OF Space Exploration

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CONQUERING MARS:
Exploring, Colonizing and Remaking the Red Planet

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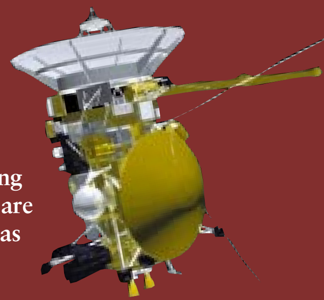
SCIENTIFIC AMERICAN PRESENTS

THE FUTURE OF Space Exploration

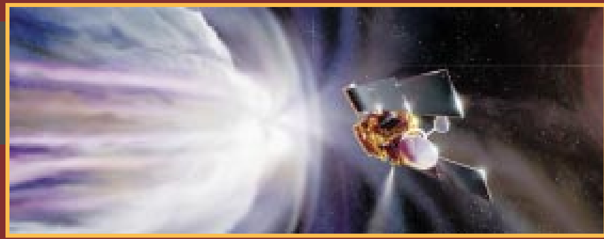
A Guide to the Voyages Unveiling the Cosmos

I SPACEFLIGHT TODAY



II EXPLORING MARS

SPRING 1999
Volume 10
Number 1



ABOUT THE COVER: The Stardust spacecraft's planned rendezvous with a comet was painted by mission artist B. E. Johnson.

The Flagships of the Space Fleet

By exploring planets, moons, asteroids and comets, these spacecraft are extending the frontiers of human knowledge

NASA

Title goes here, please

FIERY BEAUTY of a night liftoff of the shuttle **Endeavour**

Few sights are as awe-inspiring as the liftoff of a space shuttle. Propped on its pair of solid-rocket boosters, the shuttle towers over the launchpad at the Kennedy Space Center in Cape Canaveral, Fla. Hundreds of engineers and technicians man the consoles in the Launch Control Center, monitoring the shuttle's systems as the countdown proceeds. Half a minute before liftoff, the shuttle's onboard computers take over the launch sequence, and at T minus six seconds they send the command to start the main engines. Fiery exhaust billows downward from the shuttle's three rocket nozzles. At T minus zero, the solid-rocket boosters ignite, the umbilical lines retract and the shuttle climbs into the sky with 3.6 million kilograms (eight million pounds) of thrust.

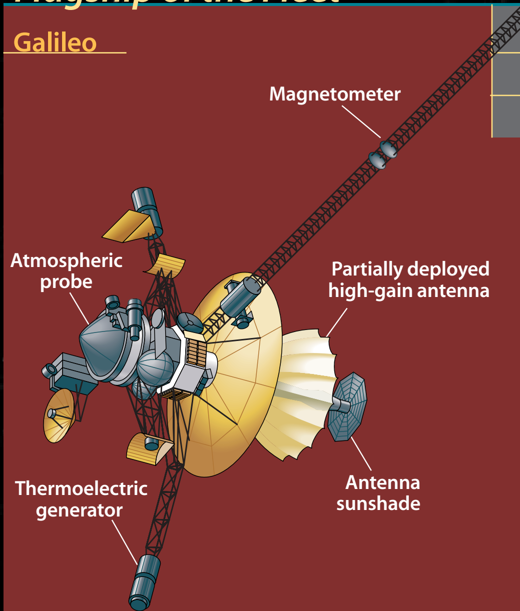
The space shuttle grabs the public's attention—and a big share of the budget of the National Aeronautics and Space Administration—because it carries astronauts into orbit. But it is by no means the only vessel in the space fleet. In recent years, NASA has sent unmanned spacecraft to explore Jupiter, Saturn, the asteroid belt and the moon. What these missions lack in personality they make up for with remarkable discoveries. The Galileo spacecraft, for example, has returned spectacular images of Jupiter's moons and that planet's Great Red Spot. Closer to home, the Lunar Prospector probe has found evidence of ice on the poles of Earth's moon.

Half a dozen of the most extraordinary unmanned spacecraft are profiled on the following pages. Three of these probes—Galileo, Cassini and the Chandra X-ray Observatory—are large, expensive machines packed with scientific instrumentation. But the three others—Near Earth Asteroid Rendezvous, Lunar Prospector and Stardust—are part of NASA's new Discovery series of "faster, better, cheaper" spacecraft. Lunar Prospector is perhaps the best example of a cost-effective craft: the mission is being done for only \$63 million. In contrast, a typical space shuttle mission costs about \$420 million.

Over the next 10 years, about 50 more unmanned science probes are expected to blast off into space (for a comprehensive list, see pages 18 and 19). Many of these craft will venture across the solar system, and others will scan the heavens from Earth's orbit. NASA will not be the only player—the European Space Agency, Russia, Japan and others plan to launch their own vessels. This international armada will revolutionize our understanding of the universe and perhaps pave the way for manned missions to other worlds. *—The Editors*

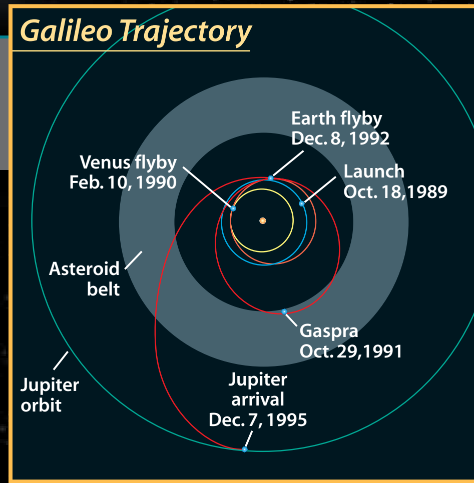
Flagship of the Fleet

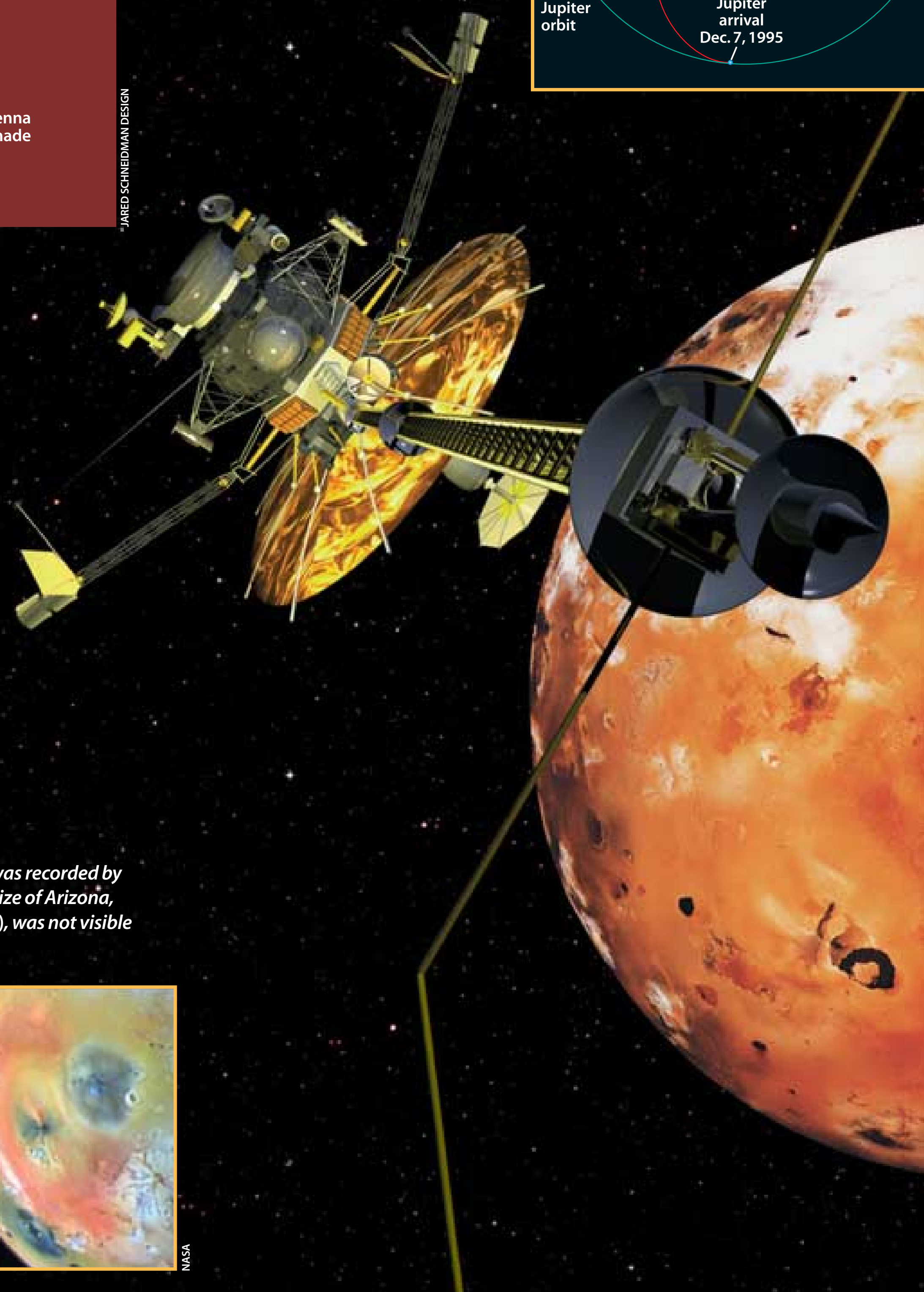
Galileo



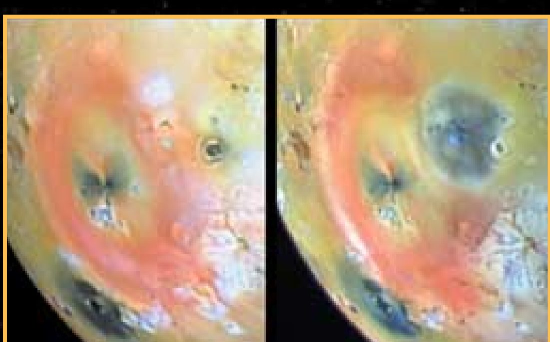
JARED SCHNEIDMAN DESIGN

Launch Date:	October 18, 1989
Cost:	$1.5 billion
Mass at Launch:	2,223 kilograms





HUGE VOLCANIC ERUPTION on Io was recorded by Galileo's cameras. A dark spot the size of Arizona, observed in September 1997 (right)*, was not visible five months earlier* (left).

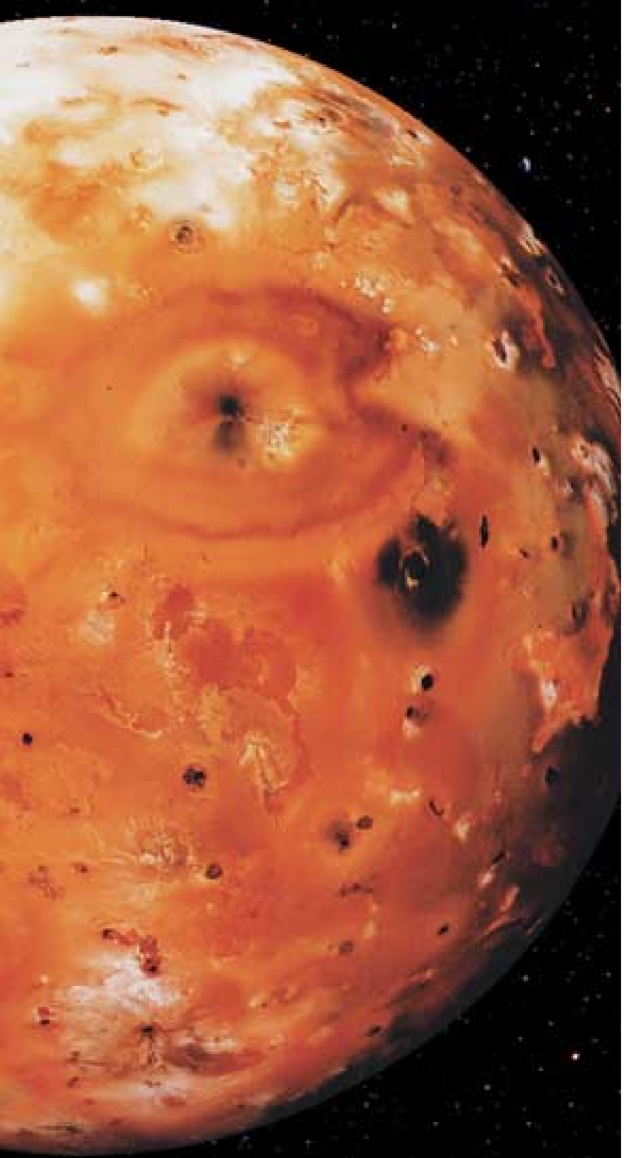


NASA

Galileo

LAURIE GRACE

Striking images of volcanic Io, Jupiter's third-largest moon, were photographed by the Galileo spacecraft during its orbital tour of the Jovian system



NASA AND SLIM FILMS

In 1610 Italian astronomer Galileo Galilei discovered the four largest moons of Jupiter using a crude telescope. In 1995 the Galileo spacecraft arrived in the Jovian system, becoming the first probe to orbit the solar system's biggest planet.

Launched by the space shuttle *Atlantis,* Galileo endured a perilous six-year journey to Jupiter. Two years into the spacecraft's flight, its high-gain antenna failed to unfurl on command. Engineers at the Jet Propulsion Laboratory in Pasadena, Calif., managed to work around the malfunction by storing information on the spacecraft's data recorder and transmitting it to Earth using the probe's much smaller low-gain antenna. "The failure required us to stretch our imagination," says Jim Erickson, manager of Project Galileo. "We came up with the idea of using data compression for a spacecraft that was not designed for it."

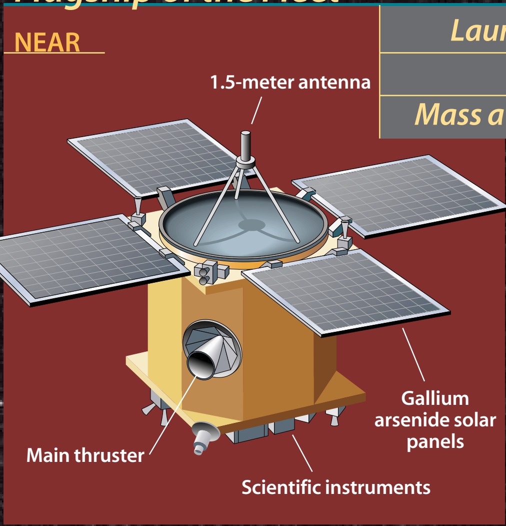
Galileo started proving its worth long before it reached Jupiter. It took the first close-up pictures of an asteroid when it zipped by Gaspra in 1991. And in 1994 Galileo transmitted images of Comet Shoemaker-Levy 9 slamming into Jupiter's far side. It was the only spacecraft in position to view this event.

Before going into orbit around Jupiter, Galileo released a 340-kilogram (750-pound) probe onto a collision course with the gas giant. The probe entered the planet's atmosphere at 170,000 kilometers per hour (106,000 miles per hour) and endured a deceleration equal to 228 g-forces before deploying its parachute. Six onboard instruments relayed data to the Galileo orbiter for about an hour before the extreme pressure and temperature of the Jovian atmosphere destroyed the probe. During the plunge, its instruments recorded wind speeds of more than 640 kilometers per hour and detected surprisingly large amounts of carbon, nitrogen and sulfur. Astronomers had previously believed that Jupiter would have the same low abundance of these elements as the sun because both bodies coalesced from the same primordial nebula. The new evidence suggests that asteroid and comet impacts may have greatly influenced the planet's evolution.

The Galileo orbiter then began a two-year survey mission, training its four cameras on Jupiter and its moons. Other instruments on board the craft measured magnetic fields and concentrations of dust and heavy ions. Galileo's orbits were plotted to allow close flybys of the Jovian moons; the spacecraft passed just 262 kilometers from Jupiter's largest moon, Ganymede, and 200 kilometers from Europa. Galileo detected the presence of a magnetosphere around Ganymede, making it the first moon known to have one. The orbiter returned images of Io that showed intense volcanic activity on the surface. But Europa provided the most startling discovery: high-resolution images showed extensive fracturing of the moon's icy crust, suggesting that there may be an ocean underneath. The possible presence of liquid water on the moon has even led some scientists to speculate that Europa may harbor life.

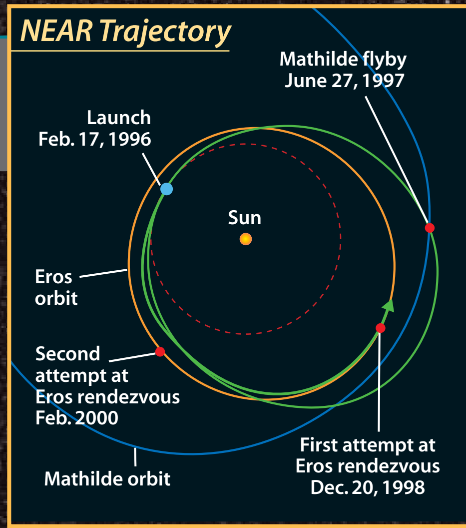
Galileo's survey was so successful that the project managers extended the mission for an additional two years, through the end of 1999, allowing eight more flybys of Europa and two of Io. The Io observations have been scheduled for the very end of the mission. Galileo will fly directly over the moon's active volcanoes and measure the amount of frozen sulfur spewed into space. During these flybys, it will pass through a belt of intense radiation surrounding Jupiter, which will eventually silence the spacecraft. But Galileo has already inspired plans for future explorations: a follow-up mission to Europa is now under study.

Flagship of the Fleet



LAURIE GRACE

Launch Date:	February 17, 1996
Cost:	$210 million
Mass at Launch:	805 kilograms



LAURIE GRACE

NEAR

Intended to be the first spacecraft to orbit an asteroid, NEAR may find clues to the early history of the solar system. The spacecraft is expected to rendezvous with 433 Eros—a 40-kilometer-long near-Earth asteroid—early next year

Near Earth Asteroid Rendezvous (NEAR) is the first of NASA's Discovery series of spacecraft. Built inexpensively from off-the-shelf hardware, the probe was launched by a Delta 2 rocket and began a three-year journey to the asteroid belt. In June 1997 NEAR passed within 1,200 kilometers (746 miles) of main-belt asteroid 253 Mathilde; the probe measured the mass and volume of the body and transmitted high-resolution images taken during the flyby. In December 1998, as NEAR approached its primary target—near-Earth asteroid 433 Eros—the spacecraft went into a tumble after an aborted engine firing. By the time mission controllers at the Johns Hopkins University Applied Physics Laboratory in Laurel, Md., regained contact with NEAR, the probe had missed its chance to rendezvous with Eros. But it is expected to approach Eros again in February 2000, allowing another attempt to put the craft into orbit around the asteroid.

The near-Earth asteroids orbit the sun inside the main asteroid belt. Scientists are particularly interested in these objects because some of them cross Earth's path; a 10-kilometer-wide asteroid in this group is believed to have slammed into Earth 65 million years ago and caused the extinction of the dinosaurs. Eros is the second largest of the known near-Earth asteroids and the first to be discovered, in 1898. It is a potato-shaped body, 40 kilometers long and 14 kilometers wide. Luckily, Eros's orbit does not intersect with Earth's.

If all goes as planned, NEAR will study Eros from the vantage of a retrograde orbit, circling only 35 kilometers from the asteroid's center of mass. The probe's camera and laser range finder will map the asteroid, which is scarred with craters and mysterious grooves. NEAR's magnetometer will determine whether Eros has a magnetic field, and other instruments will measure the distribution and thickness of the debris layer on the asteroid's surface. Scientists want to know whether the material on Eros matches the composition of the main type of meteorites that strike Earth. Many astronomers believe that meteorites originate in the asteroid belt.

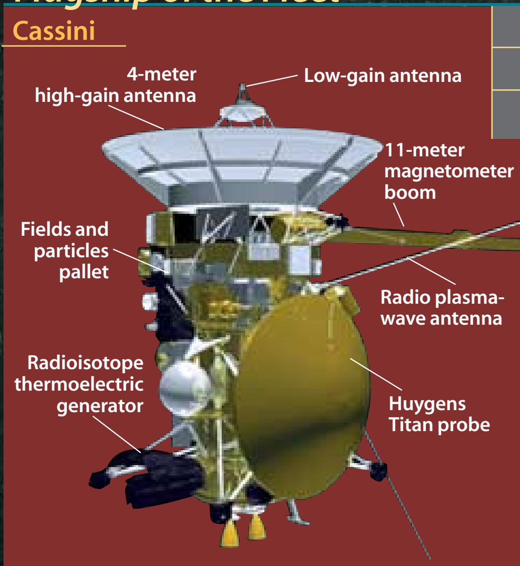
The NEAR mission may also yield clues to the early history of the solar system. Spectrometer readings from Earth indicate that Eros may be a remnant of a much larger object—a body with a molten core—that was shattered in a catastrophic collision. NEAR's instruments will test this theory by providing a more detailed spectroscopic analysis of the asteroid.

The spacecraft will orbit Eros for about a year. There will be no mission extension; instead the NEAR team will maneuver the spacecraft ever closer to Eros, perhaps even close enough for a soft landing on the asteroid's surface. "We want to get higher resolution for our images of Eros," comments Andrew Cheng, project scientist for the NEAR mission. "And we also want to practice the techniques for flying a spacecraft very close to the surface of an irregular body. There will be some chance of making contact."

Because NEAR's antenna has no independent pointing capability, Cheng and his team will try to land the spacecraft on its side so that it can transmit data back to Earth during its impact. By measuring the deceleration of the spacecraft as it hits Eros, scientists hope to get a better idea of the structure of the asteroid—specifically, whether it is a solid rock or a pile of rubble loosely bound by gravity. Even if NEAR survives the landing, Cheng's team will soon lose communication with it, and the first Discovery mission will abruptly become an orphan in space.

SLIM FILMS

Flagship of the Fleet

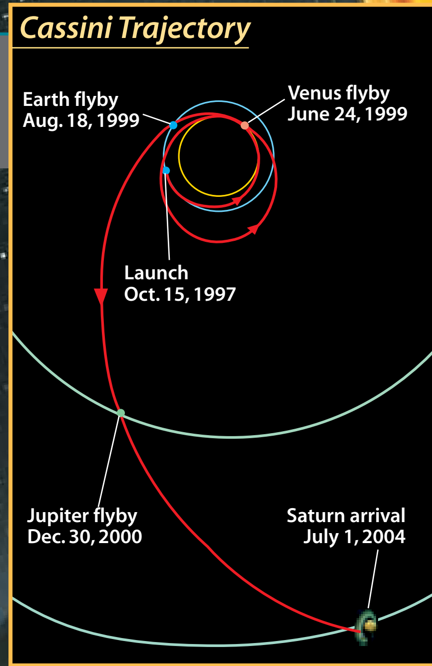


NASA

Launch Date: October 15, 1997

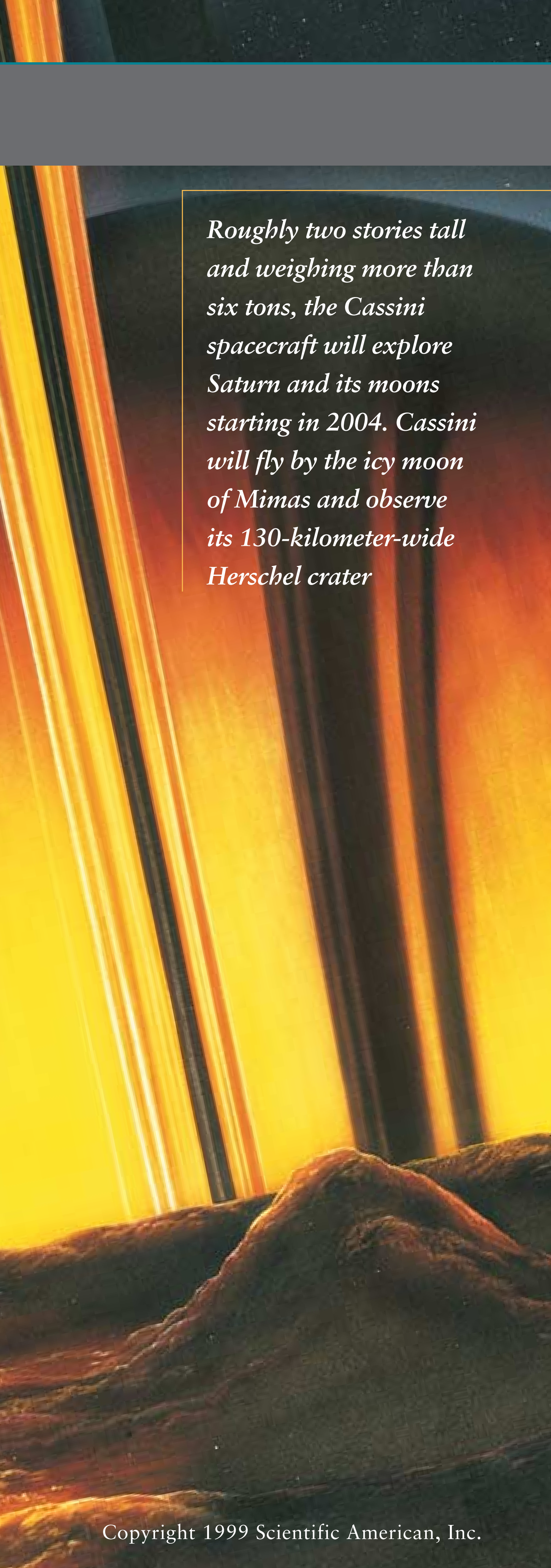
Cost: $3.3 billion

Mass at Launch: 5,700 kilograms



LAURIE GRACE

Cassini



CARL-W. RÖHRIG

Roughly two stories tall and weighing more than six tons, the Cassini spacecraft will explore Saturn and its moons starting in 2004. Cassini will fly by the icy moon of Mimas and observe its 130-kilometer-wide Herschel crater

Cassini is the biggest interplanetary spacecraft ever launched by NASA. Nearly seven meters high and four meters wide, it contains 1,630 circuits, 22,000 wire connections and 14 kilometers of cables. And Cassini has an equally big mission: in July 2004 the probe will arrive at Saturn, the solar system's second-largest planet, and begin conducting the most extensive survey to date of any planetary system.

Named for French-Italian astronomer Jean-Dominique Cassini, who discovered four of Saturn's moons in the 17th century, the spacecraft was launched by a powerful Titan 4 booster with a Centaur upper stage. Cassini swung by Venus in April 1998 and will require three more gravity-assist swings—flying past Venus again, then Earth and Jupiter—to build up enough speed to reach Saturn. So far the probe is performing perfectly. "We expected some flaws to show up by now, but none have," states Dennis Matson, the project's chief scientist at the Jet Propulsion Laboratory.

Cassini is well equipped for exploration: it has 12 onboard instruments, including an imaging system that can take pictures in visible, near-ultraviolet and near-infrared light. Once in orbit around Saturn, it will analyze the gases in the planet's atmosphere and observe Saturn's strong winds, which can reach speeds of more than 1,600 kilometers per hour at the planet's equator. Cassini will also study the internal structure of the gas giant and investigate the planet's magnetosphere. The spacecraft will pay special attention to Saturn's rings, mapping them and measuring the size and chemical composition of their particles. Some astronomers believe the rings may have formed from a shattered moon; Cassini's observations may help determine whether this theory is correct.

After four months in orbit, Cassini will release a probe to explore Saturn's largest moon, Titan, the only satellite in the solar system known to have an appreciable atmosphere. The 350-kilogram probe is named after Christian Huygens, the 17th-century Dutch astronomer who discovered Titan, and it was built by the European Space Agency. (Cassini is the biggest international space mission launched so far; half of its 230 scientists are European.)

The Huygens probe will enter Titan's atmosphere at a speed of 22,000 kilometers per hour, then deploy two parachutes to slow its descent. The probe's six instruments will measure wind speeds, temperatures and the distribution of various gases. Titan's atmosphere is believed to contain complex organic molecules, although the moon is probably too cold to support life. "It's possible that there are things on Titan that relate to the biochemistry of early Earth history," Matson says. Huygens will also determine the nature of Titan's surface; some scientists believe the moon may be covered by vast lakes of liquid ethane. If Huygens survives the landing, it will continue to transmit information back to Cassini for up to half an hour.

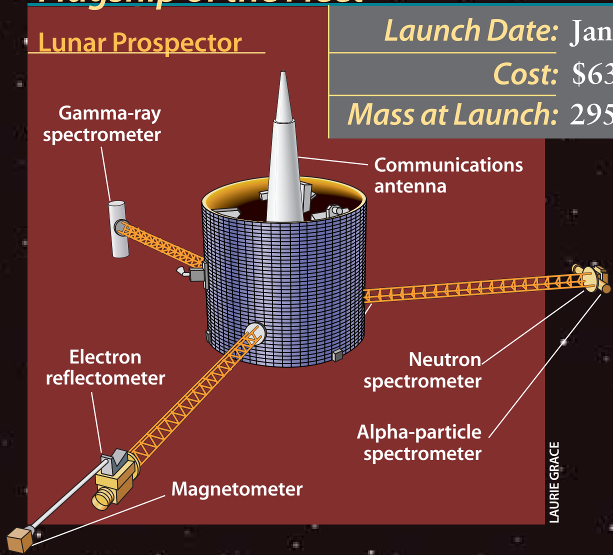
Once Huygens has completed its mission, Cassini will continue its survey of Saturn and its moons until 2008. The orbiter will make dozens of close flybys of Titan and several of the 17 other known moons. If Cassini is still operating after 2008, the mission may be extended to include riskier observations, such as a close-up look at Saturn's rings.

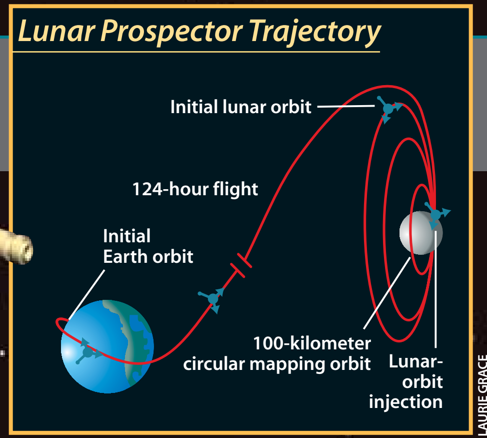
Flagship of the Fleet

Launch Date: January 6, 1998

Cost: $63 million

Mass at Launch: 295 kilograms





Lunar Prospector

A relatively small and inexpensive spacecraft, Lunar Prospector found strong evidence of ice at the poles of Earth's moon

SLIM FILMS

Lunar Prospector is a squat, cylindrical spacecraft not much larger than a washing machine. It looks like a soup can with its ends cut off, but this unassuming vessel made one of the biggest scientific discoveries of 1998. Just weeks after it was launched by an Athena 2 rocket, Lunar Prospector detected strong indications that water ice lies in the perpetually shadowed areas at the poles of Earth's moon.

An earlier spacecraft called Clementine had found signs of lunar ice, but the evidence was sketchy. Lunar Prospector began its mission by going into a polar orbit of the moon, flying an average of 100 kilometers (62 miles) above the surface. The probe's spectrometers measured the number of neutrons ejected when cosmic rays strike the moon. The readings indicated the presence of hydrogen in areas kept permanently cold by the shadows in polar craters. Because hydrogen gas would escape the moon's weak gravity, mission scientists believe the probe has detected hydrogen atoms locked in water molecules.

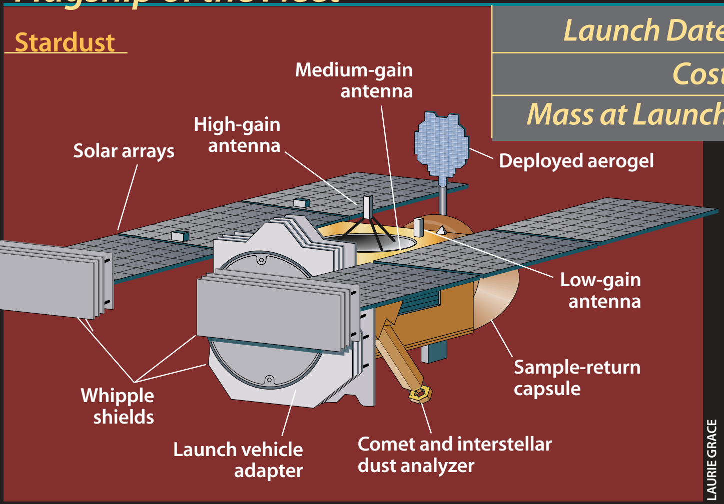
According to Alan Binder, the mission's principal investigator, the water is probably in the form of ice granules buried in the top 50 centimeters of lunar soil. Binder estimates that the north and south poles may contain up to six billion metric tons of ice, possibly deposited in layers by comets hitting the moon. In other regions of the moon, Binder says, sunlight would quickly vaporize the ice, but in the constantly dark polar areas the ice would remain in the soil. The ice would be a boon to colonists on future lunar bases, who could separate the water into hydrogen rocket fuel and breathable oxygen.

But Lunar Prospector has done much more than look for water. Its five instruments are surveying the 75 percent of the moon's surface that was not studied during the Apollo missions. It is analyzing the composition of the lunar crust and searching for trace elements such as thorium and uranium. The probe is also mapping the moon's gravity and its variable magnetic fields. Unlike Earth, the moon does not have a planetary magnetic field; scientists believe that lunar rocks may have been magnetized by comet and meteorite impacts.

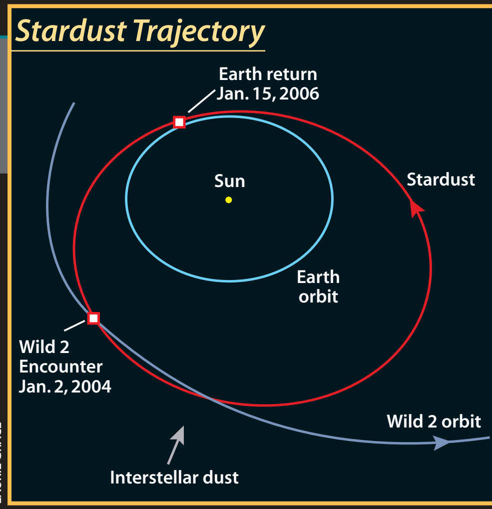
One of the spacecraft in NASA's Discovery series, Lunar Prospector was developed and built in just 22 months. "We wanted to show the efficiency of a small, simple spacecraft," Binder says. "The science data we're getting are 10 times better than what we promised NASA." Binder helped to design the probe in the early 1990s, when he worked for Lockheed Martin. He is now the director of the Lunar Research Institute, which is managing the mission jointly with Lockheed and the NASA Ames Research Center.

In January, after a year in orbit, Lunar Prospector began a six-month extended mission, dropping to an elliptical orbit that comes as close as 10 kilometers to the moon's surface. In the lower orbit, the spacecraft is more at risk of hitting the moon; the probe has to fire its engine every few weeks to maintain its altitude. But the lower orbit allows the spacecraft's instruments to gather better data, especially for measuring the moon's magnetic fields. When the probe runs out of fuel, it will crash onto the moon's surface, but Lunar Prospector is nowhere near empty yet. "We'll run out of money before we run out of fuel," Binder remarks.

Flagship of the Fleet



Launch Date:	February 1999
Cost:	$200 million
Mass at Launch:	385 kilograms



IN JANUARY 2004 the Stardust spacecraft will plunge into the coma—an immense cloud of dust and gas—surrounding the nucleus of Comet Wild 2. The Whipple shields at the front of the spacecraft will protect the scientific instruments from impacts with the dust particles.

AFTER THE ENCOUNTER with Wild 2, Stardust will store samples of the comet's dust in a clamshell-like capsule. The spacecraft will return to Earth in January 2006, ejecting the sample-return capsule for a parachute landing in Utah.

Stardust

Streaking 150 kilometers in front of the nucleus of Comet Wild 2, the Stardust spacecraft will collect samples of the comet's dust

Stardust has the most elegant name ever attached to a space probe and a mission profile so quixotic that it resembles the plot of a Ray Bradbury story: in the loneliness of space, Stardust will pass a distant comet, collect some of its essence and bring it back to Earth.

The probe is scheduled to be lofted by a Delta 2 rocket early this year. Stardust will spend its first five years making gravity-assist swings to put it on a trajectory intersecting the path of its target, Comet Wild 2, by 2004. The gravity-assist technique minimizes the energy needed to propel the probe to Wild 2 and also lets Stardust meet the comet at a low velocity—which translates into a longer rendezvous.

Scientists learned a hard lesson about speed after the probe Giotto's encounter with Comet Halley in 1986. Traveling at a closure rate of about 246,000 kilometers per hour, the probe was struck so hard by particles from Halley's tail that it was sent tumbling. By the time Giotto was back under control, it had sped past Halley, missing the window of opportunity to take close-up pictures. "The plan here is to fly through the head of the comet, not through its tail," states Kenneth L. Atkins, Stardust's project manager at the Jet Propulsion Laboratory. The spacecraft will approach Wild 2 at under 22,000 kilometers per hour. Wild 2 produces less dust than Halley, so scientists believe Stardust's photographs will be clear enough to reveal details about the comet's size, shape and perhaps even period of rotation.

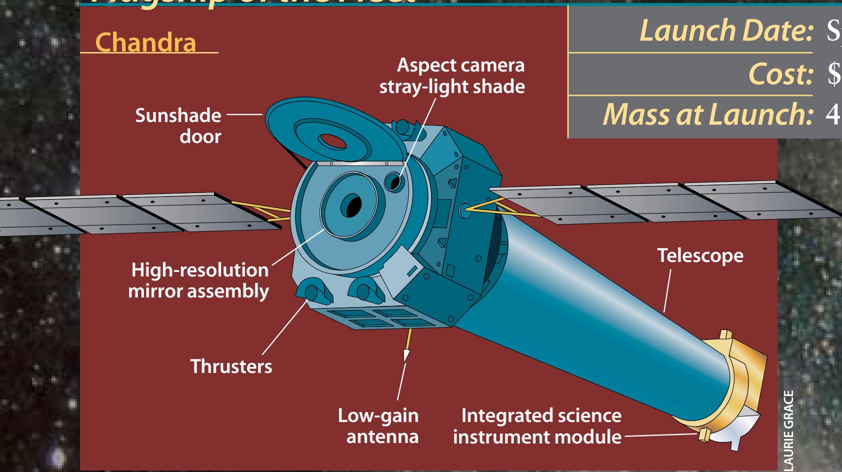
Stardust will also collect samples of the dust coming off Wild 2. Researchers are particularly interested in the comet because of its history—its original path took it outside the orbit of Jupiter, but in 1974 the gas giant thrust the comet into a new orbit closer to the sun. "This comet has spent most of its existence in an area that has been virtually unchanged since the dawn of the solar system," Atkins says. "Wild 2 is a time capsule with which we can look back at the materials that were the solar system's basic building blocks."

To catch the dust, Stardust carries a retractable grid in the shape of a tennis racket, coated on both sides with cells of a substance called aerogel. Essentially a glass foam that is 99 percent empty, the aerogel will trap the particles and leave a record of their trajectory angles. One side of the grid will collect comet particles, whereas the other side will gather interstellar dust streaming from other parts of the galaxy. To prevent damage to the craft as it passes within 150 kilometers of Wild 2, Stardust is shielded with blankets of ceramic cloth.

Once the probe has its samples, the collector grid will retract into a clamshell-like capsule, and Stardust will begin a two-year voyage back to Earth. Returning the samples is a cost-saving measure: the probe does not need elaborate instrumentation for analyzing the dust in space. As it nears Earth, Stardust will eject the sample-return capsule for a parachute landing on an air force training range in Utah. Then the spacecraft will go into a permanent orbit around the sun. "We expect that the craft will be alive and healthy, with a camera on board that works," Atkins says. "Somebody may come along and figure out something to do with it."

B. E. JOHNSON

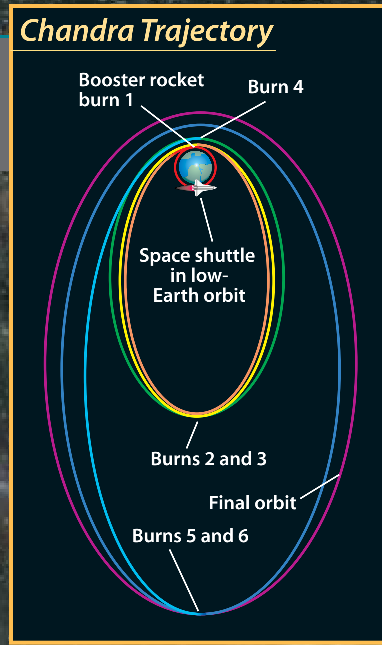
Flagship of the Fleet



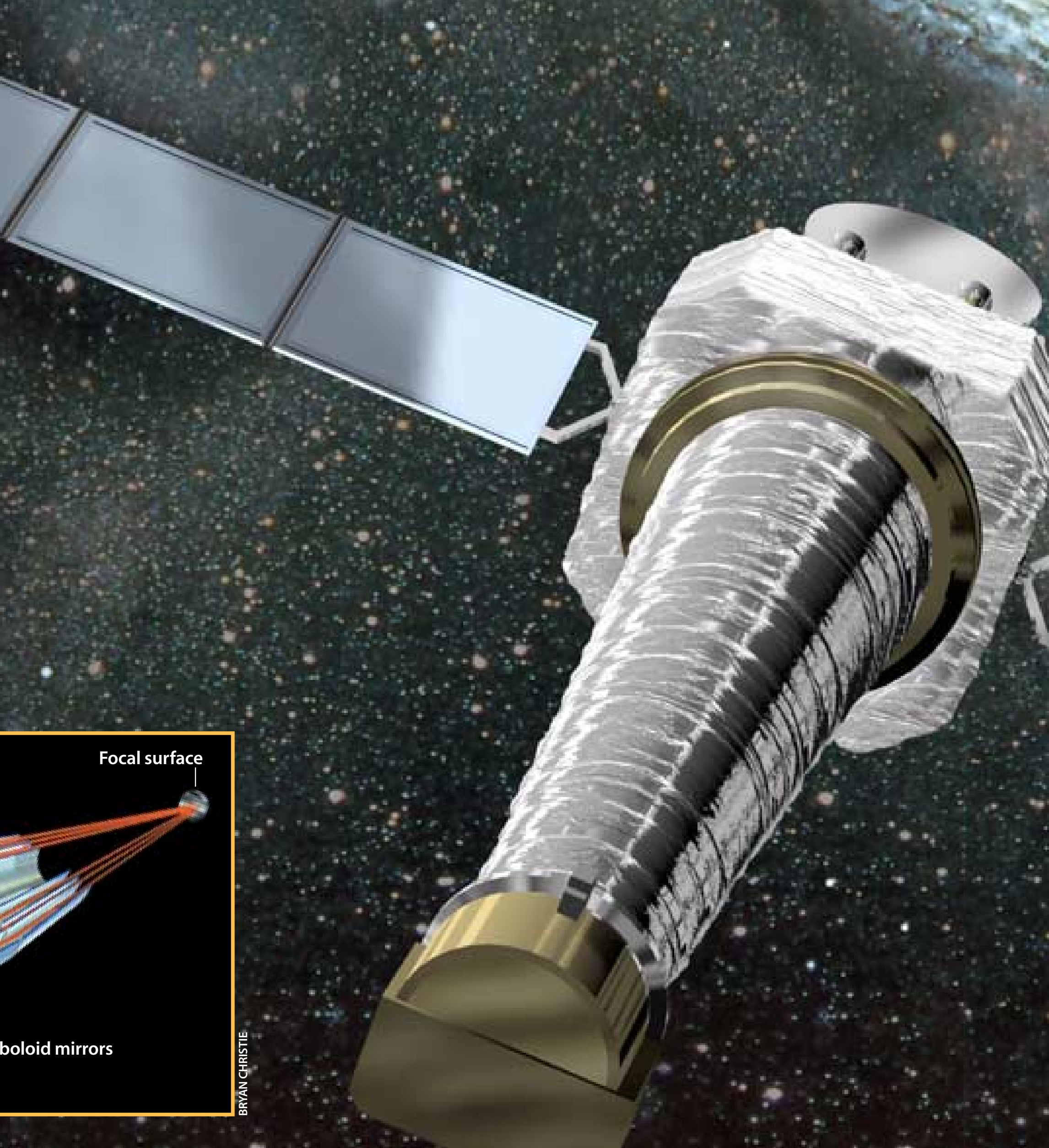
LAURIE GRACE

Launch Date:	Spring 1999
Cost:	$1.6 billion
Mass at Launch:	4,790 kilograms

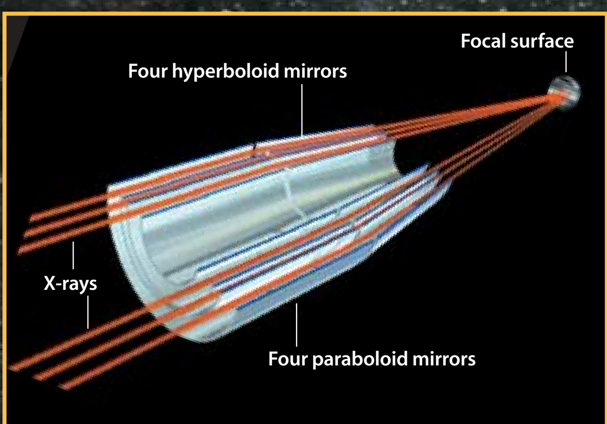
Chandra Trajectory



LAURIE GRACE



X-RAY MIRRORS of the Chandra telescope are shaped like barrels so that the incoming x-rays strike the reflective inner surfaces at a grazing angle.



BRYAN CHRISTIE

Chandra

The third of NASA's "Great Observatories," the Chandra X-ray Observatory will view powerful x-ray sources at the hearts of galaxies

DON FOLEY

Black holes, quasars and supernovae emit huge quantities of radiation in the x-ray wavelength, but astronomers have long been frustrated by the fact that x-rays are absorbed by Earth's atmosphere. The Chandra X-ray Observatory, scheduled to be launched by the space shuttle this spring, will finally open a window on the x-ray universe. The new telescope is named after Subrahmanyan Chandrasekhar, the late Indian-American astrophysicist known for his work on black holes and supernovae.

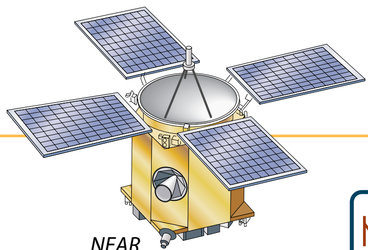
Chandra is the third of NASA's four "Great Observatories," following the Hubble Space Telescope and the Compton Gamma Ray Observatory. (The fourth, the Space Infrared Telescope, is scheduled for launch in 2001.) Although Chandra will not be the first x-ray telescope in orbit, it will be far more sensitive than any of its predecessors. The giant observatory—at 14 meters (46 feet) long, it is as big as a boxcar—will see x-ray sources 20 times fainter than any seen previously and will produce images with 50 times more detail.

Because of their high energy, x-rays would pass right through the dish-shaped mirrors used in optical telescopes. X-rays can be reflected only if they strike a mirror at an angle of one degree or less, like a stone skipping across the surface of a pond. Consequently, each of Chandra's mirrors is shaped like a barrel: x-rays enter the hollow cylinder and graze the inner surface, which is coated with highly reflective iridium. The mirrors are nested inside one another to increase their collecting ability. They will focus the x-rays on two instruments at the rear of the telescope, a high-resolution camera and an imaging spectrometer.

Chandra must operate above Earth's Van Allen belts because the charged particles in the belts would interfere with its instruments. After the telescope is released by the space shuttle, booster rockets will raise it to an elliptical orbit with an apogee of 140,000 kilometers—a third of the way to the moon. The shuttle will not be able to reach Chandra for repair missions, so NASA and its contractors must make sure that the x-ray telescope works properly the first time—unlike Hubble.

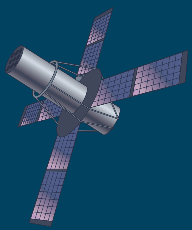
Astronomers plan to use Chandra to observe the cores of active galaxies, which generate tremendous amounts of x-rays. Scientists theorize that the radiation may be produced by massive black holes sucking in whole stars. Chandra will also be trained on distant galactic clusters, where the space between galaxies is filled with x-ray-emitting gas. These observations may shed light on the nature of so-called dark matter, the missing mass that scientists believe is holding the clusters together. Because x-rays are not absorbed by interstellar dust, Chandra can also be used to peer into the center of our own galaxy.

Chandra is designed to operate for at least five years but has enough fuel for 10. The mission will be managed by the NASA Marshall Space Flight Center. "This is the greatest x-ray observatory ever built," says Martin Weisskopf, Chandra's chief scientist at the Marshall center. "I think that in five years we will talk about it having changed our understanding of physics and the universe."



NEAR

Key Space Explora



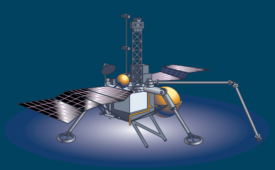
HESSI

the sun

Name of Mission (Sponsor)	Main Purpose of Mission	Launch Date
ACE, Advanced Composition Explorer (NASA)	Monitor solar atomic particles and the interplanetary environment	1997
TRACE, Transition Region and Coronal Explorer (NASA)	Photograph the sun's coronal plasmas in the ultraviolet range	1998
Coronas F (Russia)	Observe the sun's spectrum during a solar maximum	1999
HESSI, High Energy Solar Spectroscopic Imager (NASA)	Study solar flares through x-rays, gamma rays and neutrons	2000
Photon (Russia)	Analyze gamma rays from the sun	2000
SST, Space Solar Telescope (China and Germany)	Study the sun's magnetic field	2001
Genesis (NASA)	Gather atomic nuclei from the solar wind and return them to Earth	2001
Solar B (Japan)	Study the sun's magnetic field around violent events	2004
Solar Probe (NASA)	Measure particles, fields, x-rays and light in the sun's corona	2007

the moon

Name of Mission (Sponsor)	Main Purpose of Mission	Launch Date
Lunar A (Japan)	Analyze the moon's subsurface soil	1999
Euromoon 2000 (ESA)	Explore the moon's south pole (two-part mission)	2000 and 2001
Selene (Japan)	Map the moon, studying fields and particles	2003



Mars Surveyor 1998

the planets

Name of Mission (Sponsor)	Main Purpose of Mission	Launch Date
Mars Global Surveyor (NASA)	Map Mars and relay data from other missions	1996
Planet-B (Japan)	Study interactions between the solar wind and Mars's atmosphere	1998
Mars Surveyor 1998 (NASA)	Explore a site near Mars's south pole (two-part mission)	1998 and 1999
Deep Space 2 (NASA)	Analyze Martian subsurface soil	1999
Mars Surveyor 2001 (NASA)	Land a rover on Mars (two-part mission)	2001
VESPER, Venus Sounder for Planetary Exploration (NASA)	Observe Venus's atmosphere (under study)	2002
Mars Surveyor 2003 (NASA)	Collect Martian soil samples (two-part mission, under study)	2003
Mars Express (ESA)	Analyze Martian soil, using an orbiter and two landers	2003
Europa Orbiter (NASA)	Determine if Jupiter's fourth-largest moon has an ocean	2003
MESSENGER, Mercury Surface, Space Environment, Geochemistry and Ranging (NASA)	Map Mercury and its magnetic field (under study)	2004
Pluto-Kuiper Express (NASA)	Explore the solar system's only unvisited planet and the Kuiper belt (under study)	2004
Mars Surveyor 2005 (NASA)	Return Martian rock and soil samples to Earth (under study)	2005

Rosetta

comets

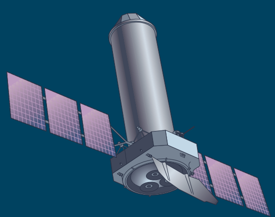
Name of Mission (Sponsor)	Main Purpose of Mission	Launch Date
CONTOUR, Comet Nucleus Tour (NASA)	Produce spectral maps of three comet nuclei	2002
Deep Space 4 (NASA)	Land a probe on Comet Tempel 1's nucleus	2003
Rosetta (ESA and France)	Land a probe on Comet Wirtanen's nucleus	2003

tions of the Next Decade

asteroid belt

Name of Mission (Sponsor)	Main Purpose of Mission	Launch Date
Deep Space 1 (NASA)	Test spacecraft technologies en route to asteroid 1992 KD	1998
MUSES-C (Japan)	Return a sample of material from an asteroid	2002

deep space



XMM

Name of Mission (Sponsor)	Main Purpose of Mission	Launch Date
RXTE, Rossi X-ray Timing Explorer (NASA)	Watch x-ray sources change over time	1995
Beppo-SAX (Italy and the Netherlands)	Observe x-ray sources over a wide energy range	1996
HALCA (Japan)	Study galactic nuclei and quasars via radio interferometry	1997
SWAS, Submillimeter Wave Astronomy Satellite (NASA)	Search for oxygen, water and carbon in interstellar clouds	1998
Odin (Sweden)	Detect millimeter-wavelength emissions from oxygen and water in interstellar gas	1999
FUSE, Far Ultraviolet Spectroscopic Explorer (NASA)	Detect deuterium in interstellar space	1999
WIRE, Wide-Field Infrared Explorer (NASA)	Observe galaxy formation with a cryogenic telescope	1999
ABRIXAS, A Broad-Band Imaging X-ray All-Sky Survey (Germany)	Make a hard x-ray, all-sky survey	1999
SXG, Spectrum X-Gamma (Russia)	Measure x-ray emissions from pulsars, black holes, supernova remnants and active galactic nuclei	1999
HETE II, High Energy Transient Experiment (NASA)	Study gamma-ray bursters	1999
XMM, X-ray Multi-Mirror (ESA)	Observe spectra of cosmic x-ray sources	2000
Astro-E (Japan)	Make high-resolution x-ray observations	2000
MAP, Microwave Anisotropy Probe (NASA)	Study the universe's origin and evolution through the cosmic microwave background	2000
Radioastron (Russia)	Observe high-energy phenomena via radio interferometry	2000
SIRTF, Space Infrared Telescope Facility (NASA)	Make infrared observations of stars and galaxies	2001
INTEGRAL, International Gamma-Ray Astrophysics Lab (ESA)	Obtain spectra of neutron stars, black holes, gamma-ray bursters and active galactic nuclei	2001
GALEX, Galaxy Evolution Explorer (NASA)	Observe stars, galaxies and heavy elements at ultraviolet wavelengths (under study)	2001
Spectrum UV (Russia)	Study astrophysical objects at ultraviolet wavelengths	2001
Deep Space 3 (NASA)	Test techniques for flying spacecraft in formation	2002
Corot (France)	Search for evidence of planets around distant stars	2002
SIM, Space Interferometry Mission (NASA)	Image stars that may host Earth-like planets (under study)	2005
Constellation X-ray Mission (NASA)	Perform high-resolution x-ray spectroscopy (under study)	After 2005
OWL, Orbiting Wide-Angle Light Collectors (NASA)	Study cosmic-ray effects on Earth's atmosphere (under study)	After 2005
FIRST, Far Infrared Submillimeter Telescope, and Planck (ESA)	Discern the fine structure of the cosmic microwave background (combined mission)	2007
NGST, Next Generation Space Telescope (NASA)	View space at infrared wavelengths (under study)	2008
TPF, Terrestrial Planet Finder (NASA)	Find planets and protoplanets orbiting nearby stars (under study)	2010

ILLUSTRATIONS BY JARED SCHNEIDMAN DESIGN

The International Space Station:

A WORK IN PROGRESS

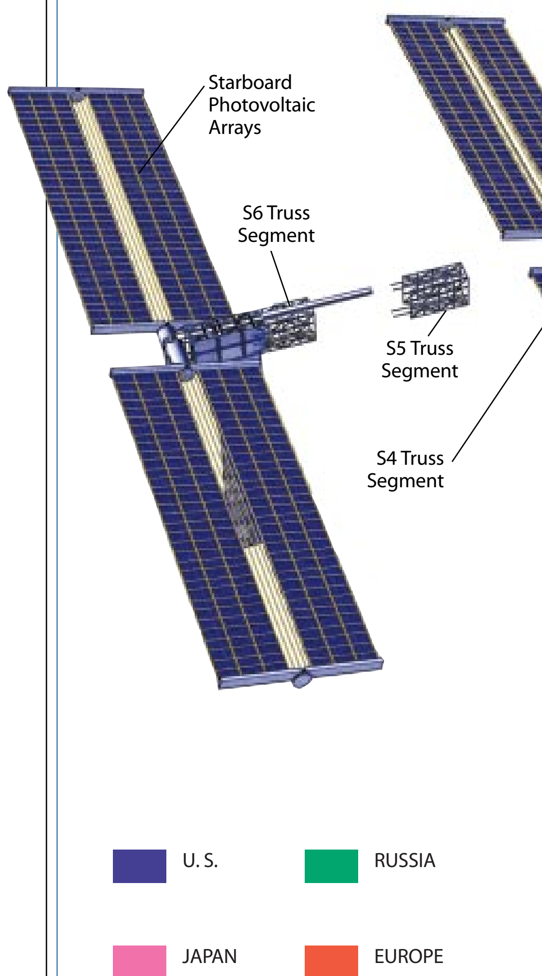
The U.S. and its international partners are finally building a space station, even as they continue to argue about the blueprints

by Tim Beardsley, *staff writer*

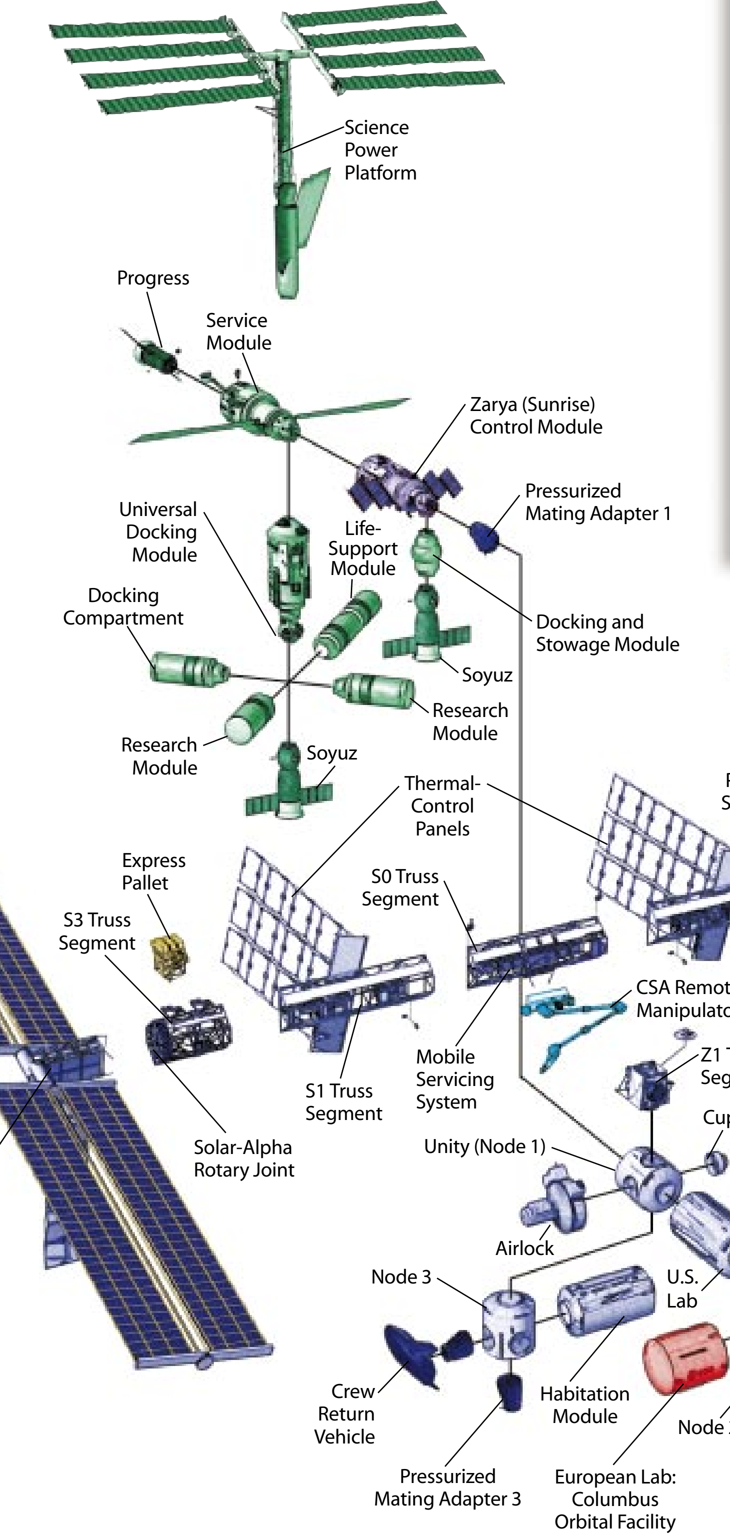
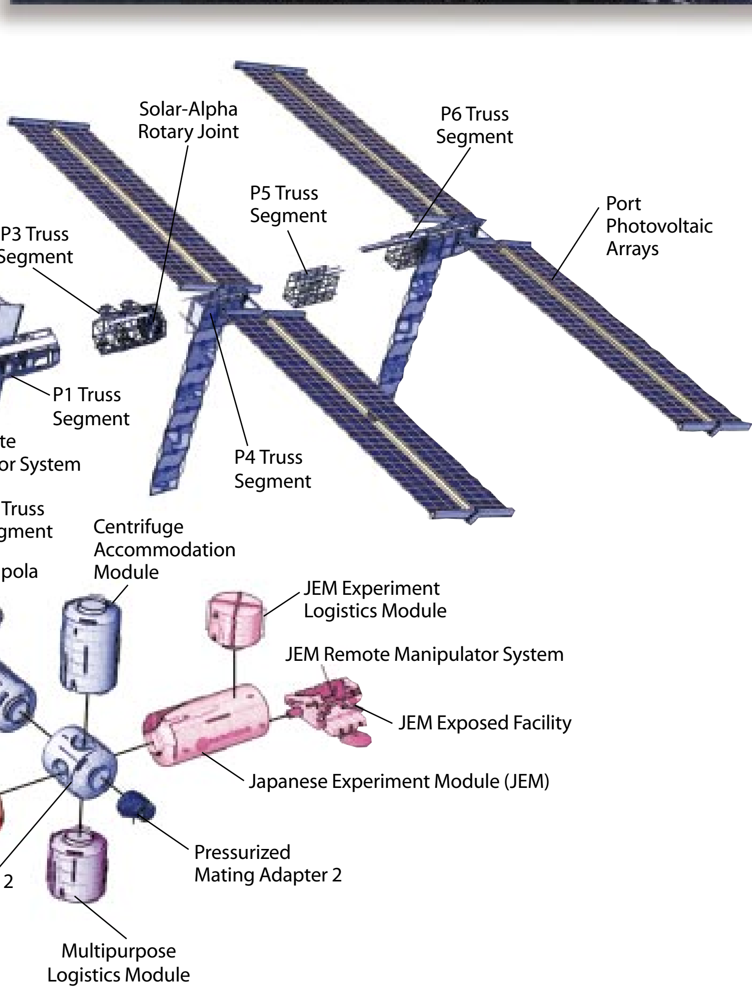
The construction site in space that is for the next six years the International Space Station is nothing if not ambitious. Writers have an array of superlatives they can choose from to describe the program: it is by far the most complex in-orbit project ever attempted and arguably one of the biggest engineering endeavors of any kind. More than 100 separate elements weighing 455,000 kilograms (over a million pounds) on Earth will be linked together during the assembly operation, making it the most massive thing in orbit: it will have the equivalent of two 747 jetliners' worth of laboratory and living space. The job will need 45 flights by U.S. shuttles and Russian rockets, and over 50 more launches will take up supplies, crew and fuel to maintain the station in its orbit. Contributions come from 16 countries, making it the most cosmopolitan space program. Hooking the pieces together will take at least 1,700 hours of space walks, many more than have been made during the entire history of space exploration to date. Robotic arms and hands will be required, and free-flying robotic "eyes" might be employed for inspection flights.

But one remarkable aspect of the project received little attention during the hoopla surrounding the successful launch and mating of the first two components late last year. With construction work on the station well under way in its orbit 400 kilometers (250 miles) up, the final configuration of the edifice is not yet settled. Indeed, it could look very different from current artists' impressions.

In large part, the changes are the result of pressure that Congress has put on the National Aeronautics and Space Administration to reduce the program's near-total reliance on Russia as a provider of essential station components and rocket launches.



BOB SAULS *John Frassanito & Associates*

CANADA

BRAZIL

ITALY

INTERNATIONAL SPACE STATION will include more than 100 components from 16 countries. The U.S. will contribute a laboratory, a habitation module and the station's primary solar-power arrays. Russia had planned to provide additional laboratories, but those contributions are now in doubt. The European Space Agency and Japan will build their own research modules. When complete, the station will stretch more than 100 meters across and weigh nearly 500 tons (*inset at top*).

BOB SAULS *John Frassanito & Associates*

Concern has focused especially on the Russian Service Module, which is scheduled to provide living quarters, life support, propulsion, navigation and communications for the station during the early years of assembly. The Service Module will, if all goes well, be the next major component in orbit after the Zarya tug and Unity Connecting Module that are now flying.

But all has not been going well with construction of the Service Module at the Khrunichev State Research and Production Space Center in Moscow. Originally scheduled for completion in April 1998, the module has been a victim of Russia's financial crisis. Work on the module, which was originally to be part of a Russian space station, started as long ago as 1985, long before Russia joined the International Space Station. Yet the unit is now not expected to be completed until this summer. Russia's failure to finish the component in time is the main reason the start of station assembly was delayed from 1997 until late 1998. Without the propulsion provided by the Service Module, the station as originally envisaged would be incapable of staying in orbit for more than 500 days. Friction with the sparse air molecules in low-Earth orbit would gradually cause it to lose altitude.

NASA has had to employ creative accounting techniques to justify sending the Russian Space Agency ever mounting sums to complete the module. Last year it gave the Russians an extra $60 million (the official explanation was that these funds would purchase additional stowage space and experiment time for the U.S. during the construction phase). But NASA has acknowledged that over the next four years it will most likely have to send a further $600 million to ensure the completion of other modules. Many Russian space workers have not been paid for months.

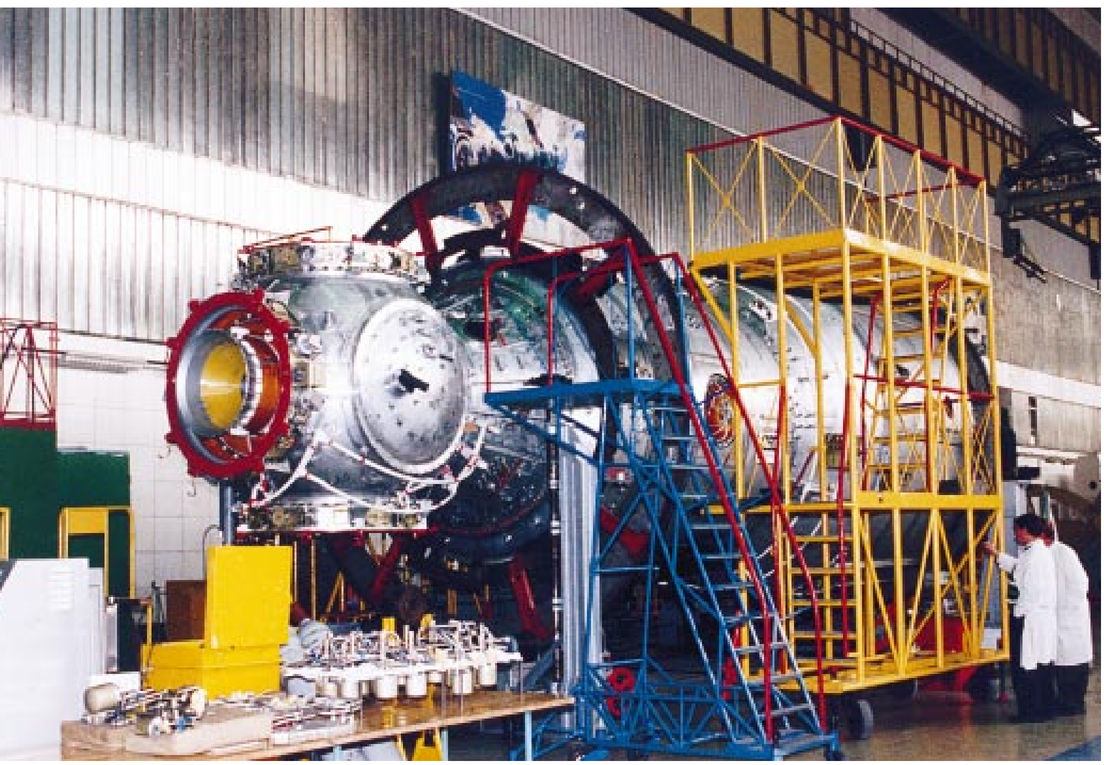
The Price of Progress

This $660-million contribution is in addition to $728 million NASA has already paid the Russians between 1994 and 1998 for space station work and the joint flights on the Russian space station Mir, according to the Congressional Research Service. Although having Russia in the program was originally intended to save money, NASA now admits that it has actually added about $1 billion to the station's cost. NASA has had to work hard to secure from the Russians an agreement that they will shut down the Mir space station this summer, despite opposition from Russian nationalists. Keeping Mir alive could drain Russian resources from the international station, NASA fears.

Not that cost overruns are restricted to Russia. NASA figures indicate that U.S. construction costs are running 30 percent over projections, and an independent commission headed by Jay Chabrow, a former TRW executive, estimated that the overrun will reach 42 percent. NASA has irked scientists who had planned to run experiments on the station by transferring some $460 million from science accounts to help meet U.S. construction costs. The station's expense, including the cost of shuttle flights, is now likely to exceed $40 billion, and it has become "an albatross around the agency's neck," in the view of space policy expert Marcia S. Smith of the Congressional Research Service. The General Accounting Office puts the total cost of the program at $95.6 billion.

All these estimates assume nothing major goes wrong during assembly. The British magazine *New Scientist* has decided, on the basis of a statistical analysis of risks, that there is a 73.6 percent chance of at least one catastrophic failure that would result in the loss of station hardware during one of the U.S. or Russian assembly launches.

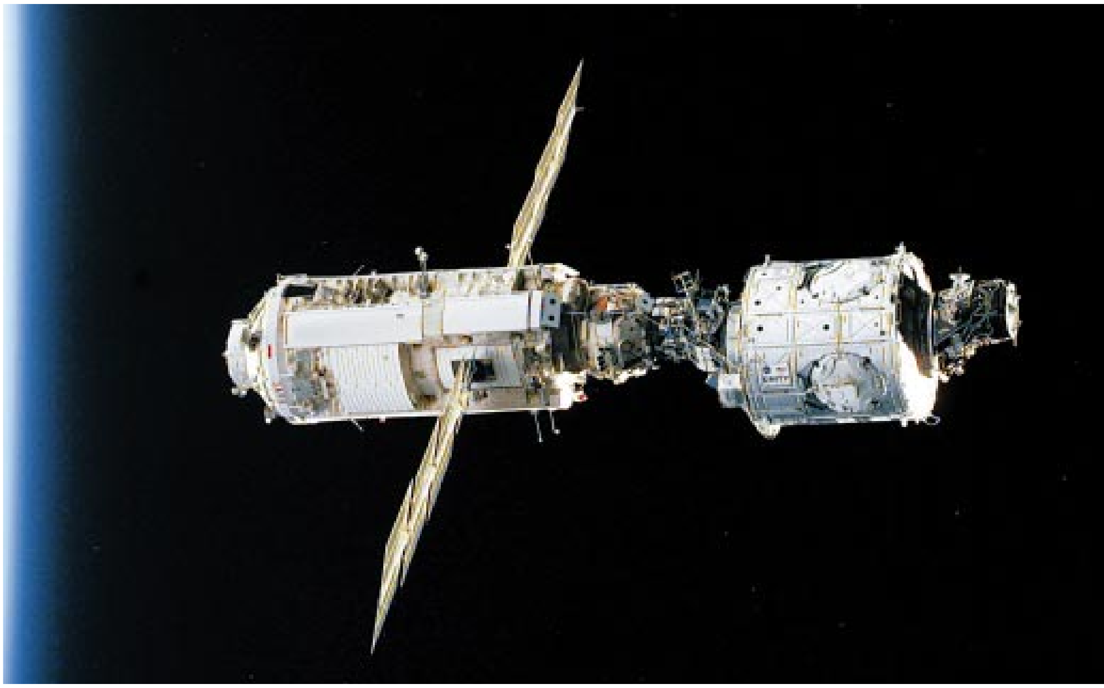
While the costs of keeping Russia as a partner have been growing, its planned contributions have declined. Russian officials have announced a "core program" on the space station that no longer includes a science power platform, two research laboratories and a life-support module. Russia is discussing constructing one laboratory with Ukraine—but "we don't see much design and development work" on the life-support module, says W. Michael Hawes, Sr., senior engineer for the space station. Hawes says the changing design has now made the Russian life-support module redundant. The status of other Russian components is unclear. Perhaps more worrying, Russia is unlikely to be able to sup-



NASA

SERVICE MODULE, designed to provide living quarters and propulsion for the International Space Station, is shown under construction at the Khrunichev State Research and Production Space Center in Moscow. Russia's failure to complete the module on schedule has delayed the assembly of the space station and prompted U.S. officials to redesign the station to reduce their reliance on Russia.

FIRST PIECES of the International Space Station—the Unity node (*far right*) built by the U.S. and the Zarya module built by Russia—were linked by the crew of the space shuttle *Endeavour* in December 1998. A total of 36 shuttle flights and nine Russian launches will be required to complete the assembly of the station by 2005.



ply the seven Progress and two Soyuz refueling and crew rotation flights each year that it had undertaken to do: congressional overseers now think five such flights each year is more realistic.

To satisfy Congress's demands for a backup plan, NASA has quietly been changing the assembly sequence and designing and modifying hardware to reduce its vulnerability. The first of these late-arriving additions is a $156-million Interim Control Module, which is now nearing completion at the Naval Research Laboratory. The module is a modified version of a previously classified upper-stage rocket, and it could by itself provide attitude control and reboost for the station for a year or two. NASA also modified Zarya (which the U.S. owns) prior to launch to improve its station boosting and control capabilities.

The European Space Agency has agreed to provide propellant for the Service Module, according to Daniel Hedin of NASA's space development office. And NASA is now also planning to modify all its space shuttles to increase their capacity to boost the station. The fix should mean the station needs only about 30 Progress refueling boosts instead of the baseline number of 53, according to Hedin. Moreover, NASA does not rule out launching the Interim Control Module sometime in 2000 even if the Service Module does launch this year, because it would provide insurance against a future shortage of Progress rockets.

The Interim Control Module will not be the only addition to the station undertaken because of Russia's crippling budget problems. NASA is now also negotiating with Boeing to build a U.S. propulsion module, at an expected cost of $350 million. It would eliminate the need for about half of the currently scheduled Progress resupply flights and offer a permanent solution in the event that the Service Module never arrives.

Other aspects of the station are almost as fluid. No final decisions have yet been made on provisions for returning crew to Earth in the event of some emergency. In the early construction phase that role will be played by a Soyuz spacecraft attached to the station. A Soyuz, however, can transport only three astronauts, and the station's final scheduled crew numbers seven. The U.S. is planning to build a larger Crew Return Vehicle capable of bringing home all the permanent crew, but it will most likely not be ready until 2003 at the earliest, and the station will probably have a crew of more than three before then. NASA is considering buying one or more Soyuz vehicles to provide an interim emergency return capability.

In any event, the U.S. crew return vehicle's final form is still undecided. The current design, based on the X-38 experimental craft, offers only nine hours of life support. NASA and the European Space Agency are discussing modifications to the design that would turn it into a transfer vehicle that could be launched on an Ariane rocket.

Even the basic design of the main American habitation module is still up for grabs. Engineers at the NASA Johnson Space Center have proposed an inflatable structure known as TransHab as a substitute for the aluminum habitation module in the present design. TransHab would have a hard composite core surrounded by Kevlar and foam layers for micrometeorite protection. Its main selling point is that it might serve to test a mode of construction that could, because of its low mass, be advantageous in future crewed moon or Mars expeditions.

But the station's value as a test bed for a future crewed mission to Mars can be questioned. The most important physical hazards facing such a crew are likely to be loss of bone mass, which seems to be a common result of prolonged weightlessness, and radiation from solar storms. Yet a vehicle designed to go to Mars could easily be furnished with artificial gravity, by separating it into two connected sections and slowly spinning them, says Ivan Bekey, a former head of advanced concepts at NASA. Furthermore, the station's orbit is too low to experience the full fury of solar storms. An earlier design would have tested five innovative space technologies, including a high-voltage power transmission system and solar-thermal power generation. They, however, were dropped from the final scheme, Bekey notes.

The International Space Station is principally a foreign-policy enterprise. And as such it may be a success. Thousands of Russian scientists and engineers who without the American bailout might have gone to well-paying jobs designing weapons for rogue states are now still at work on peaceful systems. Politicians and officials and technical experts in countries throughout the world have had the opportunity to collaborate and link their destinies in an organizationally demanding endeavor. Perhaps the value of that return cannot be measured in dollars. SA

ROBOTS v
Who Should

Unmanned spacecraft are exploring the solar system more cheaply and effectively than astronauts are

by Francis Slakey

The National Aeronautics and Space Administration has a difficult task. It must convince U.S. taxpayers that space science is worth $13.6 billion a year. To achieve this goal, the agency conducts an extensive public-relations effort that is similar to the marketing campaigns of America's biggest corporations. NASA has learned a valuable lesson about marketing in the 1990s: to promote its programs, it must provide entertaining visuals and stories with compelling human characters. For this reason, NASA issues a steady stream of press releases and images from its human spaceflight program.

Every launch of the space shuttle is a media event. NASA presents its astronauts as ready-made heroes, even when their accomplishments in space are no longer groundbreaking. Perhaps the best example of NASA's public-relations prowess was the participation of John Glenn, the first American to orbit Earth, in shuttle mission STS-95 last year. Glenn's return to space at the age of 77 made STS-95 the most avidly followed mission since the Apollo moon landings. NASA claimed that Glenn went up for science—he served as a guinea pig in various medical experiments—but it was clear that the main benefit of Glenn's space shuttle ride was publicity, not scientific discovery.

Continued on page 26

NASA AND CARNEGIE MELLON UNIVERSITY

NOMAD ROVER developed by the Robotics Institute at Carnegie Mellon University is shown traversing the icy terrain of Antarctica late last year. Scientists are testing the prototype in inhospitable environments on Earth to develop an advanced rover for future unmanned space missions.

s. HUMANS

Explore Space?

Astronaut explorers can perform science in space that robots cannot

by Paul D. Spudis


NASA

APOLLO 17 **ASTRONAUT Harrison Schmitt investigates a huge boulder at the Taurus-Littrow landing site on the moon in 1972. Schmitt, a geologist, made important discoveries about the moon's composition and history, thus demonstrating the value of astronauts as space explorers.**

Criticism of human spaceflight comes from many quarters. Some critics point to the high cost of manned missions. They contend that the National Aeronautics and Space Administration has a full slate of tasks to accomplish and that human spaceflight is draining funds from more important missions. Other critics question the scientific value of sending people into space. Their argument is that human spaceflight is an expensive "stunt" and that scientific goals can be more easily and satisfactorily accomplished by robotic spacecraft.

But the actual experience of astronauts and cosmonauts over the past 38 years has decisively shown the merits of people as explorers of space. Human capability is required in space to install and maintain complex scientific instruments and to conduct field exploration. These tasks take advantage of human flexibility, experience and judgment. They demand skills that are unlikely to be automated within the foreseeable future. A program of purely robotic exploration is inadequate in addressing the important scientific issues that make the planets worthy of detailed study.

Many of the scientific instruments sent into space require careful emplacement and alignment to work properly. Astronauts have successfully deployed instruments in Earth orbit—for example, the Hubble Space Telescope—and on the sur-

Continued on page 30

Slakey, *continued from page 24*

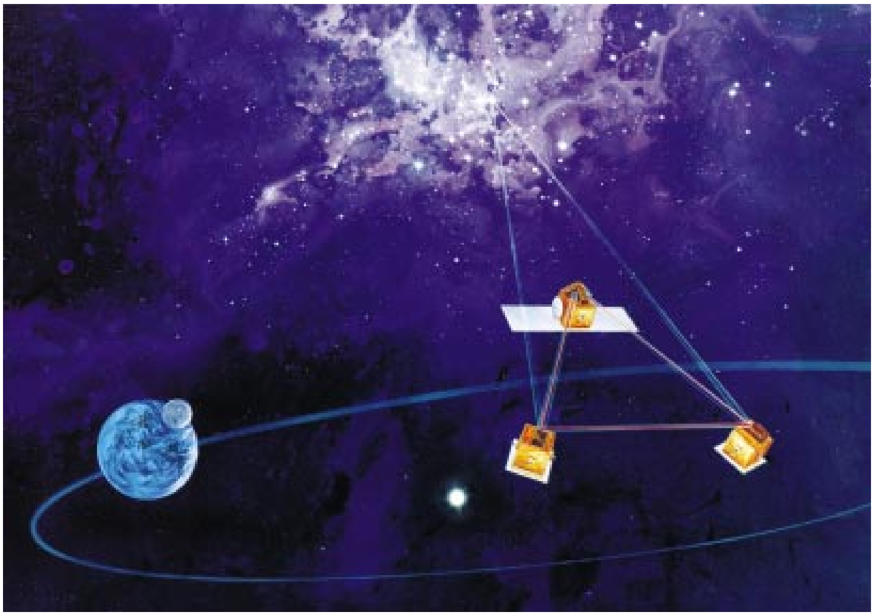
NASA is still conducting grade-A science in space, but it is being done by unmanned probes rather than astronauts. In recent years the Pathfinder rover has scoured the surface of Mars, and the Galileo spacecraft has surveyed Jupiter and its moons. The Hubble Space Telescope and other orbital observatories are bringing back pictures of the early moments of creation. But robots aren't heroes. No one throws a ticker-tape parade for a telescope. Human spaceflight provides the stories that NASA uses to sell its programs to the public. And that's the main reason NASA spends nearly a quarter of its budget to launch the space shuttle about half a dozen times each year.

The space agency has now started building the International Space Station, the long-planned orbiting laboratory. NASA says the station will provide a platform for space research and help determine how people can live and work safely in space. This knowledge could then be used to plan a manned mission to Mars or the construction of a base on the moon. But these justifications for the station are largely myths. Here are the facts, plain as potatoes: The International Space Station is not a platform for cutting-edge science. Unmanned probes can explore Mars and other planets more cheaply and effectively than manned missions can. And a moon colony is not in our destiny.

The Myth of Science

In 1990 the American Physical Society, an organization of 41,000 physicists, reviewed the experiments then planned for the International Space Station. Many of the studies involved examining materials and fluid mechanics in the station's microgravity environment. Other proposed experiments focused on growing protein crystals and cell cultures on the station. The physical society concluded, however, that these experiments would not provide enough useful scientific knowledge to justify building the station. Thirteen other scientific organizations, including the American Chemical Society and the American Crystallographic Association, drew the same conclusion.

Since then, the station has been redesigned and the list of planned experiments has changed, but the research community remains overwhelmingly opposed. To date, at least 20 scientific organizations from around the world have determined that the experiments in their respective fields are a waste of time and money. All



NASA/JET PROPULSION LABORATORY

UNMANNED SPACECRAFT are becoming more versatile. In the Deep Space 3 mission, scheduled for launch in 2002, three vessels will fly in formation to create an optical interferometer, which will observe distant stars at high resolution. The spacecraft will fly between 100 meters and one kilometer apart.

these groups have recommended that space science should instead be done through robotic and telescopic missions.

These scientists have various reasons for their disapproval. For researchers in materials science, the station would simply be too unstable a platform. Vibrations caused by the movements of astronauts and machinery would jar sensitive experiments. The same vibrations would make it difficult for astronomers to observe the heavens and for geologists and climatologists to study Earth's surface as well as they could with unmanned satellites. The cloud of gases vented from the station would interfere with any experiments in space nearby that require near-vacuum conditions. And last, the station would orbit only 400 kilometers (250 miles) overhead, traveling through a region of space that has already been studied extensively.

Despite the scientific community's disapproval, NASA plans to go ahead with the proposed experiments on the space station. The agency has been particularly enthusiastic about studying the growth of protein crystals in microgravity; NASA claims the studies may spur the development of better medicines. But in July 1998 the American Society for Cell Biology bluntly called for the cancellation of the crystallography program. The society's review panel concluded that the proposed experiments were not likely to make any serious contributions to the knowledge of protein structure.

The Myth of Economic Benefit

Human spaceflight is extremely expensive. A single flight of the space shuttle costs about $420 million. The shuttle's cargo bay can carry up to 23,000 kilograms (51,000 pounds) of payload into orbit and can return 14,500 kilograms back to Earth. Suppose that NASA loaded up the shuttle's cargo bay with confetti before launching it into space. Even if every kilogram of confetti miraculously turned into a kilogram of gold during the trip, the mission would still lose $270 million.

The same miserable economics hold for the International Space Station. Over the past 15 years the station has undergone five major redesigns and has fallen 11 years behind schedule. NASA has already spent nearly twice the $8 billion that the original project was supposed to cost in its entirety. The construction budget is now expected to climb above $40 billion, and the U.S. General Accounting Office estimates that the total outlay over the station's expected 10-year lifetime will exceed $100 billion.

NASA had hoped that space-based manufacturing on the station would offset some of this expense. In theory, the microgravity environment could allow the production of certain pharmaceuticals and semiconductors that would have advantages over similar products made on Earth. But the high price of sending anything to the station has dissuaded most companies from even exploring the idea.

NASA/JET PROPULSION LABORATORY

DEEP SPACE 4 mission will test the technologies for landing an unmanned probe on a comet. Slated for launch in 2003, the spacecraft will rendezvous with Comet Tempel 1, land a probe on the comet's nucleus and return drilling samples to Earth.

So far the station's only economic beneficiary has been Russia, one of America's partners in the project. Last year NASA announced plans to pay $660 million over four years to the Russian Space Agency so it can finish construction of key modules of the station. The money was needed to make up for funds the Russians could not provide because of their country's economic collapse. U.S. Congressman James Sensenbrenner of Wisconsin, who chairs the House Science Committee, bitterly referred to the cash infusion as "bailout money" for Russia.

But what about long-term economic benefits? NASA has maintained that the ultimate goal of the space station is to serve as a springboard for a manned mission to Mars. Such a mission would probably cost at least as much as the station; even the most optimistic experts estimate that sending astronauts to the Red Planet would cost tens of billions of dollars. Other estimates run as high as $1 trillion. The only plausible economic benefits of a Mars mission would be in the form of technology spin-offs, and history has shown that such spin-offs are a poor justification for big-money space projects.

In January 1993 NASA released an internal study that examined technology spin-offs from previous missions. According to the study, "NASA's technology-transfer reputation is based on some famous examples, including Velcro, Tang and Teflon. Contrary to popular opinion, NASA created none of these." The report concluded that there have been very few technology-transfer successes at NASA over the past three decades.

The Myth of Destiny

Now it's time to get personal. When I was seven years old, I had a poster of the Apollo astronauts on my bedroom wall. My heroes had fearlessly walked on the moon and returned home in winged glory. They made the universe seem a bit smaller; they made my eyes open a bit wider. I was convinced that one day I would follow in their footsteps and travel to Mars.

So, what happened? I went to Mars three times—twice with the Viking landers in the late 1970s and the last time with the Mars Pathfinder mission in July 1997. I wasn't alone: millions of people joined me in front-row seats to watch Pathfinder's rugged Sojourner rover scramble over the Martian landscape. I've also traveled to Jupiter's moons with the Galileo spacecraft and seen hints of a liquid ocean on Europa. In 2004 I'll go to Saturn with the Cassini probe and get a close-up view of the planet's rings.

In recent years there have been tremendous strides in the capabilities of unmanned spacecraft. NASA's Discovery program has encouraged the design of compact, cost-effective probes that can make precise measurements and transmit high-quality images. Mars Pathfinder, for example, returned a treasure trove of data and pictures for only $265 million. And NASA's New Millennium program is testing advanced technologies with spacecraft such as the Deep Space 2 microprobes. These two-kilogram instruments, now riding piggyback on the Mars Polar Lander spacecraft launched earlier this year, will plunge to the surface of Mars and penetrate up to two meters underground, where they will analyze soil samples and search for subsurface ice.

These spacecraft will still need human direction, of course, from scientists and engineers in control rooms on Earth. Unlike astronauts, mission controllers are usually not celebrated in the press. But if explorers Lewis and Clark were alive today, that's where they would be sitting. They would not be interested in spending their days tightening bolts on a space station.

Building a manned base on the moon makes even less sense. Unmanned spacecraft can study the moon quite efficiently, as the Lunar Prospector probe has recently shown. It is not our destiny to build a moon colony any more than it is to walk on our hands.

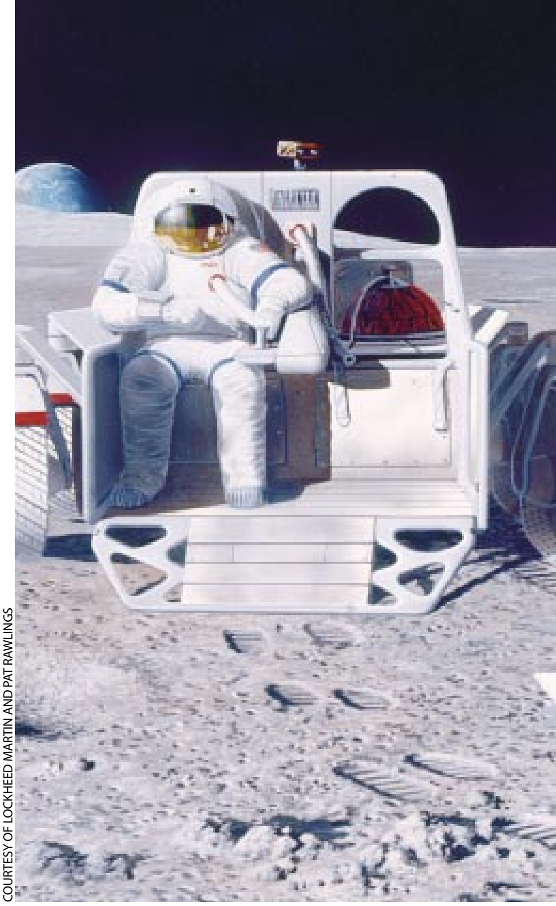
What's Next?

For the present, NASA appears committed to maintaining its human spaceflight program, whatever the cost. But in the next decade the space agency may discover that it does not need human characters to tell compelling stories. Mars Pathfinder proved that an unmanned mission can thrill the public just as much as a shuttle flight. The Pathfinder World Wide Web site had 720 million hits in one year. Maybe robots can be heroes after all.

Instead of gazing at posters of astronauts, children are now playing with toy models of the Sojourner rover. The next generation of space adventurers is growing up with the knowledge that one can visit another planet without boarding a spacecraft. Decades from now, when those children are grown, some of them will lead the next great explorations of the solar system. Sitting in hushed control rooms, they will send instructions to far-flung probes and make the final adjustments that point us toward the stars. SA

Francis Slakey is an adjunct professor of physics at Georgetown University and associate director of public affairs for the American Physical Society. He received his Ph.D. in physics in 1992 from the University of Illinois, where his research focused on the optical properties of high-temperature superconductors. He writes and lectures on the subject of science policy; his commentaries have appeared in the *New York Times* and the *Washington Post*.

FUTURE ASTRONAUTS perform maintenance on a telescope on the moon's surface in this artist's conception. Humans are far more capable than robots in deploying scientific instruments and repairing complex equipment in space.



COURTESY OF LOCKHEED MARTIN AND PAT RAWLINGS

Spudis, *continued from page 25*

face of Earth's moon. In the case of the space telescope, the repair of the originally flawed instrument and its continued maintenance have been ably accomplished by space shuttle crews on servicing missions. From 1969 to 1972 the Apollo astronauts carefully set up and aligned a variety of experiments on the lunar surface, which provided scientists with a detailed picture of the moon's interior by measuring seismic activity and heat flow. These experiments operated flawlessly for eight years until shut down in 1977 for fiscal rather than technical reasons.

Elaborate robotic techniques have been envisioned to allow the remote emplacement of instruments on planets or moons. For example, surface rovers could conceivably install a network of seismic monitors. But these techniques have yet to be demonstrated in actual space operations. Very sensitive instruments cannot tolerate the rough handling of robotic deployment. Thus, the auto-deployed versions of such networks would very likely have lower sensitivity and capability than their human-deployed counterparts do.

The value of humans in space becomes even more apparent when complex equipment breaks down. On several occasions astronauts have been able to repair hardware in space, saving missions and the precious scientific data that they produce. When Skylab was launched in 1973, the lab's thermal heat shield was torn off and one of its solar panels was lost. The other solar panel, bound to the lab by restraining ties, would not release. But the first Skylab crew—astronauts Pete Conrad, Joe Kerwin and Paul Weitz—installed a new thermal shield and deployed the pinned solar panel. Their heroic efforts saved not only their mission but also the entire Skylab program.

Of course, some failures are too severe to be repaired in space, such as the damage caused by the explosion of an oxygen tank on the *Apollo 13* spacecraft in 1970. But in most cases when spacecraft equipment malfunctions, astronauts are able to analyze the problem, make on-the-spot judgments and come up with innovative solutions. Machines are capable of limited self-repair, usually by switching to redundant systems that can perform the same tasks as the damaged equipment, but they do not possess as much flexibility as people. Machines can be designed to fix expected problems, but so far only people have shown the ability to handle unforeseen difficulties.

Astronauts as Field Scientists

Exploration has two stages: reconnaissance and field study. The goal of reconnaissance is to acquire a broad overview of the compositions, processes and history of a given region or planet. Questions asked during the reconnaissance phase tend to be general—for instance, What's there? Examples of geologic reconnaissance are an orbiting spacecraft mapping the surface of a planet, and an automated lander measuring the chemical composition of the planet's soil.

The goals of field study are more ambitious. The object is to understand planetary processes and histories in detail. This requires observation in the field, the creation of a conceptual model, and the formulation and testing of hypotheses. Repeated visits must be made to the same geographic location. Field study is an open-ended, ongoing activity; some field sites on Earth have been studied continuously for more than 100 years and still provide scientists with important new insights. Field study is not a simple matter of collecting data: it requires the guiding presence of human intelligence. People are needed in the field to analyze the overabundant data and determine what should be collected and what should be ignored.

The transition from reconnaissance to field study is fuzzy. In any exploration, reconnaissance dominates the earliest phases. Because it is based on broad questions and simple, focused tasks, reconnaissance is the type of exploration best suited to robots. Unmanned orbiters can provide general information about the atmosphere, surface features and magnetic fields of a planet. Rovers can traverse the planet's surface, testing the physical and chemical properties of the soil and collecting samples for return to Earth.

But field study is complicated, interpretive and protracted. The method of solving the scientific puzzle is often not apparent immediately but must be formulated, applied and modified during the course of the study. Most important, fieldwork nearly always involves uncovering the unexpected. A surprising discovery may lead scientists to adopt new exploration methods or to make different observations. But an unmanned probe on a distant planet cannot be redesigned to observe unexpected phenomena. Although robots can gather significant amounts of data, conducting science in space requires *scientists*.

It is true that robotic missions are much less costly than human missions; I contend that they are also much less capable. The unmanned Luna 16, 20 and 24 spacecraft launched by the Soviet Union in the 1970s are often praised for returning soil samples from the moon at little cost. But the results from those missions are virtually incomprehensible without the paradigm provided by the results from the manned Apollo program. During the Apollo missions, the geologically trained astronauts were able to select the most representative samples of a given locality and recognize interesting or exotic rocks and act on such discoveries. In contrast, the Luna samples were scooped up indiscriminately by the robotic probes. We understand the geologic makeup and structure of each Apollo site in much greater detail than those of the Luna sites.

For a more recent example, consider the Mars Pathfinder mission, which was widely touted as a major success. Although Pathfinder discovered an unusual, silica-rich type of rock, because of the probe's limitations we do not know whether this composition represents an

igneous rock, an impact breccia or a sedimentary rock. Each mode of origin would have a widely different implication about the history of Mars. Because the geologic context of the sample is unknown, the discovery has negligible scientific value. A trained geologist could have made a field identification of the rock in a few minutes, giving context to the subsequent chemical analyses and making the scientific return substantially greater.

The Melding of Mind and Machine

Human dexterity and intelligence are the prime requirements of field study. But is the physical presence of people really required? Telepresence—the remote projection of human abilities into a machine—may permit field study on other planets without the danger and logistical problems associated with human spaceflight. In telepresence the movements of a human operator on Earth are electronically transmitted to a robot that can reproduce the movements on another planet's surface. Visual and tactile information from the robot's sensors give the human operator the sensation of being present on the planet's surface, "inside" the robot. As a bonus, the robot surrogate can be given enhanced strength, endurance and sensory capabilities.

If telepresence is such a great idea, why do we need humans in space? For one, the technology is not yet available. Vision is the most important sense used in field study, and no real-time imaging system developed to date can match human vision, which provides 20 times more resolution than a video screen. But the most serious obstacle for telepresent systems is not technological but psychological. The process that scientists use to conduct exploration in the field is poorly understood, and one cannot simulate what is not understood.

Finally, there is the critical problem of time delay. Ideally, telepresence requires minimal delays between the operator's command to the robot, the execution of the command and the observation of the effect. The distances in space are so vast that instantaneous response is impossible. A signal would take 2.6 seconds to make a round-trip between Earth and its moon. The round-trip delay between Earth and Mars can be as long as 40 minutes, making true telepresence impossible. Robotic Mars probes must rely on a cumbersome interface, which forces the operator to be more preoccupied with physical manipulation than with exploration.

Robots and Humans as Partners

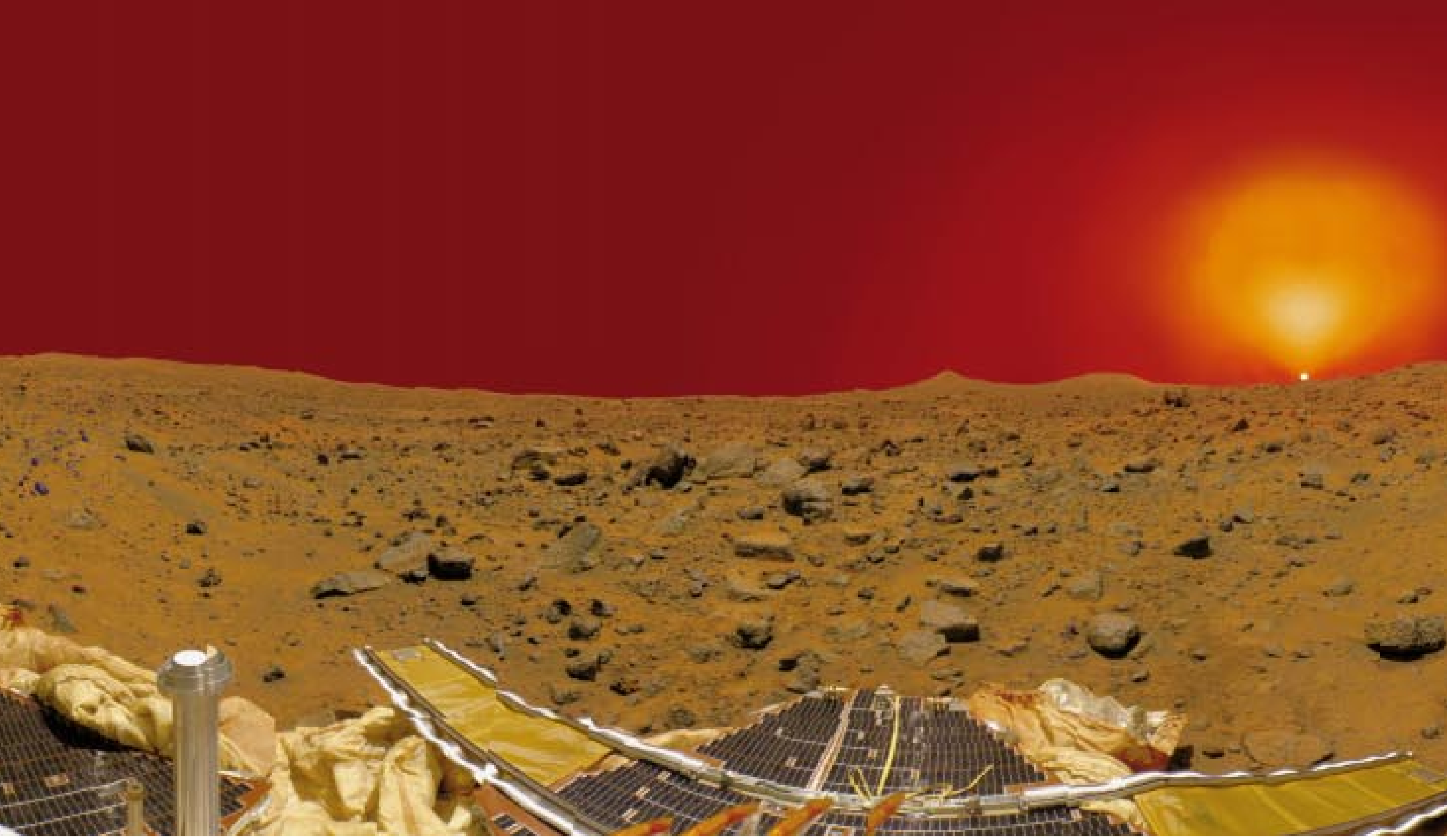
Currently NASA is focusing on the construction of the International Space Station. The station is not a destination, however; it is a place to learn how to roam farther afield. Although some scientific research will be done there, the station's real value will be to teach astronauts how to live and work in space. Astronauts must master the process of in-orbit assembly so they can build the complex vehicles needed for interplanetary missions. In the coming decades, the moon will also prove useful as a laboratory and test bed. Astronauts at a lunar base could operate observatories and study the local geology for clues to the history of the solar system. They could also use telepresence to explore the moon's inhospitable environment and learn how to mix human and robotic activities to meet their scientific goals.

The motives for exploration are both emotional and logical. The desire to probe new territory, to see what's over the hill, is a natural human impulse. This impulse also has a rational basis: by broadening the imagination and skills of the human species, exploration improves the chances of our long-term survival. Judicious use of robots and unmanned spacecraft can reduce the risk and increase the effectiveness of planetary exploration. But robots will never be replacements for people. Some scientists believe that artificial-intelligence software may enhance the capabilities of unmanned probes, but so far those capabilities fall far short of what is required for even the most rudimentary forms of field study.

To answer the question "Humans or robots?" one must first define the task. If space exploration is about going to new worlds and understanding the universe in ever increasing detail, then both robots and humans will be needed. The strengths of each partner make up for the other's weaknesses. To use only one technique is to deprive ourselves of the best of both worlds: the intelligence and flexibility of human participation and the beneficial use of robotic assistance.

Paul D. Spudis is a staff scientist at the Lunar and Planetary Institute in Houston. He earned his Ph.D. in geology from Arizona State University in 1982 and worked for the U.S. Geological Survey's astrogeology branch until 1990. His research has focused on the moon's geologic history and on volcanism and impact cratering on the planets. He has served on numerous committees advising NASA on exploration strategies and is the author of *The Once and Future Moon* (Smithsonian Institution Press, 1996).

The Mars Pathfinder



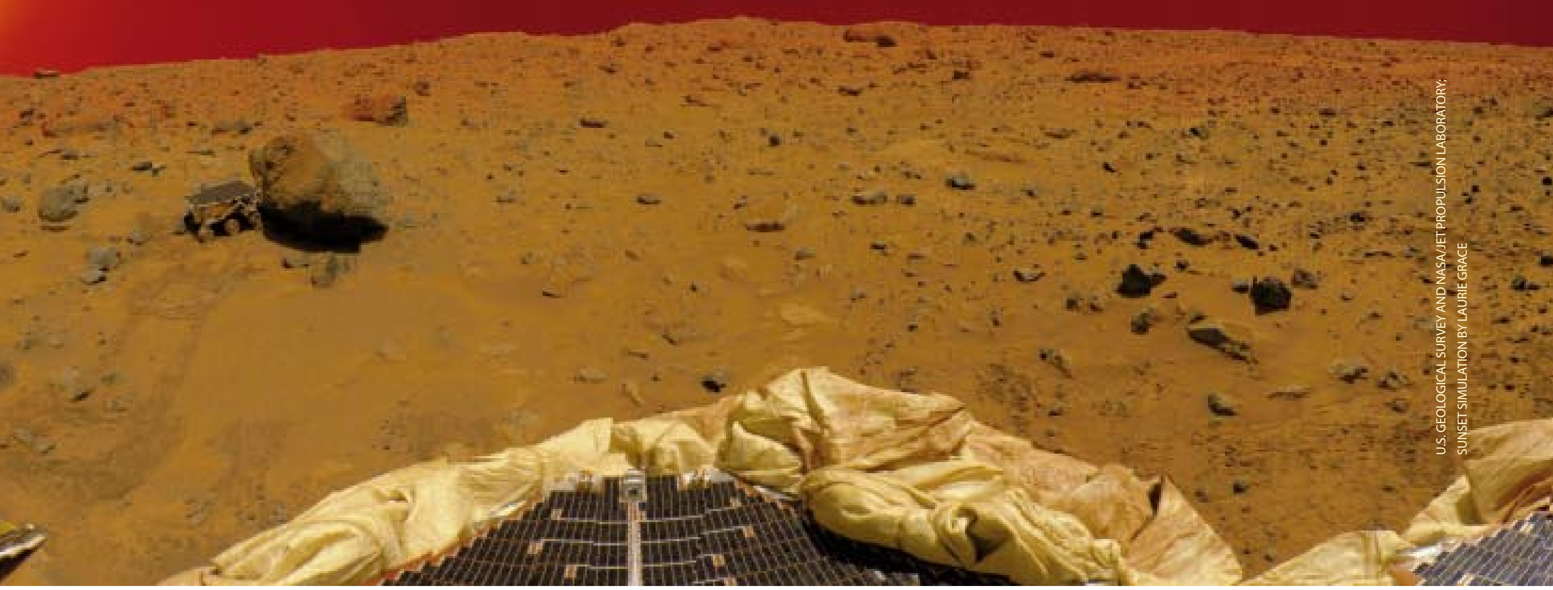
Rocks, rocks, look at those rocks," I exclaimed to everyone in the Mars Pathfinder control room at about 4:30 P.M. on July 4, 1997. The Pathfinder lander was sending back its first images of the surface of Mars, and everyone was focused on the television screens. We had gone to Mars to look at rocks, but no one knew for sure whether we would find any, because the landing site had been selected using orbital images with a resolution of roughly a kilometer. Pathfinder could have landed on a flat, rock-free plain. The first radio downlink indicated that the lander was nearly horizontal, which was worrisome for those of us interested in rocks, as most expected that a rocky surface would result in a tilted lander. The very first images were of the lander so that we could ascertain its condition, and it was not until a few tense minutes later that the first pictures of the surface showed a rocky plain—exactly as we had hoped and planned for.

Why did we want rocks? Every rock carries the history of its formation locked in its minerals, so we hoped the rocks would tell us about the early Martian environment. The two-part Pathfinder payload, consisting of a main lander with a multispectral camera and a mobile rover with a chemical analyzer, was suited to looking at rocks. Although it could not identify the minerals directly—its analyzer could measure only their constituent chemical elements—our plan was to identify them indirectly based on the elemental composition and the shapes, textures and colors of the rocks. By landing Pathfinder at the mouth of a giant channel where a huge vol-

Mission

The first rover to explore Mars found in situ evidence that the Red Planet may once have been hospitable to life

by Matthew P. Golombek



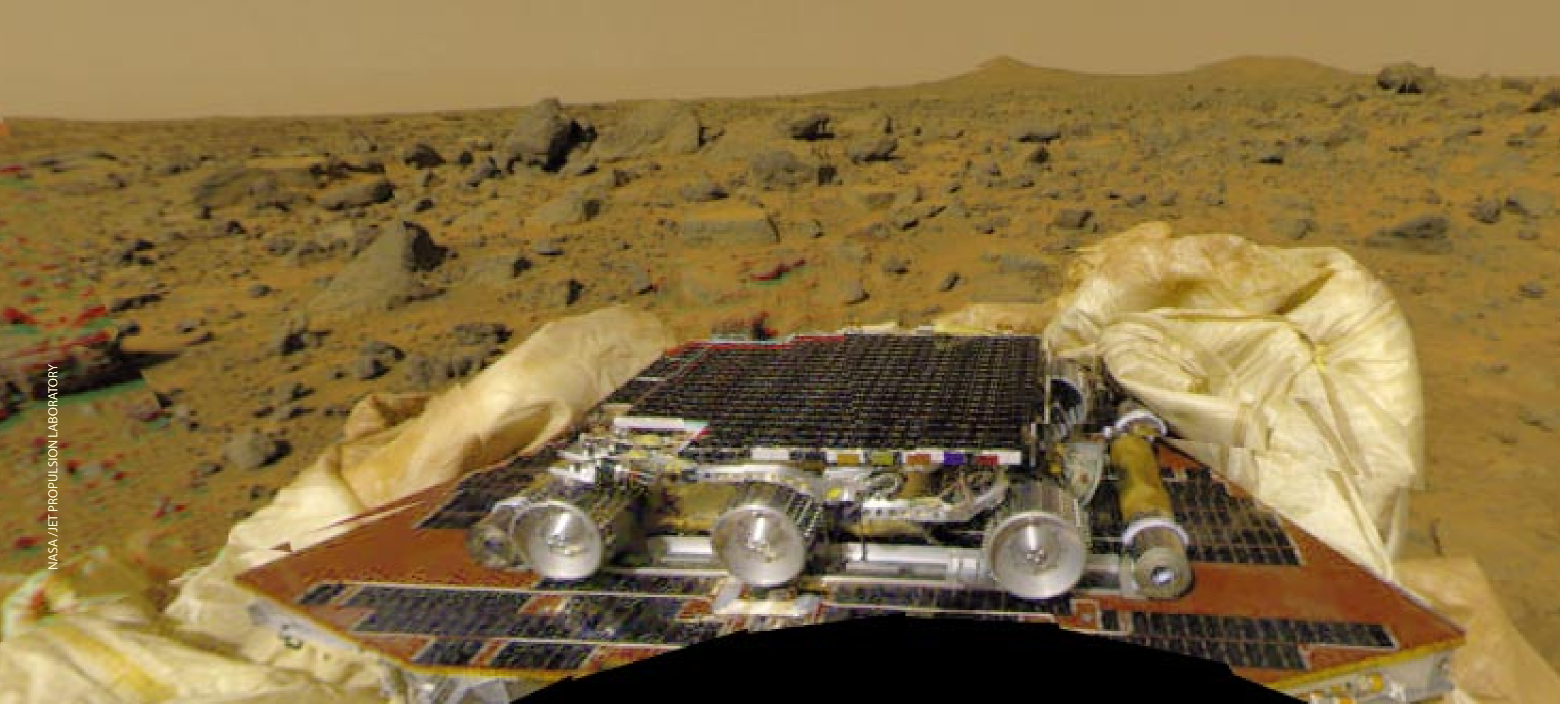
U.S. GEOLOGICAL SURVEY AND NASA/JET PROPULSION LABORATORY; SUNSET SIMULATION BY LAURIE GRACE

TWILIGHT AT ARES VALLIS, Pathfinder's landing site, is evoked in this 360-degree panorama, a composite of a true sunset (*inset at left*) and other images. The rover is analyzing the rock Yogi to the right of the lander's rear ramp. Farther right are whitish-pink patches on the ground known as Scooby Doo (*closer to lander*) and Baker's Bench. The rover tried to scratch the surface of Scooby Doo but could not, indicating that the soil in these patches is cemented together. The much studied Rock Garden appears left of center. Flat Top, the flat rock in front of the garden, is covered with dust, but steep faces on other large rocks are clean; the rover analyzed all of them. (In this simulation, parts of the sky and terrain were computer-adjusted to complete the scene. During a real sunset, shadows would of course be longer and the ground would appear darker.) —*The Editors*

ume of water once flowed briefly, we sought rocks that had washed down from the ancient, heavily cratered highlands. Such rocks could offer clues to the early climate of Mars and to whether conditions were once conducive to the development of life [*see top illustration on page 36*].

The most important requirement for life on Earth (the only kind we know) is liquid water. Under present conditions on Mars, liquid water is unstable: because the temperature and pressure are so low, water is stable only as ice or vapor; liquid would survive for just a brief time before freezing or evaporating. Yet Viking images taken two decades ago show drainage channels and evidence for lakes in the highlands. These features hint at a warmer and wetter past on Mars in which water could persist on the surface [see "Global Climatic Change on Mars," by Jeffrey S. Kargel and Robert G. Strom; Scientific American, November 1996]. To be sure, other explanations have also been suggested, such as sapping processes driven by geothermal heating in an otherwise frigid and dry environment. One of Pathfinder's scientific goals was to look for evidence of a formerly warm, wet Mars.

The possible lake beds are found in terrain that, judging from its density of impact craters, is roughly the same age as the oldest rocks on Earth, which show clear evidence for life 3.9 billion to 3.6 billion



FIRST IMAGES
from Mars Pathfinder were assembled into this panorama of dark rocks, yellowish-brown dust and a butterscotch sky. Many rocks, particularly in the Rock Garden (*center*), are inclined and stacked—a sign that they were deposited by fast-moving water. About a kilometer behind the garden on the west-southwest horizon are the Twin Peaks, whose prominence identified the landing site on Viking orbiter images. After touching down, the lander pulled back the air bag and unfurled two ramps; the rover trundled down the rear ramp onto the surface the next day. (The small green and red streaks are artifacts of data compression.)

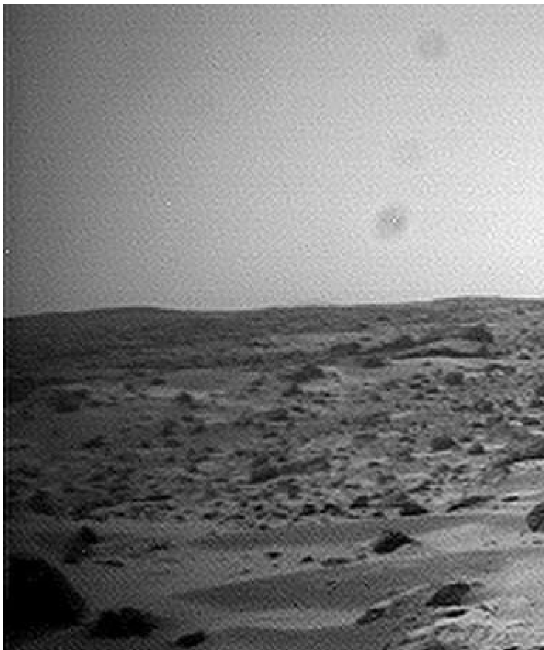
years ago. If life was able to develop on Earth at this time, why not on Mars, too, if the conditions were similar? This is what makes studying Mars so compelling. By exploring our neighboring planet, we can seek answers to some of the most important questions in science: Are we alone in the universe? Will life arise anywhere that liquid water is stable, or does the formation of life require something else as well? And if life did develop on Mars, what happened to it? If life did not develop, why not?

Pathfinding

Pathfinder was a Discovery-class mission—one of the National Aeronautics and Space Administration's "faster, cheaper, better" spacecraft—to demonstrate a low-cost means of landing a small payload and mobile vehicle on Mars. It was developed, launched and operated under a fixed budget comparable to that of a major motion picture (between $200 million and $300 million), which is a mere fraction of the budget typically allocated for space missions. Built and launched in a short time (three and a half years), Pathfinder included three science instruments: the Imager for Mars Pathfinder, the Alpha Proton X-ray Spectrometer and the Atmospheric Structure Instrument/Meteorology Package. The rover itself also acted as an instrument; it was used to conduct 10 technology experiments, which studied the abrasion of metal films on a wheel of the rover and the adherence of dust to a solar cell as well as other ways the equipment on Pathfinder reacted to its surroundings.

In comparison, the Viking mission, which included two orbiter-lander pairs, was carried out more than 20 years ago at roughly 20 times the cost. Viking was very successful, returning more than 57,000 images that scientists have been studying ever since. The landers carried sophisticated experiments that tested for organisms at two locations; they found none.

The hardest part of Pathfinder's mission was the five minutes during which the spacecraft went from the relative security of interplanetary cruising to the stress of atmospheric entry, descent and landing [*see illustration on page 37*]. In that short time, more than 50 critical events had to be triggered at exactly the right times for the spacecraft to land safely. About 30 minutes before entry, the backpack-style cruise stage separated



SAND DUNES
provide circumstantial evidence for a watery past. These dunes, which lay in the trough behind the Rock Garden, are thought to have formed when windblown sand hopped up the gentle slope to the dune crest and cascaded down the steep side (which faces away from the rover in this image). Larger dunes have been observed from orbit, but none in the Pathfinder site. The discovery of these smaller dunes suggests that sand is more common on Mars than scientists had thought. The formation of sand on Earth is principally accomplished by moving water.

from the rest of the lander. At 130 kilometers above the surface, the spacecraft entered the atmosphere behind a protective aeroshell. A parachute unfurled 134 seconds before landing, and then the aeroshell was jettisoned. During descent, the lander was lowered beneath its back cover on a 20-meter-long bridle, or tether.

As Pathfinder approached the surface, its radar altimeter triggered the firing of three small solid-fuel rockets to slow it down further. Giant air bags inflated around each face of the tetrahedral lander, the bridle was cut, and the lander bounced onto the Martian surface at 50 kilometers per hour. Accelerometer measurements indicate that the air-bag-enshrouded lander bounced at least 15 times without losing air-bag pressure. After rolling at last to a stop, the lander deflated the air bags and opened to begin surface operations.

Although demonstrating this novel landing sequence was actually Pathfinder's primary goal, the rest of the mission also met or exceeded expectations. The lander lasted three times longer than its minimum design criteria, the rover 12 times longer. The mission returned 2.3 billion bits of new data from Mars, including more than 16,500 lander and 550 rover images and roughly 8.5 million individual temperature, pressure and wind measurements. The rover traversed a total of 100 meters in 230 commanded movements, thereby exploring more than 200 square meters of the surface. It obtained 16 measurements of rock and soil chemistry, performed soil-mechanics experiments and successfully completed the numerous technology experiments. The mission also captured the imagination of the public, garnering front-page headlines for a week, and became the largest Internet event in history at the time, with a total of about 566 million hits for the first month of the mission—47 million on July 8 alone.

Flood Stage

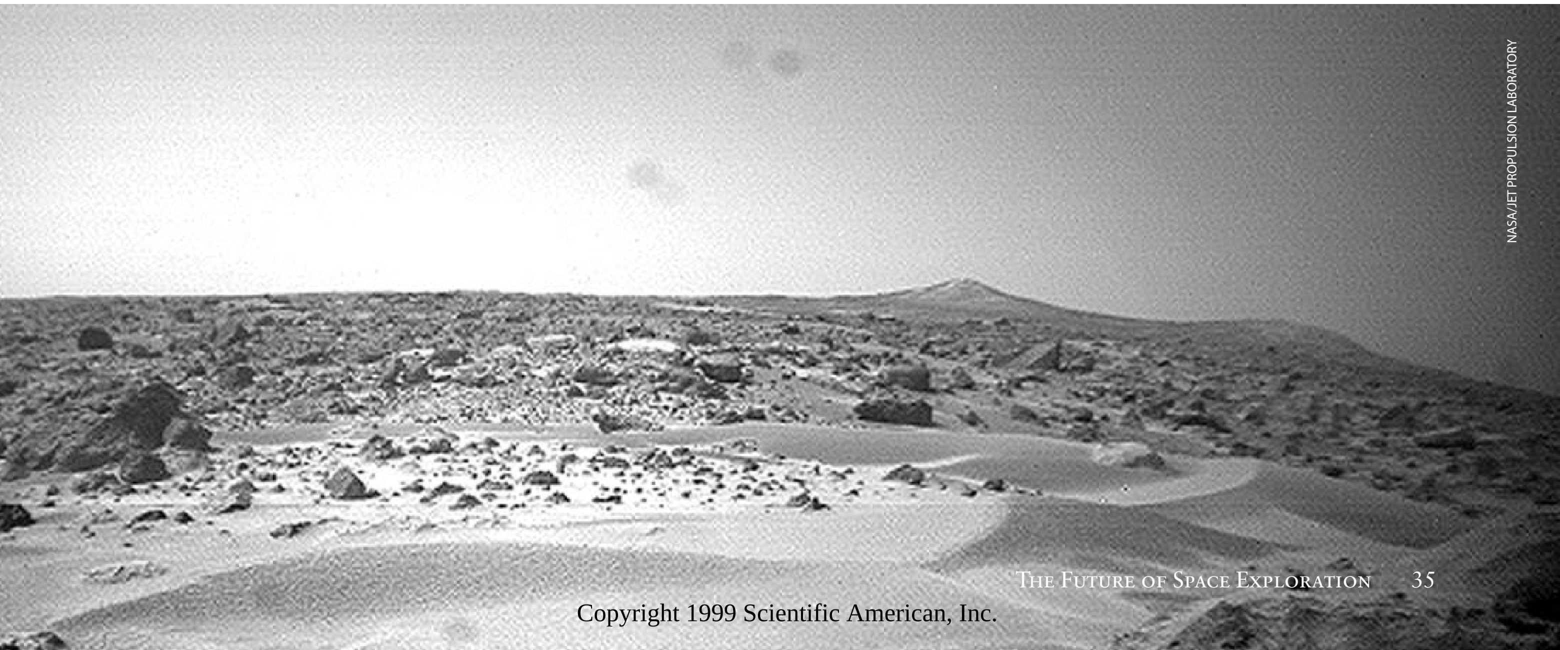
The mosaic of the landscape constructed from the first images revealed a rocky plain (about 20 percent of which was covered by rocks) that appears to have been deposited and shaped by catastrophic floods [*see top illustration on opposite page*]. This was what we had predicted based on remote-sensing data and the location of the landing site (19.13 degrees north, 33.22 degrees west), which is downstream from the mouth of Ares Vallis in the low area known as Chryse Planitia. In Viking orbiter images, the area appears analogous to the Channeled Scabland in eastern and central Washington State. This analogy suggests that Ares Vallis formed when roughly the same volume of water as in the Great Lakes (hundreds of cubic kilometers) was catastrophically released, carving the observed channel in a few weeks. The density of impact craters in the region indicates it formed at an intermediate time in Mars's history, somewhere between 1.8 billion and 3.5 billion years ago.

The Pathfinder images support this interpretation. They show semirounded pebbles, cobbles and boulders similar to those deposited by terrestrial catastrophic floods. Rocks in what we dubbed the Rock Garden, a collection of rocks to the southwest of the lander, with the names Shark, Half Dome and Moe, are inclined and stacked, as if deposited by rapidly flowing water. Large rocks in the images (0.5 meter or larger) are flat-topped and often perched, also consistent with deposition by a flood. Twin Peaks, a pair of hills on the southwest horizon, are streamlined. Viking images suggest that the lander is on the flank of a broad, gentle ridge trending northeast from Twin Peaks; this ridge may be a debris tail deposited in the wake of the peaks. Small channels throughout the scene resemble those in the Channeled Scabland, where drainage in the last stage of the flood preferentially removed fine-grained materials.

By exploring our neighboring planet, we can seek answers to some of the most important questions in science.

The rocks in the scene are dark gray and covered with various amounts of yellowish-brown dust. This dust appears to be the same as that seen in the atmosphere, which, as imaging in different filters and locations in the sky suggests, is very fine grained (a few microns in diameter). The dust also collected in wind streaks behind rocks.

Some of the rocks have been fluted and grooved, presumably by sand-size particles (less than one millimeter) that hopped along the surface in the wind. The rover's camera also saw sand dunes in the trough behind the Rock Garden [*see illustration below*]. Dirt covers the lower few centimeters of some rocks, suggesting that they have been exhumed by wind. Despite these signs of slow erosion by the wind, the rocks and surface appear to



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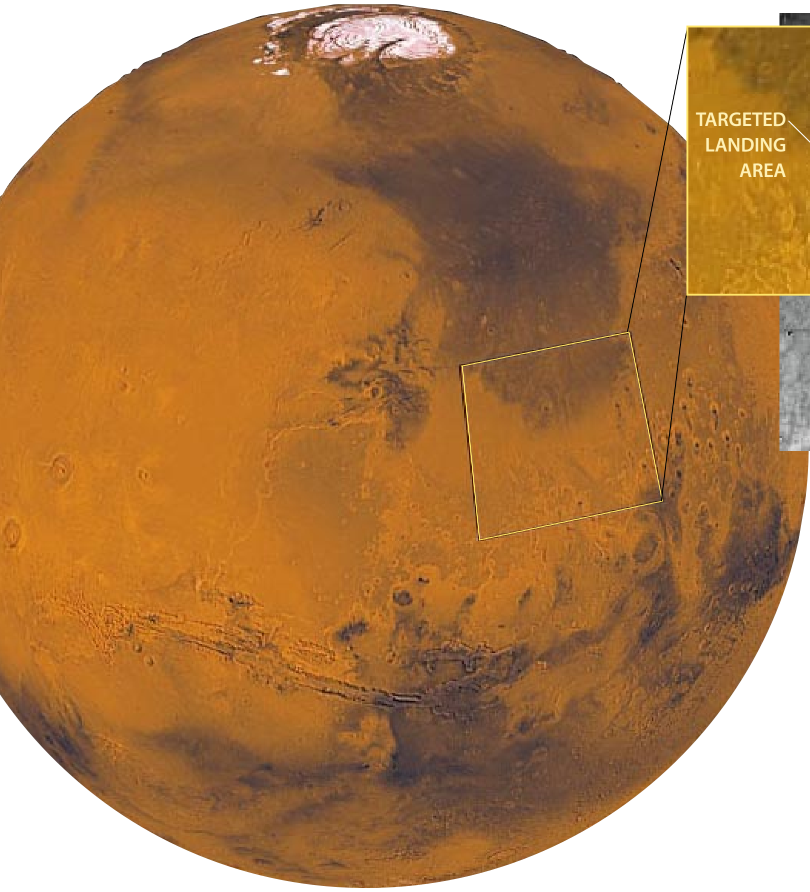
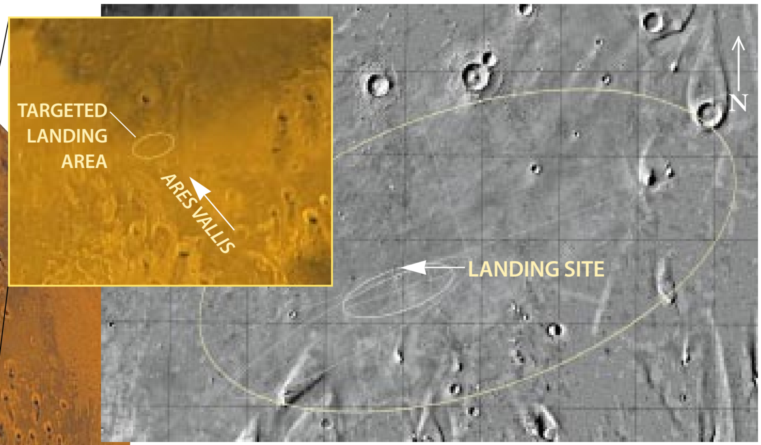




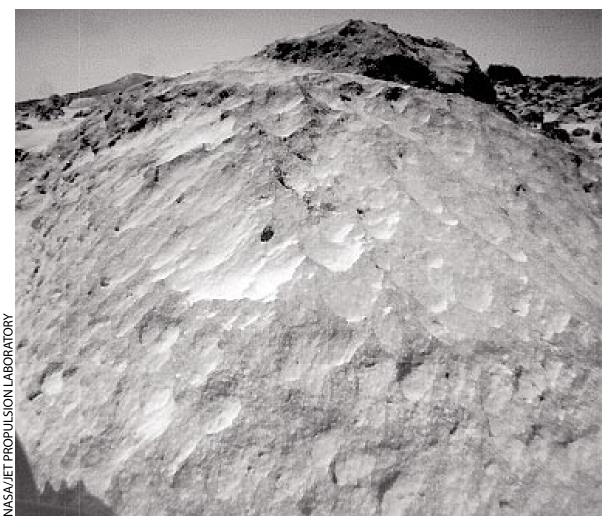
U.S. GEOLOGICAL SURVEY

LANDING SITE
is an outflow channel carved by mammoth floods billions of years ago. It was chosen as the Pathfinder landing site for three reasons: it seemed safe, with no steep slopes or rough surfaces detected by the Viking orbiters or Earth-based radars; it had a low elevation, which provided enough air density for parachutes; and it appeared to offer a variety of rock types deposited by the floods. The cratered region to the south is among the oldest terrain on Mars. The ellipses mark the area targeted for landing, as refined several times during the final approach to Mars; the arrow in the larger inset identifies the actual landing site; the arrow in the smaller inset indicates the presumed direction of water flow.

have changed little since they were deposited by the flood.

The Alpha Proton X-ray Spectrometer on the rover measured the compositions of eight rocks. The silicon content of some of the rocks is much higher than that of the Martian meteorites, our only other samples of Mars. The Martian meteorites are all mafic igneous rocks, volcanic rocks that are relatively low in silicon and high in iron and magnesium. Such rocks form when the upper mantle of a planet melts. The melt rises up through the crust and solidifies at or near the surface. These types of rocks, referred to as basalts, are the most common rock on Earth and have also been found on the moon. Based on the composition of the Martian meteorites and the presence of plains and mountains that look like features produced by basaltic volcanism on Earth, geologists expected to find basalts on Mars.

The rocks analyzed by Pathfinder, however, are not basalts. If they are volcanic, as suggested by their vesicular surface texture, presumably formed when gases trapped during cooling left small holes in the rock, their silicon content classifies them as andesites. Andesites form when the basaltic melt from the mantle intrudes deep within the crust. Crystals rich in iron and magnesium form and sink back down, leaving a more silicon-rich melt that erupts onto the surface. The andesites were a great surprise, but because we do not know where these rocks came from on the Martian surface, we do not know the full implications of this discovery. If the andesites are representative of the highlands, they suggest that ancient crust on Mars is similar in composition to continental crust on Earth. This similarity would be difficult to reconcile with the very different geologic histories of the two planets. Alternatively, the rocks could represent a minor proportion of high-silicon rocks from a predominately basaltic plain.



NASA/JET PROPULSION LABORATORY

SANDBLASTED ROCK
named Moe resembles terrestrial rocks known as ventifacts. Their fluted texture develops when sand-size particles hop along the surface in the wind and erode rocks in their path. On Earth, such particles are typically produced when water breaks down rocks. Moe's grooves all point to the northwest, which is roughly the same orientation as the grooves seen on other rocks at the site.

Sedimentary Rocks?

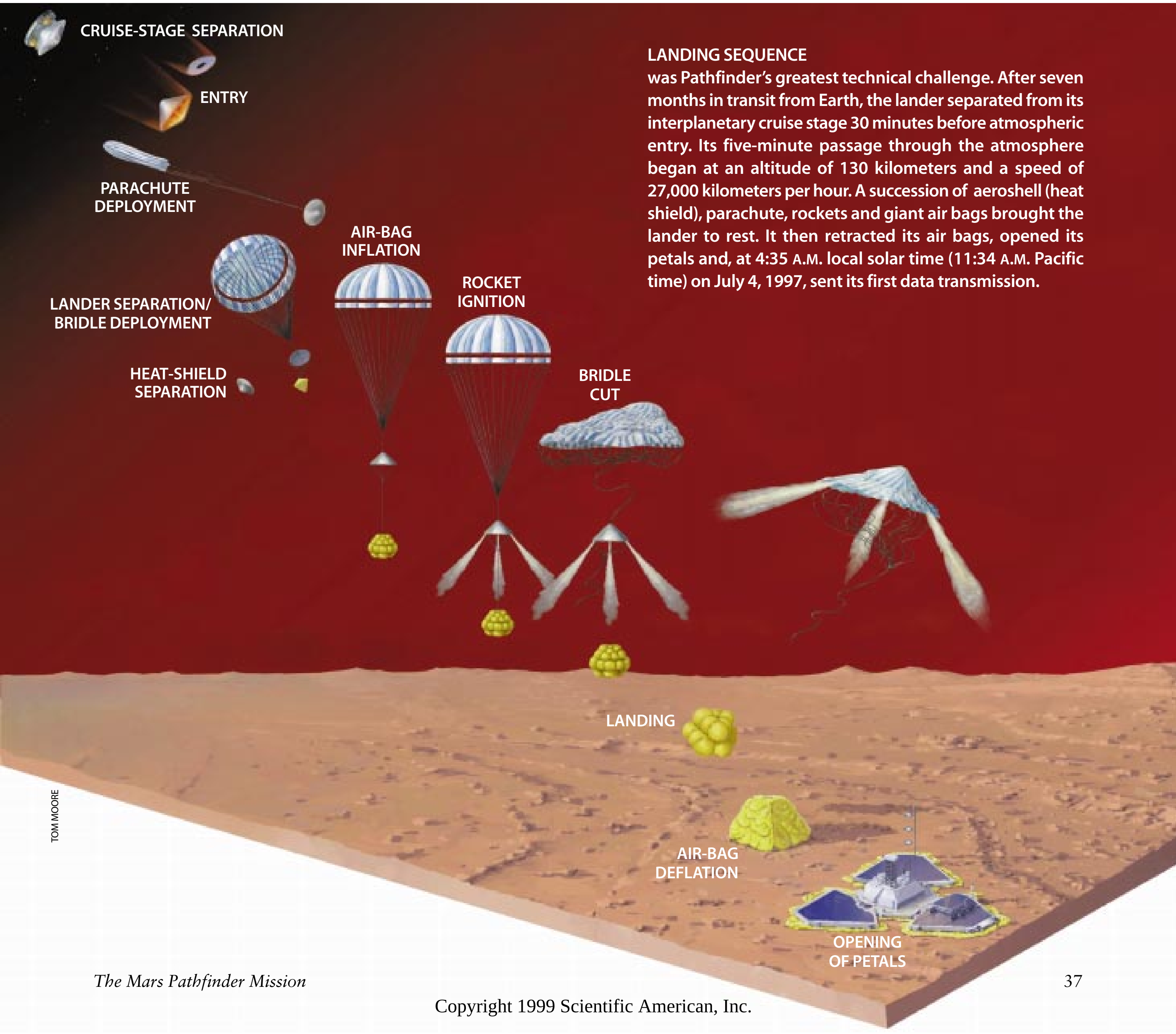
Intriguingly, not all the rocks appear to be volcanic, judging by the diversity of morphologies, textures and fabrics observed in high-resolution images. Some rocks appear similar to impact breccias, which are composed of angular fragments of different materials. Others have layers like those in terrestrial sedimentary rocks, which form by deposition of smaller fragments of rocks in water. Indeed, rover images show many rounded pebbles and cobbles on the ground. In addition, some larger rocks have what look like embedded pebbles and shiny indentations, where it looks as though rounded pebbles that were pressed into the rock during its formation have fallen out, leaving holes. These rocks may be conglomerates formed by flowing liquid water. The water would have rounded the pebbles and deposited them in a sand, silt and clay matrix; the matrix was subsequently compressed, forming a rock, and carried to its present location by the flood. Because conglomerates require a long time to form, if these Martian rocks are conglomerates (other interpretations are also possible) they strongly suggest that liquid water was once stable on the planet and that the climate was therefore warmer and wetter than at present.

Soils at the landing site vary from bright reddish dust to darker-red and darker-gray material, generally consistent with fine-grained iron oxides. Overall, the soils are lower in silicon than the rocks and richer in sulfur, iron and magnesium. Soil compositions are generally similar to those measured at the Viking sites, which are on opposite hemispheres (Viking 1 is 800 kilometers west of Pathfinder; Viking 2 is thousands of kilometers away on the opposite, eastern side of the northern hemisphere). Thus, the soil appears to include materials distributed globally on Mars, such as the airborne dust. The similarity in compositions among the soils implies that the variations in color at each site may be the result of slight differences in iron mineralogy or in particle size and shape [*see top right illustration on next page*].

A bright reddish or pink material also covered part of the site. Similar to the soils in composition, it seems to be indurated or cemented because it was not damaged by scraping with the rover wheels.

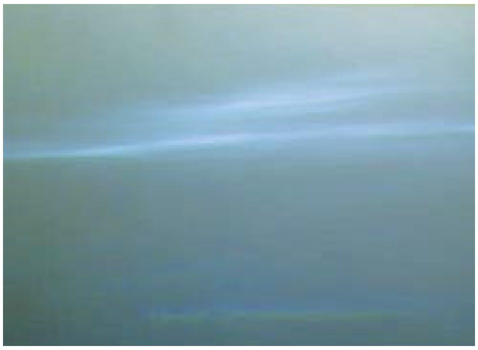
Pathfinder also investigated the dust in the atmosphere of Mars by observing its deposition on a series of magnetic targets on the spacecraft. The dust, it turned out, is highly magnetic. It may consist of small silicate (perhaps clay) particles, with some stain or cement of a highly magnetic mineral known as maghemite. This finding, too, is consistent with a watery past. The iron may have dissolved out of crustal materials in water, and the maghemite may be a freeze-dried precipitate.

The sky on Mars had the same butter-



LANDING SEQUENCE was Pathfinder's greatest technical challenge. After seven months in transit from Earth, the lander separated from its interplanetary cruise stage 30 minutes before atmospheric entry. Its five-minute passage through the atmosphere began at an altitude of 130 kilometers and a speed of 27,000 kilometers per hour. A succession of aeroshell (heat shield), parachute, rockets and giant air bags brought the lander to rest. It then retracted its air bags, opened its petals and, at 4:35 A.M. local solar time (11:34 A.M. Pacific time) on July 4, 1997, sent its first data transmission.

WISPY, BLUE CLOUDS in the dawn sky, shown in this color-enhanced image taken on sol 39 (the 39th Martian day after landing), probably consist of water ice. During the night, water vapor froze around fine-grained dust particles; after sunrise, the ice evaporated. The total amount of water vapor in the present-day Martian atmosphere is paltry; if it all rained out, it would cover the surface to a depth of a hundredth of a millimeter. The basic appearance of the atmosphere is similar to what the Viking landers saw more than 20 years ago.



MULTICOLORED SOILS were exposed by the rover's wheels. The rover straddles Mermaid Dune, a pile of material covered by dark, sand-size granules. Its wheel tracks also reveal dark-red soil (*bottom left*) beneath the bright-reddish dust. Scientists were able to deduce the properties of surface materials by studying the effect that the wheels had on them.

PHOTOGRAPHS BY NASA/JET PROPULSION LABORATORY

scotch color as it did when imaged by the Viking landers. Fine-grained dust in the atmosphere would explain this color. Hubble Space Telescope images had suggested a very clear atmosphere; scientists thought it might even appear blue from the surface. But Pathfinder found otherwise, suggesting either that the atmosphere always has some dust in it from local dust storms or dust devils, or that the atmospheric opacity varies appreciably over a short time. The inferred dust-particle shape and size (a few microns in diameter) and the amount of water vapor in the atmosphere (equivalent to a pitiful hundredth of a millimeter of rainfall) are also consistent with measurements made by Viking. Even if Mars was once lush, it is now drier and dustier than any desert on Earth.

Freezing Air

The meteorological sensors gave further information about the atmosphere. They found patterns of diurnal and longer-term pressure and temperature fluctuations. The temperature reached its maximum of 263 kelvins (–10 degrees Celsius) every day at 2:00 P.M. local solar time and its minimum of 197 kelvins (–76 degrees C) just before sunrise. The pressure minimum of just under 6.7 millibars (roughly 0.67 percent of pressure at sea level on Earth) was reached on sol 21, the 21st Martian day after landing. On Mars the air pressure varies with the seasons. During winter, it is so cold that 20 to 30 percent of the entire atmosphere freezes out at the pole, forming a huge pile of solid carbon dioxide. The pressure

Summary of Evidence for a Warmer, Wetter Mars

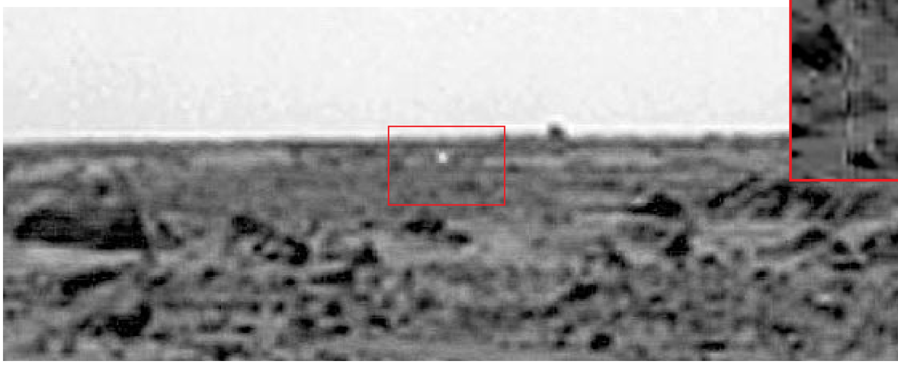
Over the past three decades, scientists have built the case that Mars once looked much like Earth, with rainfall, rivers, lakes, maybe even an ocean. Pathfinder has added evidence that strengthens this case (*red*).

GEOLOGIC FEATURE	PROBABLE ORIGIN	IMPLICATION
Riverlike valley networks	Water flow out of ground or from rain	Either atmosphere was thicker (allowing rain) or geothermal heating was stronger (causing groundwater sapping)
Central channel ("thalweg") in broader valleys	Fluid flow down valley center	Valleys were formed by water flow, not by landslides or sapping
Lakelike depressions with drainage networks; layered deposits in canyons	Flow through channels into lake	Water existed at the surface, but for unknown time
Possible strand lines and erosional beaches and terraces	Possible shoreline	Northern hemisphere might have had an ocean
Rimless craters and highly eroded ancient terrain	High erosion rates	Water, including rain, eroded surface
Rounded pebbles and possible conglomerate rock	Rock formation in flowing water	Liquid water was stable, so atmosphere was thicker and warmer
Abundant sand	Action of water on rocks	Water was widespread
Highly magnetic dust	Maghemite stain or cement on small (micron-size) silicate grains	Active hydrologic cycle leached iron from crustal materials to form maghemite

LISA BURNETT

PIECES OF PATHFINDER

spacecraft show up as bright spots in these highly magnified images. The heat shield (*below*) fell about two kilometers southwest of the lander. The backshell (*right*) landed just over a kilometer to the southeast. These resting places and the location of the lander indicate that a breeze was blowing from the southwest.



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minimum seen by Pathfinder indicates that the atmosphere was at its thinnest, and the south polar cap its largest, on sol 21.

Morning temperatures fluctuated abruptly with time and height; the sensors positioned 0.25, 0.5 and one meter above the spacecraft took different readings. If you were standing on Mars, your nose would be at least 20 degrees C colder than your feet. This suggests that cold morning air is warmed by the surface and rises in small eddies, or whirlpools, which is very different from what happens on Earth, where such large temperature disparities do not occur. Afternoon temperatures, after the air has warmed, do not show these variations.

In the early afternoon, dust devils repeatedly swept across the lander. They showed up as sharp, short-lived pressure changes with rapid shifts in wind direction; they also appear in images as dusty funnel-shaped vortices tens of meters across and hundreds of meters high. They were probably similar to events detected by the Viking landers and orbiters and may be an important mechanism for raising dust into the Martian atmosphere. Otherwise, the prevailing winds were light (clocked at less than 36 kilometers per hour) and variable.

Pathfinder measured atmospheric conditions at higher altitudes during its descent. The upper atmosphere (altitude above 60 kilometers) was colder than Viking had measured. This finding may simply reflect seasonal variations and the time of entry: Pathfinder came in at 3:00 A.M. local solar time, whereas Viking arrived at 4:00 P.M., when the atmosphere is naturally warmer. The lower atmosphere was similar to that measured by Viking, and its conditions can be attributed to dust mixed uniformly in comparatively warm air.

As a bonus, mission scientists were able to use radio communications signals from Pathfinder to measure the rotation of Mars. Daily Doppler tracking and less frequent two-way ranging during communication sessions determined the position of the lander with a precision of 100 meters. The last such positional measurement was done by Viking more than 20 years ago. In the interim, the pole of rotation has precessed—that is, the direction of the tilt of the planet has changed, just as a spinning top slowly wobbles. The difference between the two positional measurements yields the precession rate. The rate is governed by the moment of inertia of the planet, a function of the distribution of mass within the planet. The moment of inertia had been the single most important number about Mars that we did not yet know.

From Pathfinder's determination of the moment of inertia we now know that Mars must have a central metallic core that is between 1,300 and 2,400 kilometers in radius. With assumptions about the mantle composition, derived from the compositions of the Martian meteorites and the rocks measured by the rover, scientists can now start to put constraints on interior temperatures. Before Pathfinder, the composition of the Martian meteorites argued for a core, but the size of this core was completely unknown. The new information about the interior will help geophysicists understand how Mars has evolved over time. In addition to the long-term precession, Pathfinder detected an annual variation in the planet's rotation rate, which is just what would be expected from the seasonal exchange of carbon dioxide between the atmosphere and the ice caps.

Taking all the results together suggests that Mars was once more Earth-like than previously appreciated. Some crustal materials on Mars resemble, in silicon content, continental crust on Earth. Moreover, the rounded pebbles and the possible conglomerate, as well as the abundant sand- and dust-size particles, argue for a formerly water-rich planet. The earlier environment may have been warmer and wetter, perhaps similar to that of the early Earth. In contrast, since floods produced the landing site 1.8 billion to 3.5 billion years ago, Mars has been a very un-Earth-like place. The site appears almost unaltered since it was deposited, indicating very low erosion rates and thus no water in relatively recent times.

Although we are not certain that early Mars was more like Earth, the data returned from Pathfinder are very suggestive. Information from the Mars Global Surveyor, now orbiting the Red Planet, should help answer this crucial question about our neighboring world. SA

Matthew P. Golombek is project scientist of Mars Pathfinder, with responsibility for the overall scientific content of the mission. He conducts his work at the Jet Propulsion Laboratory in Pasadena, Calif. He is chair of the Pathfinder Project Science Group, deputy of the Experiment Operations Team and a member of the project management group. He has written numerous papers on the spacecraft and its results and has organized press conferences and scientific meetings. Golombek's research focuses on the structural geology and tectonics of Earth and the other planets, particularly Mars. This article updates a version that appeared in the July 1998 issue of *Scientific American*.

What's Next for Mars

In the coming decade the planet named for the god of war will be the target of a scientific armada from Earth. Researchers hope to settle many questions about Mars, including whether life ever flourished there

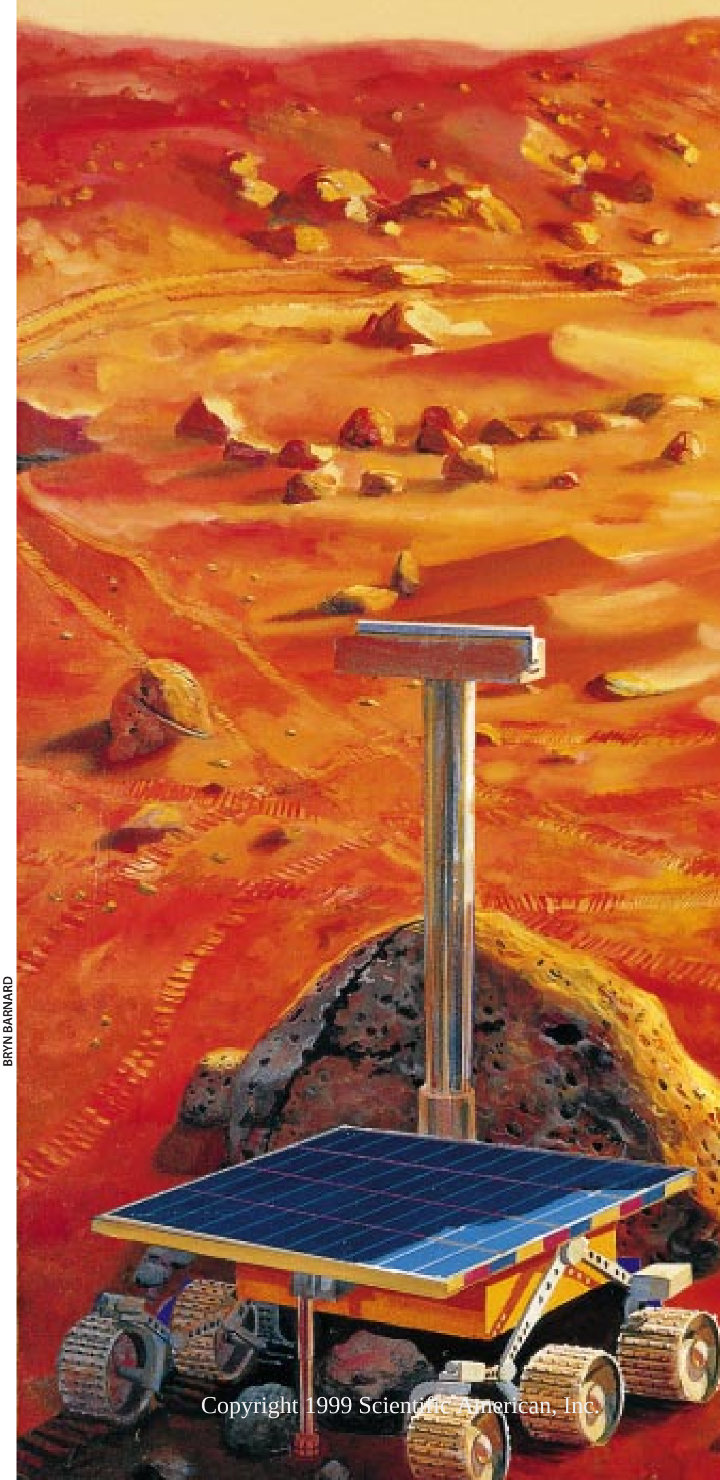
by Glenn Zorpette, *staff writer*

An invasion of Earth by a Martian fleet has been one of the staples of science fiction, from H. G. Wells's 1898 *The War of the Worlds* to the 1996 motion picture *Mars Attacks!* But although there have been many imaginative outpourings from countless writers and directors, few foresaw that the invasion would actually be in the reverse direction, by a robotic fleet from Earth.

Over the next 10 years the National Aeronautics and Space Administration and its European partners plan to send at least four orbiters and four landers to the Martian surface, culminating in a mission that will use highly sophisticated rovers to collect samples of rock and soil that will be delivered to Earth by 2008. The agenda holds out the possibility of seven or so additional trips to the Red Planet, including several relatively inexpensive "micromissions" and a second series of flights that would return dozens more samples between 2008 and 2012. The ambitious series of probes is in addition to the Mars Global Surveyor spacecraft, which has been orbiting the planet since 1997, and a Japanese orbiter called Planet-B, launched last July on a two-year mission to study Mars's atmosphere and ionosphere. Not since the heady days of the space race to the moon more than three decades ago has a single celestial body been the target of so many spacecraft in so short a period.

The upcoming Mars missions are being designed to pursue a couple of relatively well defined goals: expanding what is known about Mars's climate, geology and hydrology, both past and present, particularly in relation to the question of whether life has ever existed on the planet, and laying the groundwork for future human exploration of the planet, possibly as soon as 2020. Robotic vehicles will roam several kilometers, taking scores of samples as part of the most extensive search yet for signs that microbial life persists in the soil below the surface of the red world or that organic matter exists in its rocks or soil.

These goals emerged from the scientific furor over a meteorite found in Antarctica in 1984. Analysis showed that the rock came from Mars, apparently after having been hurled into space when a big meteoroid smashed into the planet 16 million years ago. In 1996 a team of researchers from



BRYN BARNARD

BLASTOFF ON MARS of an ascent vehicle containing a kilogram of Martian soil is planned for 2004. The solid-fuel rocket, a little over a meter tall, will probably destroy the lander as it lofts its precious payload for an orbital rendezvous, two years later, with a spacecraft that will bring it and another set of samples to Earth. But the solar-powered sample-gathering rover (*foreground, at left*) could continue to function for up to a year, transmitting data to Earth via satellites in orbit around Mars.

DENDRITIC PATTERN (*near right*), such as this one photographed in California, is extremely common on Earth. The pattern is similar in some respects to that of box canyons, which have been photographed on Mars by the Viking spacecraft (*center, next page*) and in the Al Ghaydah region of Yemen by a Landsat satellite orbiting Earth (*far right*). Their similarities notwithstanding, box canyons—unlike dendritic streams—are not considered conclusive evidence of rainfall.


WILLIAM GARNETT

the NASA Johnson Space Center and Stanford University announced its conclusion that unusual features of the rock could most plausibly be interpreted as vestiges of ancient Martian bacterial life. Lately a growing number of scientists studying the same evidence have discounted that idea. Nevertheless, says director Norman R. Haynes of the Mars Exploration Directorate at the Jet Propulsion Laboratory in Pasadena, Calif., the surge of interest in the Martian meteorite was a "bombshell" that "raised the question 'What is the proper response of the Mars program?'"

NASA's answer was to focus its planned Mars missions more strongly on the search for evidence of past life and the gathering of data on the history of water and climate on the planet. To make good progress in these reemphasized endeavors, a panel of scientists convened by JPL concluded that it would be necessary to return soil and rock samples from the Red Planet to Earth.

Although the mission is daunting, it has the felicitous quality of being both inspiring to nonscientists and compelling to researchers. Says Steven W. Squyres, a professor of astronomy at Cornell University and the principal investigator of the project to build rovers for the sample-return missions: "To build a robotic field geologist to go to what I find to be the most interesting planet in the solar system and to return samples to distribute them to the best laboratories on Earth—what could be more exciting? If we do our job right, if we get the samples back in one piece, some very interesting science is going to come out of them."

From Earth to Mars

Opportunities to send spacecraft from Earth to Mars—or from Mars to Earth—occur every 26 Earth-months, when the planets are positioned so the trip takes just 10 or 11 months. NASA intends to capitalize on every one of these launch windows until at least 2005. The agency plans to spend about $250 million a year for the next decade or so on Mars exploration, a sum officials hope to augment with contributions of launch vehicles, spacecraft and other hardware from NASA's counterparts in France, Italy and possibly other countries.

NASA's Mars missions constitute a program called Surveyor. The first of the group is the Mars Global Surveyor, an orbiter that arrived at the planet in September 1997. Since then, mission controllers have been easing the spacecraft into a circular polar orbit using a new aerobraking technique. The orbiter's speed is slowed by aerodynamic drag as it grazes the top of Mars's thin atmosphere. Controllers are aerobraking very slowly and gently to minimize stress on one of the craft's solar panels, on which a surface piece has cracked.

The craft carries more advanced sensors than any other orbiter in the Surveyor series. Key instruments include a thermal-emission spectrometer for analyzing the planet's atmosphere and mineral composition from the heat it emits, and two magnetometers for studying the planet's magnetic field. The orbiter's most unique instrument, however, is a visible-light camera capable of resolving surface features as small as about five meters (16 feet). For comparison, the best images of Mars before Global Surveyor—taken during the Viking missions in the late 1970s—have 35-meter resolution.

Mission controllers began operating some of the instruments as soon as the spacecraft went into orbit around Mars. In its very first orbits, Global Surveyor contributed a significant finding: the fact that Mars does not have a global magnetic field. Subsequently, the orbiter dipped beneath the region in which the solar wind interacts with the planet's atmosphere and ionosphere and found that the planet has many small magnetic fields, oriented differently and scattered all over its surface. The discovery is interesting because it gives scientists another clue to the thermal history of the planet. It may help them understand how the planet cooled, thereby placing constraints on the history of water on Mars.

Earth's single magnetic field is generated by the motion of an electrically conductive fluid core, which acts as a kind of dynamo. Mars's many fragmentary fields are be-

U.S. GEOLOGICAL SURVEY

EARTH SATELLITE CORPORATION

lieved to be what was left when the planet's fluid dynamo stopped working, probably because it had solidified. Planetary geologists hope that further study of the remnant fields will reveal when the dynamo became extinguished and how the planet's crust evolved.

This March, after Global Surveyor is in its intended circular orbit, mission controllers will use the spacecraft's laser altimeter to map systematically the surface features of the entire planet. "We'll have a better global topography for Mars than we have for Earth," notes Arden L. Albee, Global Surveyor's project scientist and dean of graduate studies at the California Institute of Technology. The controllers will use the orbiter's camera to shoot relatively low-resolution, wide-angle images of the whole planet each day and to chart daily meteorological changes and seasonal climatic variation.

Higher-resolution images will be crucial for what many scientists regard as the central subject of Mars studies: the history of liquid water on the planet. Researchers have abundant evidence that liquid water, a necessary requirement for life as we know it, once sculpted Mars's surface. They do not know, however, whether that water came from rain or from permafrost that was occasionally but only temporarily converted to liquid water—and even massive flash floods—by catastrophic events such as lava flows and meteorite strikes. The distinction is important because many scientists believe that life could not have flourished without rain. Rain could only occur, they note, in a wet, warm atmosphere, above a surface on which liquid water was stable—and which could therefore support life.

A strong sign that rain once fell on a piece of land is evidence of dendritic streams, in which successively smaller tributaries branch out from fewer, larger ones, like limbs on a tree. So far this pattern has never been seen unambiguously on Mars—but if it exists there, Global Surveyor's high-resolution camera will be able to distinguish it. According to Albee, basically all the evidence seen on Mars of ancient streams is in formations that resemble box canyons on Earth. Box canyons are formed when water seeps out between layers in a cliff and flows down, eroding the soil and rock underneath. They are evidence of flowing water but not necessarily of rainfall.

"Nothing that we've seen so far," Albee notes, "rules out Mars having lost most of its atmosphere very early on"—perhaps 3.5 billion to 3.9 billion years ago, only a few hundred million years after the planet formed. If that was the case, then the chances that Mars ever had large amounts of liquid water on its surface for extended periods are slim indeed.

Global Surveyor's planetwide studies will be extended by the next mission in the series, Mars Surveyor 1998, which includes an orbiter and lander that were launched separately. The Mars Climate Orbiter, which left Earth last December 11, will arrive at Mars this coming September. Like Global Surveyor, the Climate Orbiter will fly in a nearly circular polar orbit and will carry a sophisticated thermal sensor, a camera and a radio transceiver for relaying signals from landers to Earth. The Climate Orbiter's thermal sensor, technically an infrared radiometer, will sense atmospheric variations in temperature, pressure, and concentrations of dust, water vapor and condensates.

The other half of the recently launched Surveyor pair is the Mars Polar Lander, which blasted off early this year and is expected to descend next December to a spot near the northern edge of the planet's southern polar region. Mars's polar caps are of particular interest because they are believed to contain a sizable part of the planet's water, as ice. One of the craft's key goals is to dig down with its robotic arm into the layered deposits of dust, carbon dioxide ice and snow and possibly water ice, to determine mineralogical compositions and to try to piece together a record of how the planet's climate changed in geologically recent times.

Another novel feature of the Polar Lander will be its two "passengers." These microprobes, as they are known, will ride to Mars attached to the lander, each one underneath a solar panel. Just before the lander enters the planet's atmosphere, it will separate from a structural piece, called a cruise ring, to which the microprobes will remain attached for another 18 seconds. Then they, too, will separate and plunge through the atmosphere, smashing into the planet about 50 to 100 kilometers away from where the lander touches down.

The microprobes are built to withstand the shock, separating on impact into two units, one of which will penetrate up to two meters into the soil to analyze it. The other will transmit the experimental results to the Global Surveyor for retransmission to Earth.

The parade from blue planet to Red Planet will continue in the spring of 2001, when NASA plans to launch another pair of Surveyors, a lander and an orbiter. The Mars Surveyor 2001 orbiter will carry a high-resolution infrared-imaging spectrometer and a gamma-ray spectrometer for mapping the distribution of minerals and elements, respectively, on the surface. The gamma-ray device will also indicate the abundance of hydrogen just below the surface.

"I see the 2001 mission as pivotal in the program," says R. Stephen Saunders, the project scientist for the mission. "It's the end of one era and the beginning of another in Mars exploration. It will complete the global characterization of Mars"—and add to the "data set we need to find the right rocks on Mars, the rocks that are the most promising in the search for evidence of past life on Mars." After 2001, Saunders notes, NASA's missions to Mars will concentrate on returning samples and on preparing for possible human exploration of the planet.

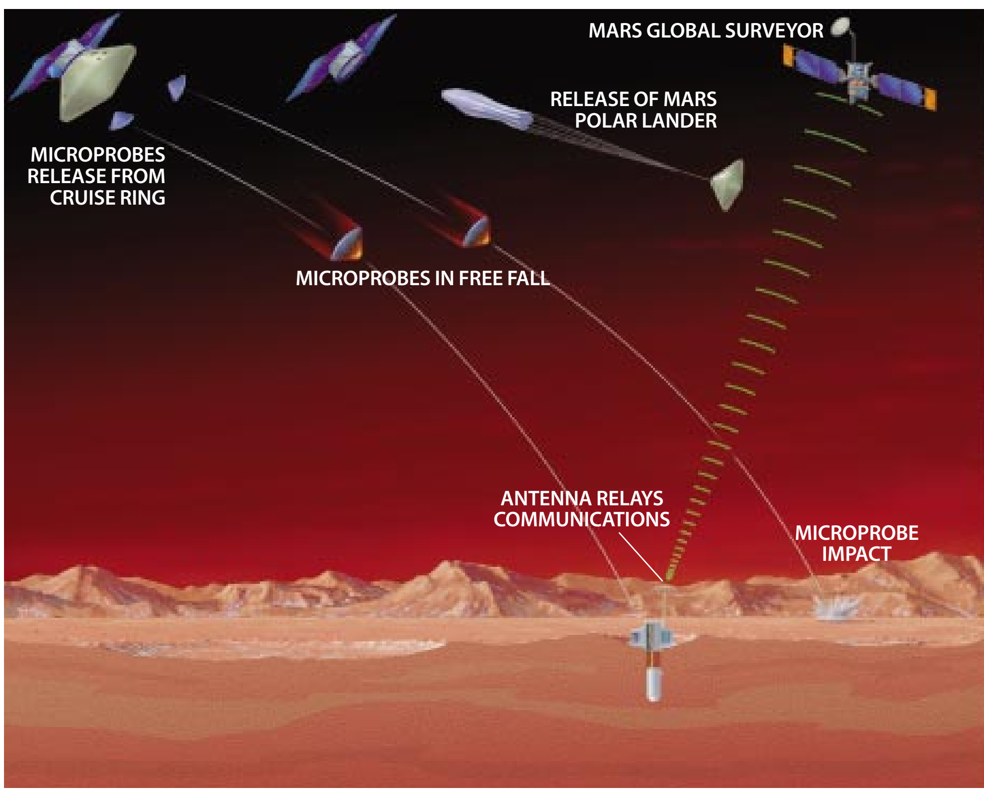
The 2001 lander will start laying the groundwork, so to speak, for these rousing goals. It will carry an infrared spectrometer, the first on a landing craft, to study the mineral composition of nearby rocks. It will also deliver a small roving vehicle. Most stirringly, perhaps, the 2001 lander will perform the first experiments aimed at finding out how harmful the Martian environment would be to people and whether rocket fuel could be made from the atmosphere.

Attached to the experiments is an essential NASA imprimatur—an acronym: HEDS, for Human Exploration and Development of Space. Some of these experiments will make use of a robotic arm, attached to the lander, that will dig up soil samples for chemical and microscopic analyses. HEDS specialists are keenly interested in the size of the smallest particles of quartz in Mars's soil. Grains smaller than about two or three microns are hazardous to humans. Inhaled into the lungs, the particles irritate the tissue and cause the formation of nodules, leading to a black-lung-like ailment known as silicosis. On Earth, water pushes quartz grains that small down into the soil. But the particles may be abundant on Mars's surface, which lacks liquid water.

In another HEDS experiment, a particle spectrometer will measure the radiation doses to which humans would be exposed on Mars. The sensor, known as the Martian Radiation Environment Experiment, will record the energy of the protons, neutrons and cosmic-ray particles bombarding Mars from space.

The third HEDS project on the 2001 lander will make liquid oxygen, a key component of rocket fuel. This "in situ propellant production" experiment will take in carbon dioxide, which constitutes 95 percent of Mars's atmosphere, and break it down to produce oxygen. The demonstration will be important because almost all scenarios for human exploration of Mars require the production on the planet of liquid oxygen, and possibly also hydrogen or methane, to fuel the return trip to Earth. Hauling enough fuel to Mars for the return trip would be impractical because it would necessitate an extremely costly launch vehicle [see "Sending Humans to Mars," on page 46].

The 2001 lander will also have a rover, called Marie Curie, which will be a twin of the Sojourner rover that captivated millions during its geologic field trip around the Pathfinder landing site in 1997. Sojourner traveled a total of 106 meters, investigating several rocks with an alpha-proton x-ray spectrometer, a key instrument that will have an encore on the Marie Curie rover. The system aims a stream of helium nuclei, also known as alpha particles, at a sample of rock or dust to determine its composition. The particles stimulate chemical elements in the rock to emit alpha particles, protons and x-rays. The intensity of the emitted radiation at different wavelengths reveals the proportions of different elements in the rock. This information, in turn, suggests which minerals may be present and also offers insights into how the



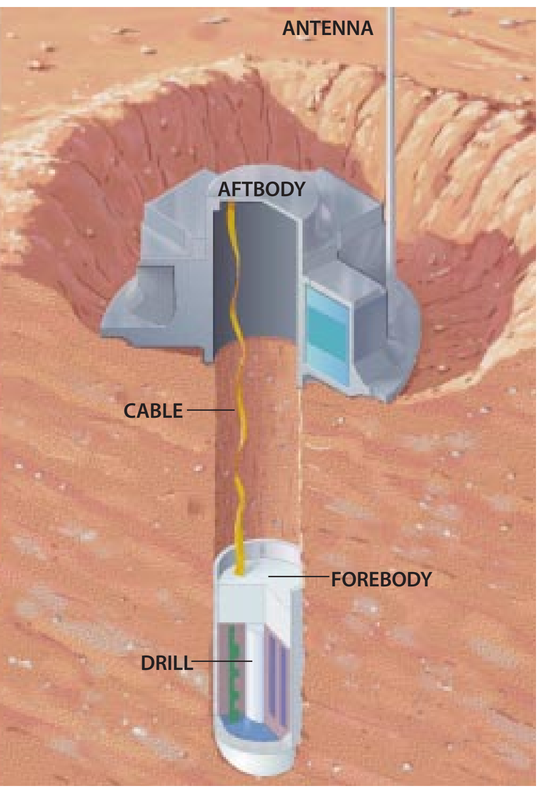
MARS MICROPROBES
will separate from the Mars Polar Lander shortly before entry into the planet's atmosphere in December 1999 (*near right*). The two units will each divide on impact into two pieces connected by a cable. One part will burrow up to two meters into the Martian soil and make measurements of ground temperature, water and other characteristics (*far right*). The other piece will remain on the surface and transmit the data to an orbiter for retransmission to Earth.

rock weathered, how the planetary crust around it formed and whether water came into contact with it in the past.

Field Geology on Mars

Marie Curie's alpha-proton x-ray spectrometer is one of four instruments collectively known as APEX, for Athena Precursor Experiment. Athena is the name of the rover being designed for the sample-return missions expected to be launched in 2003 and 2005. This highly sophisticated vehicle will identify and collect geologically interesting bits of Mars that will be returned to the landers, collected in a capsule and blasted off for a rendezvous with a spacecraft that will carry them to Earth.

The three other APEX instruments are a panoramic camera, a thermal-emission spectrometer and a Mössbauer spectrometer, which detects iron-bearing minerals. Such minerals, which probably predominate on Mars, offer clues to early environmental conditions. For the 2001 mission, the three systems will be on the lander, where they will function in concert with Marie Curie's alpha-proton device. Starting with the panoramic camera, controllers will be able to get an overview of the formations in an area, for which the thermal-emission spectrometer will give them a quick scan of mineralogical content. Then the controllers will zero in on the most geologically intriguing rocks with the Mössbauer and alpha-proton devices, which will provide more detailed information on mineralogical and elemental content.



TOM MOORE

For the 2003 and 2005 sample-return missions, all four of the instruments will be installed on the Athena rovers. As with the 2001 mission, controllers will use the panoramic camera and the thermal-emission spectrometer to pick the most interesting areas to explore and then use the other instruments to make more detailed tests on specific rocks and to select the best ones to sample from among the countless possibilities.

For that task, the Athena rovers will have another powerful, high-tech tool: a Raman spectrometer, the first ever to be transported into space. Such systems are now used in mineralogical and even medical applications, but the units are relatively large and delicate. Engineers at JPL are now at work on a tiny, rugged unit for inclusion on the Athenas. The Raman spectrometers will be the only instruments on board the Athena rovers that will be capable of detecting organic matter.

Two decades ago the Viking landers found evidence that Mars's atmosphere contains trace quantities of a strong oxidizing agent, possibly hydrogen peroxide. It would probably destroy any organic matter that might have once been on the outside of rocks or on top or just below the surface of the soil, so each Athena rover will be equipped to get samples from inside the rocks. As it identifies worthy candidates, the rover will drill into them with a "mini-corer" to extract samples. Using a mere 30 watts, the ingenious miniaturized system will take core samples of boulders and bedrock by drilling into them with concentric bits rotating at the same speed.

The Athena rover will store a few samples in a canister and then bring the canister back to the lander, inserting it into a container at the top of a Mars Ascent Vehicle, a solid-fuel rocket that will later launch the container into orbit around the planet. The rover will then repeat the procedure two or three more times, each time making successively farther excursions from the lander and depositing another canister in the ascent vehicle's nose. The 2003 and 2005 landers will also each have a robotic arm capable of taking samples close by the craft. All told, controllers hope they will be able to load as many as 40 samples weighing less than a kilogram in total.

On the 2003 and 2005 missions, the launch of the Mars Ascent Vehicle with the sample container will most likely destroy the lander, but the Athena rovers are expected to keep gathering and analyzing samples and radioing their findings to orbiters. The rovers may keep on truckin' for up to an Earth-year, traveling perhaps 10 or 20 kilometers.

Meanwhile the container and its precious contents will orbit the planet. The current plan is to send up the container from the 2003 mission and let it orbit for a couple of years, until the container from the 2005 mission can be similarly lofted. Both containers will then be retrieved in orbit by a spacecraft to be built under the aegis of the French space agency, CNES. That craft will have to not only dock with the containers but also insert them within an Earth-entry capsule and fly them back to Earth, where they will plunge through the atmosphere for a crash landing, probably in a desert in the western U.S.

Many aspects of the mission are daunting, perhaps none more than designing the sample canisters, which will have to interface with the lander, the rover, the ascent vehicle, the French-built spacecraft and the Earth-entry capsule. The canisters will also have to be tough enough to withstand an Earth landing that will probably be fairly ballistic.

The current NASA plan holds out the possibility of another round of sample-return missions, should the funds materialize, in 2007 and 2009. Administrators are also angling for five or more relatively low cost "micromissions," in which small spacecraft would "piggyback" on European Ariane 5 launch vehicles to a high-Earth orbit, from which they could get to the Red Planet using a lunar-gravity assist. They hope to use the micromissions to find landing sites for the sample-return missions, validate new technologies, relay communications or perhaps chemically analyze some samples before sending other ones to Earth.

Ten years from now scientists will have, at the very least, a much more complete and detailed picture of how Mars—and our solar system—came to be what it now is. Evidence that life flourished in the past or persisted in the present would be stunning, giving researchers their first hard data on one of the most profound and elusive of subjects: the prevalence of life in the universe. But even if Mars turns out to be as beautifully desolate as its ruddy landscapes seem, the mysterious world that has fascinated humanity for so long will at last begin yielding some of its ancient secrets. SA

A leading advocate of manned missions to Mars outlines a plan to land astronauts on the Red Planet in the next decade

Sending Humans to Mars

by Robert Zubrin

SAIC; PAT RAWLINGS

"Space is there, and we are going to climb it." These words from President John F. Kennedy in 1962 set forth the goal of sending an American to the moon within the decade. But for most of the 30 years since the Apollo moon landing, the U.S. space program has lacked a coherent vision of what its next target should be. The answer is simple: the human exploration and settlement of Mars.

This goal is not beyond our reach. No giant spaceship built with exotic equipment is required. Indeed, all the technologies needed for sending humans to Mars are available today. We can reach the Red Planet with relatively small spacecraft launched directly to Mars by booster rockets embodying the same technology that carried astronauts to the moon more than a quarter-century ago. The key to success lies with the same strategy that served the earliest explorers of our own planet: travel light and live off the land. The first piloted mission to Mars could reach the planet within a decade. Here is how the proposed plan—what I call the Mars Direct project—would work.

At a not too distant date, in 2005 perhaps, a single, heavy-lift booster rocket with a capability equal to that of the Saturn 5 rockets from the Apollo era is launched from Cape Canaveral. When the ship is high enough in Earth's atmosphere, the upper stage of the rocket detaches from the spent booster, fires its engine and throws a 45-metric-ton, unmanned payload on a trajectory to Mars.

This payload is the Earth Return Vehicle, or ERV, which, as the name implies, is built to bring astronauts back to Earth from Mars. But on this voyage no humans are on board; instead the ERV carries six tons of liquid-hydrogen cargo, a set of compressors, an automated chemical-processing unit, a few modestly sized scientific rovers, and a small 100-kilowatt nuclear reactor mounted on the back of a larger rover powered by a mixture of methane and oxygen. The ERV's own methane-oxygen tanks that will be used during the return trip are unfueled.

Arriving at Mars eight months after takeoff, the ERV slows itself down with the help of friction between its heat shield and the planet's atmosphere, in a technique known as aerobraking. The vehicle eases into orbit around Mars and then lands on the surface with the help of a parachute and retrorockets. Once the ship has touched down, scientists back at mission control on Earth telerobotically drive the large rover off the ERV and move it a few hundred meters away. Mission control then deploys the nuclear reactor, which will provide power for the compressors and the chemical-processing unit.

Inside this unit, the hydrogen brought from Earth reacts with the Martian atmosphere—which is 95 percent carbon dioxide (CO_2)—to produce water and methane (CH_4). This process, called methanation, eliminates the need for long-term storage

HUMAN EXPEDITION TO MARS
would allow astronauts to search for signs of past or present life on the Red Planet, a task that people are far better suited to than robots are. A manned mission to Mars could have explorers on the planet's surface by 2008.

of cryogenic liquid-hydrogen fuel, a difficult task. The resulting methane is liquefied and stored, and the water molecules are electrolyzed—broken apart into hydrogen and oxygen. The oxygen is then reserved for later use; the hydrogen is recycled through the chemical-processing unit to generate more water and methane.

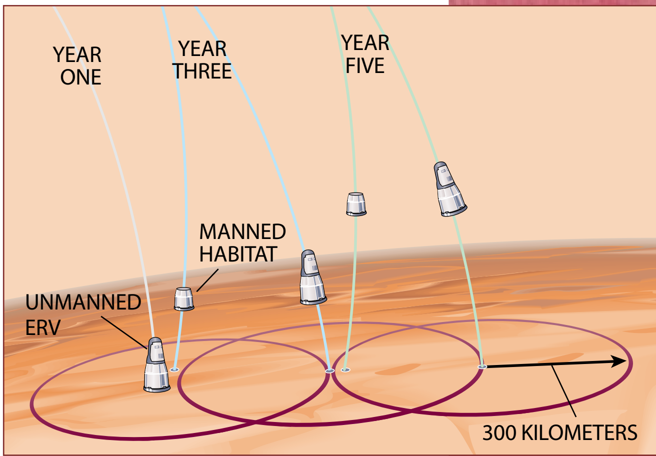
Ultimately, these two reactions, methanation and the electrolysis of water, provide 48 tons of oxygen and 24 tons of methane, both of which will eventually be burned as rocket propellant for the return voyage. To ensure that the mixture of methane and oxygen in the propellant will burn efficiently, an additional 36 tons of oxygen must be generated by breaking apart the CO_2 in the Martian atmosphere. The entire process takes 10 months, at the end of which a total of 108 tons of methane-oxygen propellant has been generated—18 times more propellant for the return trip than the original feedstock needed to produce it.

The journey home will require 96 tons of propellant, leaving an extra 12 tons for the operation of the rovers. Additional stockpiles of oxygen can also be produced, both for breathing and for conversion into water, by reacting the oxygen with the hydrogen brought from Earth. The ability to produce oxygen and water on Mars greatly reduces the amount of life-supporting supplies that must be hauled from Earth.

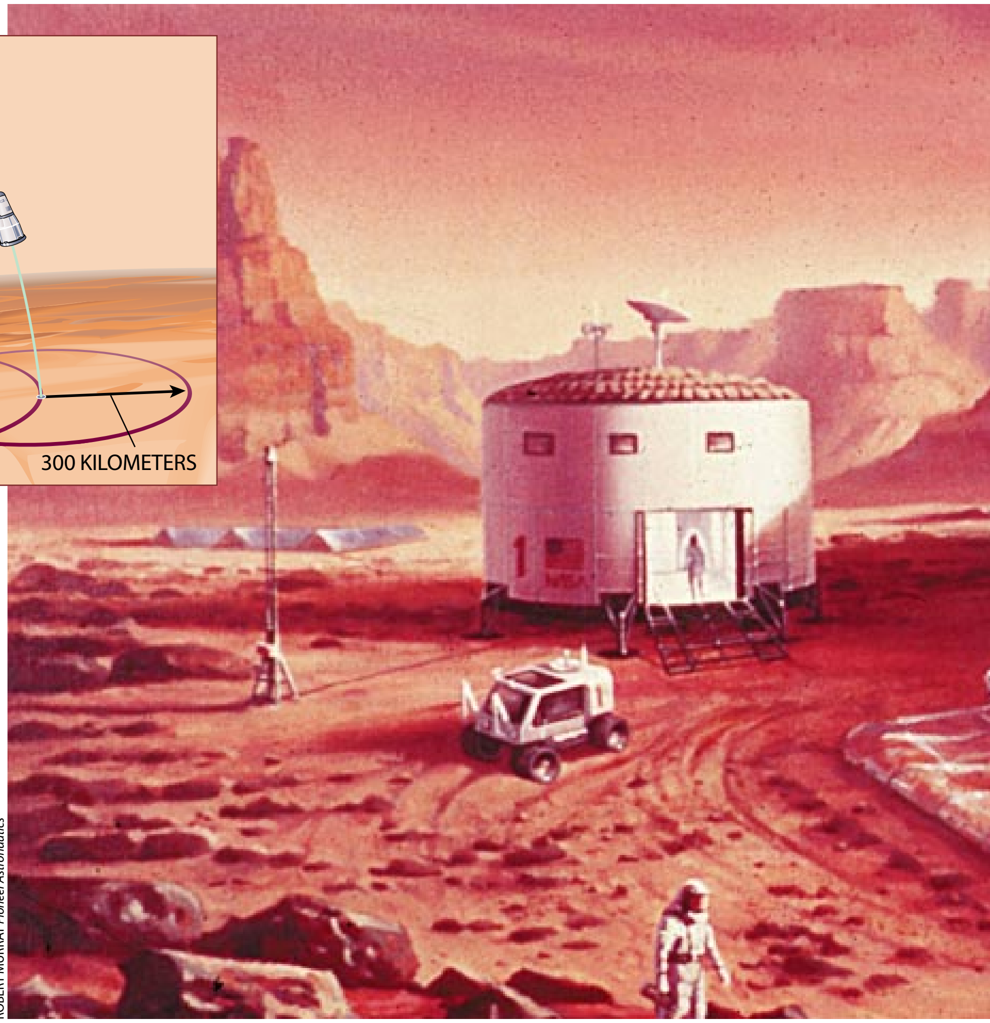
The Astronauts Arrive

With this inaugural site on Mars operating successfully, two more boosters lift off from Cape Canaveral in 2007 and again hurl their payloads toward Mars. One of these payloads is an unmanned ERV just like that launched in 2005. The other, however, consists of a manned vessel with a crew of four men and women with provisions to last three years. The ship also brings along a pressurized methane-oxygen-powered ground rover that will allow the astronauts to conduct long-distance explorations in a shirtsleeve environment.

During the trip, artificial gravity as strong as that found on Mars can be produced by first extending a tether between the inhabited module and the burned-out booster rocket's upper stage; the entire assembly is then allowed to spin. On arrival at



IAN WORPOLE



ROBERT MURRAY *Pioneer Astronautics*

MARS DIRECT PLAN
begins with the launch of an unmanned Earth Return Vehicle, or ERV, that will, on landing on Mars, manufacture its own propellant, thereby laying the groundwork for the arrival of astronauts. Two years later a manned spacecraft and another unmanned ERV blast off for the Red Planet; the astronauts head for the previous landing site, while the unmanned craft prepares for the next manned mission, scheduled to arrive in another two years. The project can continue for as long as desired, leaving behind a string of base camps across the Martian surface. During their year-and-a-half stay on Mars, astronauts would most likely inhabit a camp similar to the one shown in this artist's conception, complete with a habitat (*left*), a greenhouse (*foreground*) and an ERV (*right*).

Mars, the manned craft drops the tether to the booster, aerobrakes and then lands at the 2005 site.

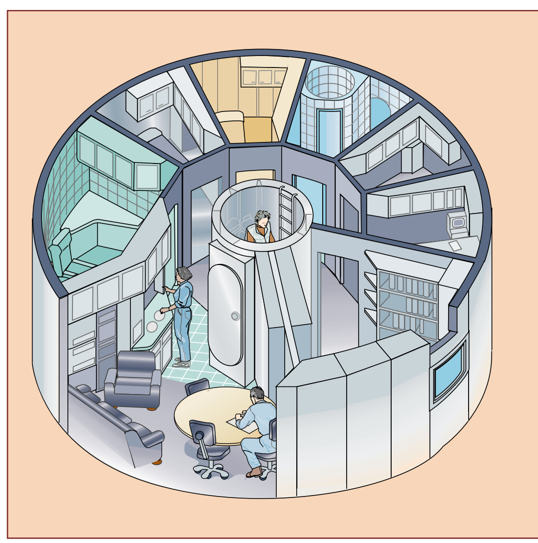
Beacons at the original location should enable the ship to touch down at just the right spot, but if the landing is off course by tens or even hundreds of kilometers, the astronauts can still drive to the correct location in their rover. And in the unlikely event that the ship sets down thousands of kilometers away, the second ERV that was launched with the manned vessel serves as a backup system. If that should fail, the extra rations sent along ensure that the crew can survive until a third ERV and additional supplies can be sent in 2009.

But with current technology, the chances of a misguided landing are small. So assuming the astronauts reach the 2005 location as planned, the second ERV touches down several hundred kilometers away. This new ERV, like its predecessor, starts making propellant, this time for the 2009 mission, which in turn will fly out with an additional ERV to open up a third Mars site.

Thus, under the Mars Direct plan, the U.S. would launch two heavy-lift booster rockets every other year: one to dispatch a team of four people to inhabit Mars and the other to prepare a new site for the next mission. The average launch rate of one a year is only about 15 percent of the rate that the U.S. currently launches space shuttles and is clearly affordable. In effect, the live-off-the-land strategy used by the Mars Direct plan removes the prospect of a manned mission to Mars from the realm of megaspacecraft fantasy and renders it a task comparable in difficulty to the launching of the Apollo missions to the moon.

The men and women sent to Mars will stay on the surface for one and a half years, taking advantage of the ground vehicles to conduct extensive exploration of the surface. With a 12-ton stockpile of fuel for these trucks, the astronauts can travel more than 24,000 kilometers during their stay, giving them the kind of mobility necessary to conduct a serious search for evidence of past or present life—an investigation that is key to revealing whether life is a phenomenon unique to Earth or commonplace throughout the universe.

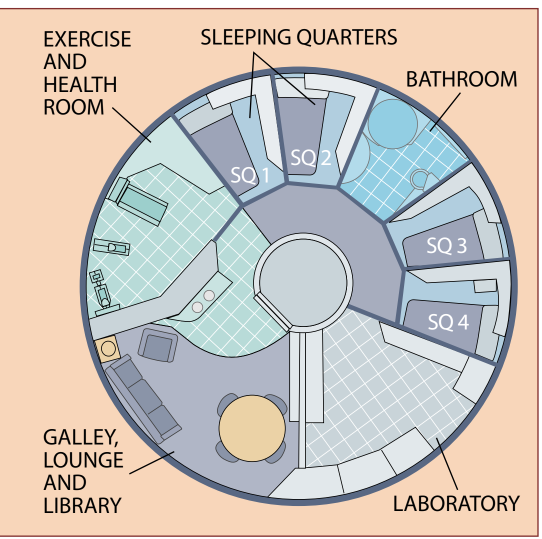
Because no one will be left in orbit, the crew will benefit from the natural gravity and protection against radiation offered by the Martian environment. As a result,



there is no need for a quick return to Earth, a complication that has plagued conventional mission plans that consist of an orbiting mother ship and small landing parties sent to the surface. At the conclusion of their stay, the Mars astronauts will return by direct flight in the ERV. As the series of missions progresses, a string of small bases will be left behind on the planet, opening broad stretches of Mars to continued human exploration and, eventually, habitation.

In 1990, when my colleague David A. Baker and I (we were then both at Martin-Marietta) first put forward the basic Mars Direct plan, the National Aeronautics and Space Administration viewed it as too radical to consider seriously. But over the past couple of years, with encouragement from Michael Griffin, NASA's former associate administrator for exploration, as well as from the current head of NASA, Daniel S. Goldin, the group in charge of designing human missions to Mars at the NASA Johnson Space Center decided to take another look at our idea.

In 1994 researchers there produced a cost estimate for a program based on an expanded version of the Mars Direct plan that had been scaled up by about a factor of two. Their result: $50 billion. Notably, in 1989 this same group assigned a $400-billion price tag to the traditional, cumbersome approach to a manned mission to Mars based on orbital assembly of megaspacecraft. I believe that with further discipline in the design of the mission, the cost could be brought down to the $20-billion to $30-billion range. Spent over 10 years, this amount would constitute an annual expenditure of about 20 percent of NASA's budget, or around 1 percent of the U.S. military's budget. It is a small price to pay for a new world.



HOME SWEET HOME on Mars might resemble this habitat, or "hab." The upper deck of the hab (*shown*) would have sleeping quarters for four people as well as a laboratory, library, galley and gym. The solar-flare storm shelter would be located in the center of the structure. The lower deck of the hab would serve as a garage, workshop and storage area.

Killing the Dragons

Nevertheless, there are plenty of opponents to the idea of sending people to Mars; these critics frequently cite several issues, which they claim make such missions too dangerous to be considered at this time. Like the dragons that once marred the maps of medieval cartographers, these fears have deterred many who otherwise might be willing to support this mission. It is therefore fitting to address these considerations here.

One of the most common concerns is the allegation that the radiation doses involved in a Mars mission present insuperable risks or are not well understood. This is untrue. Solar flare radiation, consisting of protons with energies of about one million electron volts, can be shielded by 12 centimeters (five inches) of water or provisions, and there will be enough materials on board the ship to build an adequate pantry storm shelter for use in such an event. The residual cosmic-ray dose, about 50 rem for the 2.5 year mission, represents a statistical cancer risk of about 1 percent, roughly the same as the risk from smoking for the same amount of time.

The hazards of zero gravity have caused concern among other critics. Cosmonauts have experienced marked physiological deterioration after extended stays in zero gravity on the Russian space station. Yet in 1996 American astronaut Shannon W. Lucid spent six months in zero gravity [see "Six Months on Mir," by Shannon

W. Lucid; Scientific American, May 1998]. Because she actually implemented the rigorous exercise program designed by NASA flight surgeons, she returned to Earth in acceptable physical condition, able to walk off the shuttle despite the pull of Earth's gravity. And, as I mentioned earlier, the manned ships going to Mars could be flown employing artificial gravity generated by rotating the spacecraft. The engineering challenges associated with designing such systems are modest and make the issue of zero-gravity health effects during interplanetary missions moot.

Recently some people have raised the possibility of back-contamination of our planet as a reason to shun human missions to Mars (or even sample-return trips carried out by robots). Such fears have no basis in science. The surface of Mars is too cold for liquid water, it is exposed to a near vacuum and to ultraviolet and cosmic radiation, and it contains an antiseptic mixture of peroxides that have eliminated any trace of organic material. The surface of Mars is as sterile an environment as one could ask for. And even if there were life deep underground, it is quite impossible that these life-forms would pose a threat to terrestrial animals and plants. Pathogens are specifically adapted to their hosts, and there are no highly developed animals or plants to support a pathogenic life cycle in the Martian subsurface groundwater. In any case, Earth currently receives about 500 kilograms (1,100 pounds) of Martian material each year in the form of meteorites that originated on Mars and were blown into space by meteoric impacts. The trauma that this material has experienced during ejection from Mars, the trip to Earth and entry into Earth's atmosphere is insufficient to have sterilized it. If there is the Red Death on Mars, we already have it. Members of the space community who are concerned with public health matters would do much better to offer assistance to medical relief agencies fighting infectious diseases such as HIV and tuberculosis here on Earth.

Another issue mentioned frequently by the popular media is the concern that the isolation and stress of a 2.5-year round-trip mission to Mars present forbidding difficulties. On consideration, there is little reason to believe that this is true. Compared with the stresses dealt with by previous generations of explorers, mariners, prisoners, soldiers in combat and refugees in hiding, the adversities that will be faced by the hand-picked crew of a Mars mission seem extremely modest. In fact, history indicates that the human psyche, far from being the weak link in the chain of the piloted Mars mission, is very likely to be the strongest.

Mars does have intermittent local, and occasionally global, dust storms with wind speeds up to 200 kilometers per hour (125 miles per hour). Attempting to land during such an event would certainly be a bad idea (in 1971 the Soviets lost two unmanned Mars probes this way). Once a ship is on the ground, however, the storms present little danger. The atmosphere on Mars has only about 1 percent the density of Earth's atmosphere at sea level. Thus, a wind with a speed of 200 kph on Mars exerts the same force as a 20-kph wind on Earth—really just a moderate breeze. The Viking landers endured many such storms with no damage.

Mass Allocation for Earth Return Vehicle

ERV Component	Metric Tons
ERV cabin structure	3.0
Life-support system	1.0
Consumables	3.4
Solar array (5 kilowatts of electricity)	1.0
Reaction control system	0.5
Communications and information management	0.1
Furniture and interior	0.5
Space suits (4)	0.4
Spares and margin (16 percent)	1.6
Aeroshell	1.8
Rover	0.5
Hydrogen feedstock	6.3
ERV propulsion stages	4.5
Propellant production plant	0.5
Nuclear reactor (100 kilowatts of electricity)	3.5
ERV total mass	28.6

DON DIXON

Political Problems

Humans are more than a match for Mars's dragons, but thus far politicians have been unwilling to step up to the challenge. Indeed, in the three decades since the success of the Apollo missions, we have witnessed a failure of vision of astonishing dimension. It is as though Ferdinand and Isabella had responded to the returning Christopher Columbus with a shrug. Nevertheless, the public has made it apparent, through such demonstrations as the 566 million

Consumable Requirements for Mars Direct Mission with Crew of Four

	Daily need per person (kilograms)	Percent recycled	Daily waste per person (kilograms)	Payload for 200-day return flight (kilograms)	Payload for 600-day stay on surface (kilograms)
Oxygen	1.0	80	0.2	160	0
Dry food	0.5	0	0.5	400	1,200
Whole food	1.0	0	1.0	800	2,400
Potable water	4.0	80	0.0	0	0
Wash water	26.0	90	2.6	2,080	0
Total	32.5	87	4.3	3,440	3,600

JOHNNY JOHNSON

EARTH RETURN VEHICLE blasts off from the surface of Mars with a crew of four on board. The trip back to Earth will take approximately six months.

hits on NASA's Mars World Wide Web site the month Pathfinder reached Mars's surface, that there is massive popular support for the exploration of Mars.

To mobilize this support, both to pressure the U.S. and other governments for an expanded Mars effort, including robotic and human exploration, and to initiate privately funded exploration, the Mars Society was formed in 1998. As its first private project, the society is building a Mars simulation base at the Haughton meteorite impact crater on Devon Island in the Canadian Arctic. Because of its geologic and climatic similarities to the Red Planet, this area has been of interest to NASA scientists for some time. The society's Mars Arctic Research Station, or MARS, will support a greatly expanded study of this environment and will provide a location for field-testing prototype equipment, including habitation modules, ground-mobility systems, photovoltaic systems and specialized drilling rigs. The current plan is to have the Devon Island MARS base operational by the summer of 2000. This should be possible on a budget of about $1 million.

We hope that the credibility earned through this project will enable the society to expand its financial resources. It could then help fund robotic missions to Mars and, eventually, human expeditions, perhaps on a cost-sharing basis with NASA or other government agencies. But it is clear that the fastest way to send humans to Mars is to show the government why it should invest in this endeavor. The society has therefore launched an educational campaign directed toward politicians and other power brokers.

Why We Must Go to Mars

In the summer of 1996, in one of the most exciting announcements in history, NASA scientists revealed a rock ejected from Mars by meteoric impact that showed evidence of life on the Red Planet in the distant past. If this discovery could be confirmed by finding actual fossils on the Martian surface, it would, by implication, suggest that our universe is filled with life and probably intelligence as well. From the point of view of humanity learning its true place in the universe, this would be the most important scientific enlightenment since Copernicus. Although unmanned rovers can conduct a certain amount of the search for life on Mars, the best field-work requires the ability to travel long distances across very rough terrain, climb steep slopes, and do both heavy lifting and delicate sorting, as well as exercise on-the-spot intuition. All these skills are far beyond the abilities of robotic rovers. Field paleontology requires human explorers, live rockhounds on the scene.

There are additional reasons to send humans to Mars. Nations, like people, thrive on challenge; they languish without it. The space program needs a challenge. Consider these statistics: Between 1961 and 1973, with the impetus of the moon race, NASA produced technological innovations at a rate several orders of magnitude greater than that it has shown since. Even so, NASA's average budget in real dollars then was only about 20 percent more than today ($16 billion 1998 dollars compared with $13 billion). Why the enhanced productivity? Because NASA had a goal that forced its reach to exceed its grasp. Far from being a waste of money, having NASA take on the challenge of a manned mission to Mars is the key to giving the nation a real return for its space dollars.

Such a program would also serve as an invitation to adventure for children around the world. There will be some 100 million kids in U.S. schools over the next 10 years. If a Mars program were to inspire just an additional 1 percent of them to pursue scientific educations, the net result would be one million more scientists, engineers, inventors, medical researchers and doctors.

Mars is the New World. Someday millions of people will live there. What language will they speak? What values and traditions will they cherish as they move from there to the solar system and beyond? When they look back on our time, will any of our other actions compare in value with what we do now to bring their society into being? Today we have the opportunity to be the parents, the founders, the shapers of a new branch of the human family. By so doing, we will put our stamp on the future. It is a privilege not to be disdained lightly. SA

Robert Zubrin, an astronautical engineer, is president of the Mars Society and author of *The Case for Mars: The Plan to Settle the Red Planet and Why We Must*, published by Simon & Schuster (1996). Zubrin was formerly a senior engineer at Lockheed Martin and is the founder of Pioneer Astronautics, which is involved in research and development of space exploration.

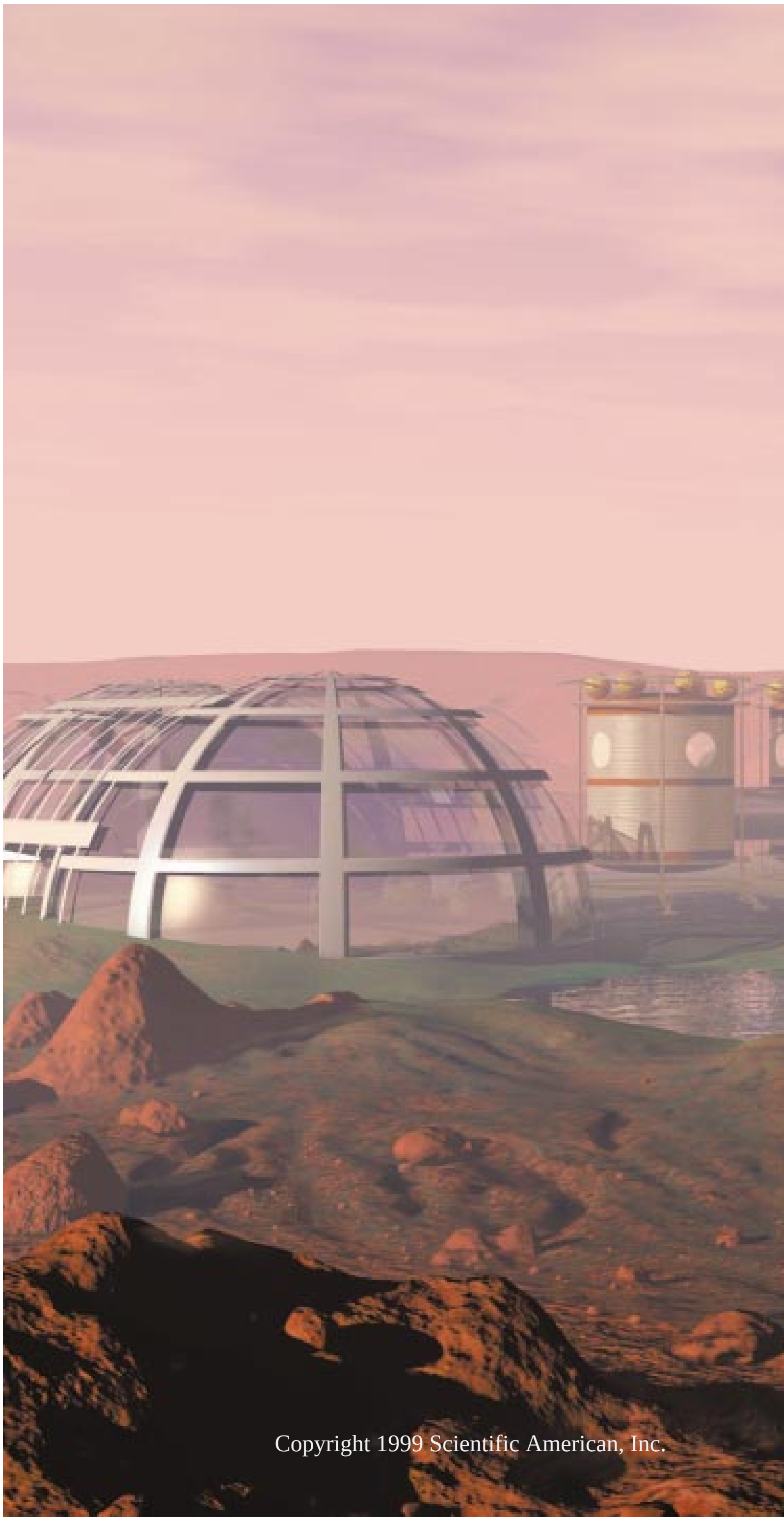
Bringing Life to Mars

by Christopher P. McKay

Climate models suggest that human beings could transform the Red Planet into a more Earth-like world using current technologies

Four billion years ago Mars was a warm and wet planet, possibly teeming with life. Spacecraft orbiting Mars have returned images of canyons and flood valleys—features that suggest that liquid water once flowed on the planet's surface. Today, however, Mars is a cold, dry, desertlike world with a thin atmosphere. In the absence of liquid water—the quintessential ingredient for life—no known organism could survive on the Red Planet.

More than 20 years ago the Mariner and Viking missions failed to find evidence that life exists on Mars's surface, although all the chemical elements needed for life were present. That result inspired biologists Maurice Averner and Robert D. MacElroy of the National Aeronautics and Space Administration Ames Research Center to consider seriously whether Mars's environment could be made hospitable to colonization by Earth-based life-forms. Since then, several scientists, using climate models and ecological theory, have concluded that the answer is probably yes: With today's technology, we could transform the climate on the planet Mars, making it suitable once more for life. Such an experiment would



ALFRED T. KAMAJIAN

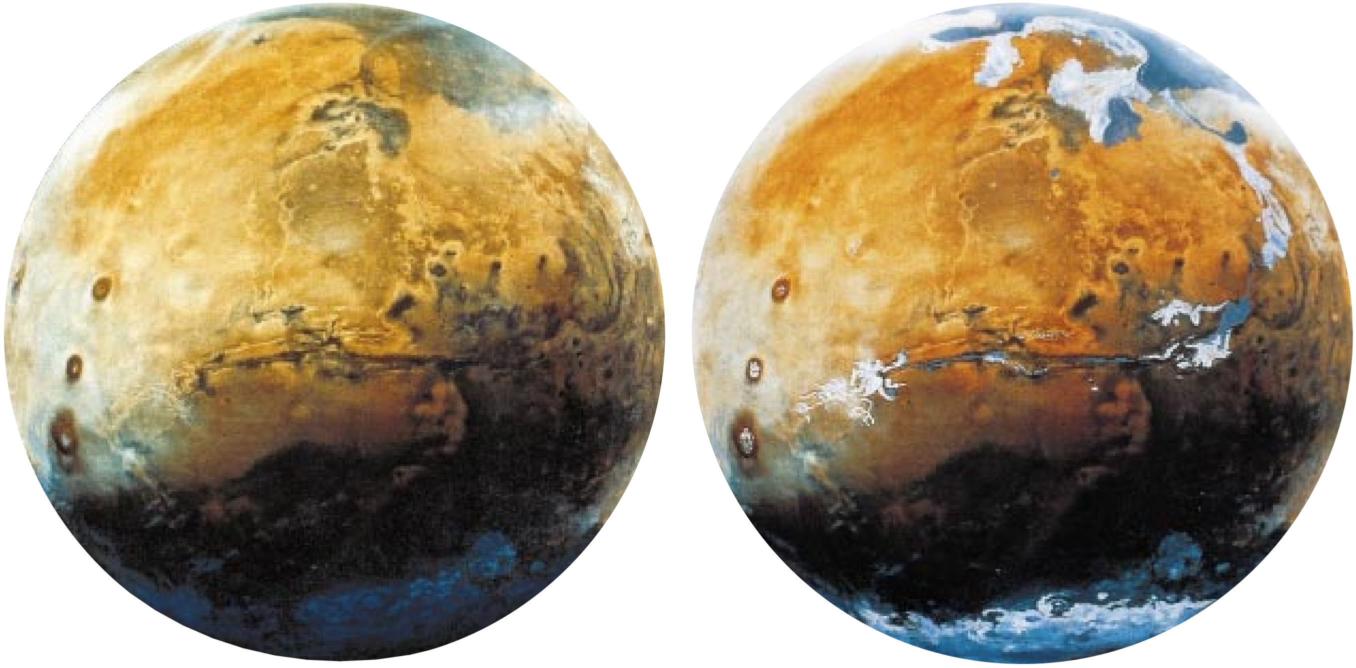
GREENING OF MARS is portrayed in this artist's conception of a Martian landscape after the planet has been warmed to Earth-like temperatures. A mobile soil-processing unit (*in foreground*) generates greenhouse gases that trap solar energy and trigger the creation of a thick carbon dioxide atmosphere. Plants imported from Earth could grow on the surface, but humans could not breathe the air and would need to carry oxygen tanks.

allow us to examine, on a grand scale, how biospheres grow and evolve. And it would give us the opportunity to spread and study life beyond Earth.

Why Mars?

Many of the key physical properties of Mars are remarkably similar to those of Earth [*see table on page 54*]. On both planets the length of day is about 24 hours—an important consideration for plants that have adapted to photosynthesize when the sun shines. Mars also experiences seasons, as the planet's axis is tilted to a similar degree as Earth's. Because Mars is farther from the sun, a Martian year is almost twice the length of an Earth year, but plants should be able to adapt to such a difference. One unalterable difference between Earth and Mars is gravity: Martian gravity is about one third that of Earth's. How life would adapt to reduced gravity is unknown. It is likely, however, that microbes and plants would adjust easily to Martian gravity, and some animals might cope just as well.

Other planets and moons in our solar system also might be considered potential sites for life, including Venus, Titan and Europa. Each of these bodies, however, possesses some basic physical parameter that is inconsistent with habitability. Titan and Europa—satellites of Saturn and Jupiter, respectively—are too far



RED PLANET TURNS BLUE
in this series of images showing how Mars might change if its surface were warmed by human effort. Rising temperatures would release the carbon dioxide and water currently frozen in the planet's polar caps (*above*). The water would collect primarily in the lowlands of the northern hemisphere, forming a large ocean. In the final stage of warming (*far right*), Mars would have the same amount of liquid water that it apparently possessed billions of years ago.

from the sun. Venus is too close, and its extremely dense atmosphere makes the planet much too hot for life. Furthermore, the planet rotates so slowly that its day is equal to about four months on Earth, which might make life difficult for plants. The technology needed to alter these physical parameters is well beyond the current scope of human capability.

Mars is currently too cold, too dry and its carbon dioxide atmosphere too thin to support life. But these parameters are interrelated, and all three can be altered by a combination of human intervention and biological changes. The key is carbon dioxide. If we were to envelop Mars in a thicker carbon dioxide atmosphere, with a surface pressure one to two times that of air at sea level on Earth, the planet would naturally warm above the freezing point of water. Adding a bit of nitrogen to the atmosphere would help satisfy the metabolic needs of plants and microbes. And the small amount of oxygen that would be produced from the photochemical degradation of carbon dioxide could create a rudimentary but effective ozone shield for the rejuvenated planet. This carbon dioxide atmosphere would support plant and microbial life but would not contain enough oxygen for animals.

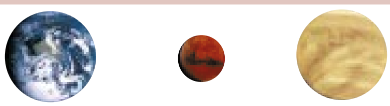
Although humans would need to carry a supply of breathable air with them, a carbon dioxide Mars would still be a much kinder, gentler place than today's Mars. The higher temperatures and atmospheric pressure would make bulky space suits and pressure domes unnecessary. And the natural growth of plants would allow the cultivation of farms and forests on Mars's surface, thus providing food for human colonists or visitors.

To make Mars suitable for animals and humans, its atmosphere would have to be made more similar to Earth's, which is composed primarily of nitrogen, with oxygen levels close to 20 percent and carbon dioxide levels less than 1 percent. The process of generating such an Earth-like, oxygen-rich environment—also called terraforming—would be much more difficult than simply thickening Mars's atmosphere. But to make Mars habitable, generating a carbon dioxide atmosphere—a process that biologist Robert Haynes of York University has dubbed ecopoiesis—would be the logical first step.

Does Mars possess the essential volatiles—carbon dioxide, nitrogen and water—needed to create a habitable environment? Ferrying these raw materials from Earth would be impractical. For example, the amount of nitrogen needed to create a breathable atmosphere on Mars is more than a million billion tons. The space shuttle can carry only about 25 tons into low-Earth orbit. Thus, if Mars does not have the necessary amount of nitrogen, it is not within near-term capabilities of humans to bring it there.

Unfortunately, we do not yet know how much of each of these key ingredients Mars has hidden below its surface. We do know

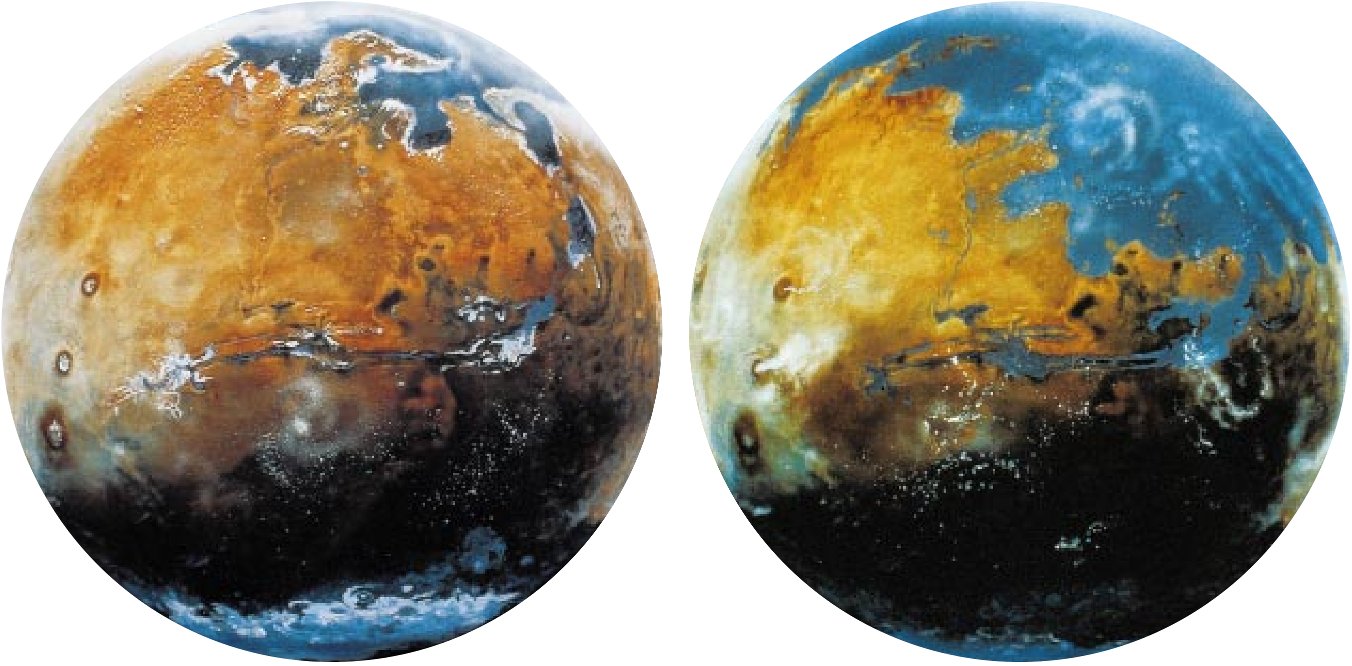
Comparing Earth, Mars and Venus



NASA

	EARTH	MARS	VENUS
Gravity (g's)	1	0.38	0.91
Length of day	24 hours	24 hours 37 minutes	117 days
Length of year	365 days	687 days	225 days
Axis tilt (degrees)	23.5	25.2	2.6
Average sunlight reaching the planet (watts per square meter)	345	147	655
Average surface temperature (degrees Celsius)	15	–60	460
Surface pressure (atmospheres)	1	0.008	95
Most abundant gases in atmosphere	Nitrogen, oxygen	Carbon dioxide	Carbon dioxide

CHRISTOPHER P. MC KAY



MICHAEL CARROLL

that the thin Martian atmosphere currently contains only small amounts of carbon dioxide, nitrogen and water vapor. But at one time Mars must have had a much thicker atmosphere. Researchers have used a variety of methods to estimate how much carbon dioxide, nitrogen and water would have been present in the early Martian atmosphere. These methods—which include measuring the ratio of nitrogen isotopes and estimating the volume of water needed to etch the Martian flood channels—yield widely different estimates of the amount of volatiles once present on the planet.

Fortunately, the range of estimates overlaps the amounts of volatiles needed to produce a breathable atmosphere and a substantial ocean [*see table below*]. It is possible that some of these volatiles have left the planet permanently, flowing out into space because of Mars's low gravity. If, however, Mars once had enough of the volatiles needed to make a biosphere, it probably still has them locked up in the subsurface. Water could be frozen as ground ice, and nitrogen could be contained in nitrates in the Martian soil. Carbon dioxide could be frozen in Mars's polar caps as well as in the soil.

Turning up the Heat

If Mars does have the essential ingredients, the first step in transforming the environment is to warm the planet. Heating the Martian surface would release the carbon dioxide, nitrogen and water vapor into the atmosphere. The energy needed for such massive heating would have to come from the sun. Compared with sunlight, human energy sources are small. For example, sunlight delivers more energy to Mars in 30 minutes than the energy that would be released by the explosion of all the nuclear warheads of the U.S. and Russia. So trapping the energy from sunlight and using it to warm the planet is really the only practical option for generating a life-friendly Mars.

Through the years, scientists have proposed and considered several methods of using sunlight to heat Mars. Some researchers suggested spreading dark soot on the polar caps to help them absorb more sunlight and melt their stores of frozen carbon dioxide. Other researchers proposed putting large mirrors in orbit around Mars to reflect sunlight onto the polar regions. But the technologies needed for these methods have never been demonstrated. The space mirror, for example, would have to be the size of the state of Texas to increase the amount of sunlight hitting Mars by just 2 percent.

Perhaps the most practical approach to warming Mars would involve using "super-greenhouse" gases to trap solar energy on the planet. This method was first suggested by British atmospheric scientist James Lovelock, who is best known for the Gaia hypothesis that the presence of life maintains the habitability of Earth. Lovelock's idea for heating Mars involved pumping gases such as methane, nitrous oxide, ammonia and perfluorocarbons (PFCs) into the Martian atmosphere. These super-greenhouse gases can trap solar energy with thousands of times the efficiency of carbon dioxide, the most abundant greenhouse gas on Mars and Earth. Even small amounts of the super-greenhouse gases can warm a planet; in fact, many scientists believe that the production of these gases is contributing to global warming here on Earth.

Computer calculations performed by myself, Owen B. Toon and James F. Kasting suggest that if Mars's atmosphere contained just a few parts per million of the super-greenhouse gases, the average temperature at the planet's surface would

The Essential Ingredients for Life on Mars

	Carbon dioxide surface pressure (atmospheres)	Nitrogen surface pressure (atmospheres)	Water ocean depth* (meters)
Amount needed for plant and microbe habitability	2	0.01	500
Amount needed for breathable atmosphere	0.2	0.3	500
Amount in the present Mars atmosphere	0.01	0.00027	0.000001
Range of estimates for amount on Mars at planet's formation	0.1–20	0.002–0.3	6–1,000

**Amount of water is measured in terms of the depth of an ocean covering the entire surface of Mars.*

CHRISTOPHER P. MCKAY

A Futile Effort?

Billions of years ago Mars had a thick carbon dioxide atmosphere and temperatures warm enough for liquid water. Why then did it become uninhabitable? And if we restored a more hospitable Martian climate, would the planet once again revert to its current barren state?

The answers lie in carbon recycling. Atmospheric carbon dioxide reacts with liquid water to form carbonic acid. This acid weathers rocks, ultimately producing calcium carbonate. As this mineral accumulates in the oceans and lake basins, carbon is effectively removed from the atmosphere.

On Earth, carbonates are recycled by plate tectonics. Subduction of oceanic plates under continental plates carries the sediments deep underground, where temperatures greater than 1,000 degrees Celsius convert the carbonates back to carbon dioxide. Mars, however, is a one-plate planet with a single thick crust. Because Mars had no plate tectonics to recycle carbonates, it gradually lost its atmospheric carbon dioxide. As the atmospheric pressure dropped, the planet's surface chilled, and its liquid water froze.

If Mars were warmed and its thick carbon dioxide atmosphere restored by human effort, it is very likely that carbonate formation would again deplete the atmosphere. After a few hundred million years,

rise from −60 to −40 degrees Celsius (−76 to −40 degrees Fahrenheit). This warming could be enough to trigger the release of carbon dioxide from the polar caps and soil into the atmosphere. Carbon dioxide would then augment the greenhouse effect even further, driving the release of more carbon dioxide and water vapor into the atmosphere. Such positive feedback would be sufficient to create a thick, warm atmosphere—the carbon dioxide Mars.

Where would the greenhouse gases come from? Although PFCs at a concentration of a few parts per million would do the job, the mass of material needed to warm Mars would be much too large to import from Earth. Instead the greenhouse gases would have to be produced locally, on Mars—chemically at first and eventually biologically, with the help of microorganisms. The gases must be easily synthesized from elements likely to be abundant on Mars and must persist in the Martian atmosphere for a relatively long time. PFCs such as CF_4 and C_2F_6, and other compounds such as SF_6, would be good choices because they absorb thermal radiation efficiently and would have long lifetimes in the Martian atmosphere, on the order of hundreds of years. Furthermore, the elements making up these compounds—carbon, fluorine and sulfur—are all abundant on Mars.

To generate enough greenhouse gases, we would need to distribute hundreds of small PFC factories across the Martian surface. Powered by solar energy, each of these Volkswagen-size machines would harvest the desired elements from Martian soil, generate PFCs and pump these gases into the atmosphere.

The Matter of Time

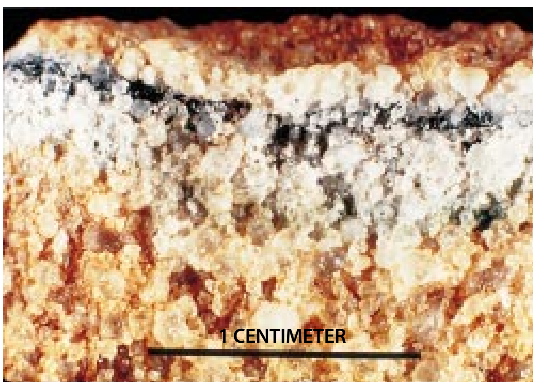
How long would it take to generate a thick carbon dioxide atmosphere? The atmospheric PFCs would have to heat the planet enough to melt the carbon dioxide and water frozen in the polar caps and to evaporate nitrogen from the soil. But how much energy is needed to raise the temperature of Mars? According to our calculations, defrosting Mars would require an energy input of five megajoules per square centimeter of planetary surface. This amount of energy is equivalent to about 10 years' worth of Martian sunlight.

Trapping this energy would vaporize the frozen carbon dioxide, generating enough gas to create a thick atmosphere. If enough carbon dioxide were generated to provide a pressure twice that of Earth's atmosphere, the average Martian surface temperature would rise to an Earth-like 15 degrees C. At this stage, the bulk of the planet's water is likely to still be frozen deep underground, where temperatures would remain much lower. Melting the reservoirs of subsurface ice would require an additional 25 megajoules per square centimeter of surface, equivalent to 50 years of Martian sunlight.

Thus, if every photon of sunlight reaching Mars were captured with 100 percent efficiency, the planet could be warmed in a decade and fully thawed in 60 years. Of course, in reality no process is 100 percent efficient. If greenhouse gases can trap sunlight with an efficiency of 10 percent, using PFCs could generate a thick carbon dioxide atmosphere in about 100 years and lead to a water-rich planet in about 600 years. These numbers are encouraging. If the answers had turned out to be millions of years, we would have to abandon our plans to turn Mars into a second home for life.

For even quicker results, the greenhouse gas effect could be amplified by coupling it with other methods, such as the deployment of huge orbital mirrors or the spreading of dark material on the planet's surface, according to calculations by Robert Zubrin. But changing Mars slowly makes sense for a number of reasons. Transforming the climate of

NASA/CHRISTOPHER P. McKAY



E. IMRE FRIEDMANN

LIFE FROM ANTARCTICA could be transplanted to Mars in the early stages of the planet's transformation. The Linnaeus Terrace in Antarctica (*left*) is one of the coldest and driest places on Earth. But lichens and algae live just below the surface of sandstone rocks in the area (*above*). These organisms might also thrive on Mars.

Mars would once again lose its capacity to support life.

But 100 million years is a long time. In fact, Earth might not be habitable for much longer than that. As the sun continues to brighten, Earth will succumb to a runaway greenhouse effect. The oceans will evaporate, creating Venus-like conditions unsuitable for life. So our second planetary home might last almost as long as our first. —*C.P.M.*

Mars over decades and centuries—as with greenhouse gases—would be financially feasible. NASA's Mars program could easily absorb the cost of shipping half a dozen PFC factories to the planet every year. Furthermore, working with longer timescales would also allow life on Mars to adapt and evolve and interact with the environment—as has been the case on Earth for billions of years. Finally, slowing the process of environmental evolution gives us ample opportunity to study the coupled biological and physical changes as they occur. Learning how biospheres are built is part of the scientific return for the investment in bringing Mars to life.

Plants and bacteria can thrive on this warm, wet, carbon dioxide–rich Mars. But producing an oxygen-rich atmosphere capable of supporting animals—and humans—is much more difficult. Thermodynamic calculations indicate that conversion of the carbon dioxide in Mars's thick atmosphere to oxygen would require about 80 megajoules of energy per square centimeter, or about 170 years of Martian sunlight. And the only mechanism that could transform the entire atmosphere is a planetwide biological process: the photosynthesis done by plants, which take in carbon dioxide and expel oxygen.

On Earth, the efficiency with which plants produce oxygen from sunlight is only a hundredth of 1 percent. With this efficiency, converting Martian carbon dioxide to oxygen would take more than a million years. Although this may sound like a long time, keep in mind that the same process on Earth took over two billion years. Of course, as plants consume the atmospheric carbon dioxide, the greenhouse effect would lessen, and Mars would once again become cold. To keep the surface temperatures warm with an atmosphere that contained mostly nitrogen and oxygen and only 1 percent carbon dioxide, the concentrations of supergreenhouse gases would have to be maintained at a few parts per million. Such quantities of greenhouse gases would be harmless to living things.

Future Martians

If Mars is currently a planet bereft of life, the Martians of the future would have to be imported from Earth. The dry valleys of Antarctica—the coldest, driest and most Mars-like place on Earth—harbor some ideal candidates for the first generation of Martians. High in the mountains, where the air temperature rarely rises above freezing, E. Imre Friedmann of Florida State University has found lichens and algae that live a few millimeters below the surface of porous sandstone rocks. When sunlight warms these rocks, enough snow melts into the sandstone to provide the moisture the microbes need to survive. Similar microorganisms that can grow without oxygen might be able to survive in their little "rock greenhouses" even in the early stages of Mars's transformation, when the planet would still be very cold.

As Mars warms, different types of plants could be introduced. James M. Graham of the University of Wisconsin likens the gradual greening of Mars to hiking down a mountainside on Earth. As one descends to lower elevations, the temperature rises and the scenery grows more lush. On Mars, the bare rock would give way to the hardy plants that thrive on Earth's tundra, and eventually the Martian landscape would blossom into the equivalent of an alpine meadow or a pine forest. The plants would generate oxygen, and eventually insects, worms and other simple animals that can tolerate high concentrations of carbon dioxide and low levels of oxygen could roam the planet.

Introducing life to Mars would be of great scientific merit and could well be relevant to understanding how to sustain the biosphere of Earth. But would such a program be desirable? What are the ethical considerations surrounding such a drastic alteration of another planet's environment?

First we must assume that Mars is currently lifeless—an assumption that must be certified to a high level of confidence before we transfer life from Earth. If Mars did harbor living organisms beneath its surface, we might consider altering the environment to allow that native life to emerge and spread across the planet. If, however, Mars has no life and we believe that life in itself has intrinsic worth, then a Mars replete with life could be considered of more value than today's Mars, beautiful but lifeless.

On Earth, environmental change almost always produces some negative effects. Would this also happen on Mars? Although we can monitor Mars as it evolves, we will not really be able to control or predict the paths that the biota and the environment will follow. The Earth's biosphere is so complex that unintended changes that adversely affect some life-forms are to be expected. But on Mars, in all likelihood, no life-forms currently exist. Thus, any biological expansion would be considered an improvement. If spreading life is the objective, making Mars habitable might allow humans to make a purely positive contribution for once. SA

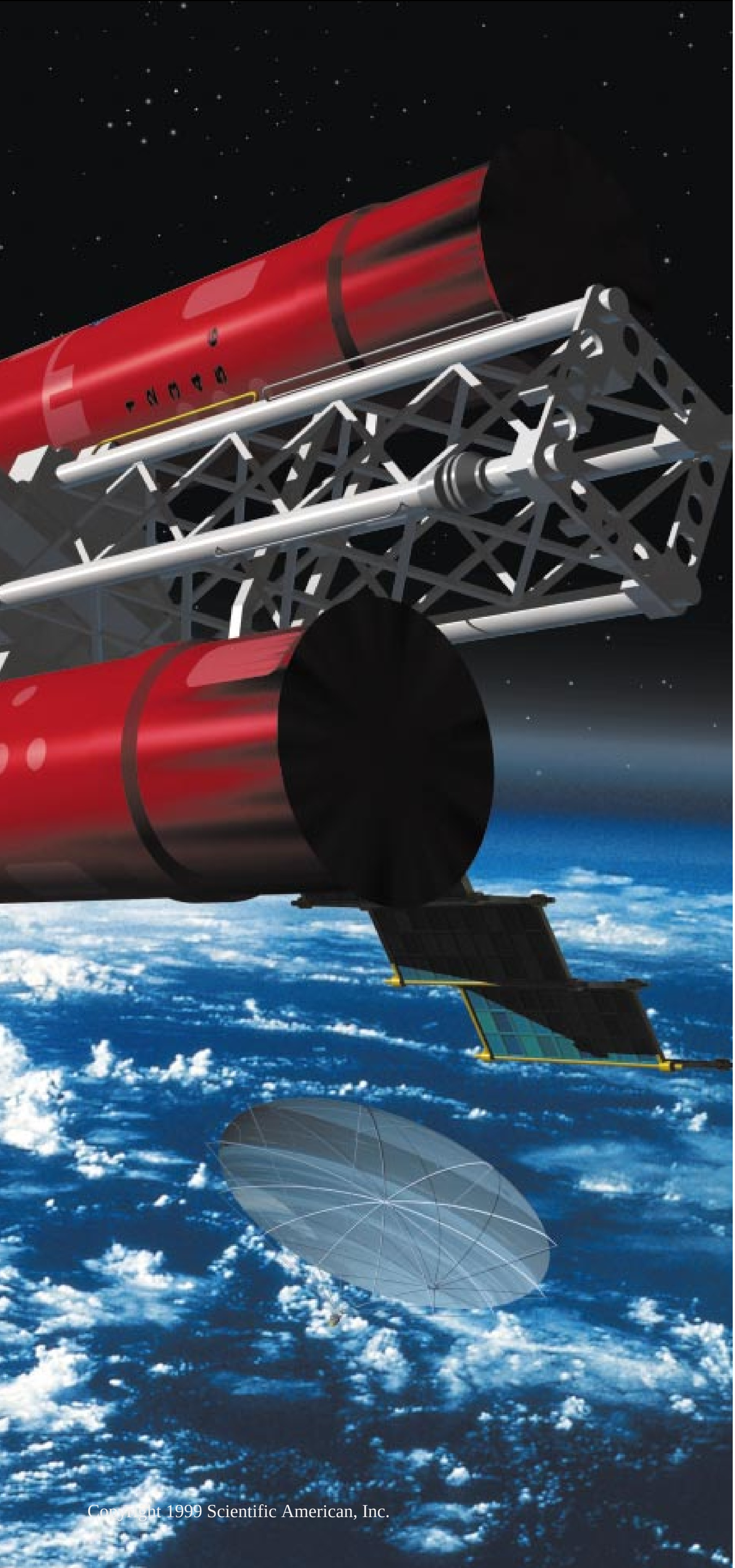
EDWARD BELL

MELTING THE POLAR CAPS on Mars would probably require at least 100 years of warming. Another 500 years would be needed to melt the planet's underground ice.

Christopher P. McKay received his doctorate in astrophysics from the University of Colorado in 1982 and has been a research scientist with the space science division of the NASA Ames Research Center ever since. The year McKay entered graduate school, the Viking spacecraft landed on Mars, an event that aroused his continuing interest in planetary science and the origins of life. Today McKay helps to plan future Mars missions, and he regularly journeys to the dry valleys of Antarctica to study life in cold, dry conditions.

The Way to Go in Space

To go farther into space, humans will first have to figure out how to get there cheaply and more efficiently. Ideas are not in short supply



by Tim Beardsley, *staff writer*

The year 1996 marked a milestone in the history of space transportation. According to a study led by the accounting firm KPMG Peat Marwick, that was when worldwide commercial revenues in space for the first time surpassed governments' spending on space, totaling some $77 billion. Growth continues. Some 150 commercial, civil and military payloads were lofted into orbit in 1997, including 75 commercial payloads, a threefold increase over the number the year before. And the number of payloads reaching orbit in 1998 was set to come close to the 1997 total, according to analyst Jonathan McDowell of Harvard University. Market surveys indicate that commercial launches will multiply for the next several years at least: one estimate holds that 1,200 telecommunications satellites will be completed between 1998 and 2007. In short, a space gold rush is now under way that will leave last century's episode in California in the dust.

SPACECRAFT DESIGNS decades from now may look very different from today's models. A solar-power station (*upper left*) beams microwaves down to a lightcraft (*lower left*) powered by magnetohydrodynamic forces; an old-style shuttle (*lower background*) has released a satellite that has been picked up by a rotating tether system (*upper right*). A single-stage-to-orbit rotary rocket craft deploys another satellite (*lower center*). Meanwhile a light-sail craft sets out for a remote destination (*lower right*).

Solar Orbit Transfer Vehicle

Approximate launch year: 2002
Approximate cost: $30 million
Power source: Solar thermal

COURTESY OF BOEING

SOLAR ORBIT TRANSFER VEHICLE is now being built by Boeing. This device utilizes a large reflector to focus the sun's rays onto a block of graphite, which is heated to 2,100 degrees Celsius and vaporizes stored liquid-hydrogen propellant to generate thrust. The vehicle gently lifts payloads from low-Earth orbits to higher orbits over a period of weeks. The light vehicle can launch satellites using smaller rockets than would otherwise be needed.

Space enthusiasts look to the day when ordinary people, as well as professional astronauts and members of Congress, can leave Earth behind and head for a space station resort, or maybe a base on the moon or Mars. The Space Transportation Association, an industry lobbying group, recently created a division devoted to promoting space tourism, which it sees as a viable way to spur economic development beyond Earth.

The great stumbling block in this road to the stars, however, is the sheer difficulty of getting anywhere in space. Merely achieving orbit is an expensive and risky proposition. Current space propulsion technologies make it a stretch to send probes to distant destinations within the solar system. Spacecraft have to follow multiyear, indirect trajectories that loop around several planets in order to gain velocity from gravity assists. Then the craft lack the energy to come back. Sending spacecraft to other solar systems would take many centuries.

Fortunately, engineers have no shortage of inventive plans for new propulsion systems that might someday expand human presence, literally or figuratively, beyond this planet. Some are radical refinements of current rocket or jet technologies. Others harness nuclear energies or would ride on powerful laser beams. Even the equivalents of "space elevators" for hoisting cargoes into orbit are on the drawing board.

"Reach low orbit and you're halfway to anywhere in the Solar System," science-fiction author Robert A. Heinlein memorably wrote. And virtually all analysts agree that inexpensive access to low-Earth orbit is a vital first step, because most scenarios for expanding humankind's reach depend on the orbital assembly of massive spacecraft or other equipment, involving multiple launches.

The need for better launch systems is already immediate, driven by private- and public-sector demand. Most commercial payloads are destined either for the now crowded geostationary orbit, where satellites jostle for elbow room 36,000 kilometers (22,300 miles) above the equator, or for low-Earth orbit, just a few hundred kilometers up. Low-Earth orbit is rapidly becoming a space enterprise zone, because satellites that close can transmit signals to desktop or even handheld receivers.

Scientific payloads are also taking off in a big way. More than 50 major observatories and explorations to other solar system bodies will lift off within the next decade. The rate of such launches is sure to grow as the National Aeronautics and Space Administration puts into practice its new emphasis on "faster, better, cheaper" craft: science missions now being developed cost a third of what a typical early-1990s mission did. Furthermore, over its expected 15-year lifetime the International Space Station will need dozens of deliveries of crew, fuel and other cargo, in addition to its 45 planned assembly flights. Scores of Earth-observing spacecraft will also zoom out of the atmosphere in coming years, ranging from secret spy satellites to weather satellites to high-tech platforms monitoring global change. The pressing demand for launches has even prompted Boeing's commercial space division to team up with RSC-Energia in Moscow and Kvaerner Maritime in Oslo to refurbish an oil rig and create a 34,000-ton displacement semisubmersible launch platform that will be towed to orbitally favorable launch sites.

After the Gold Rush

Even the most sobersided scientists would like to see many more research spacecraft monitoring Earth's environment and exploring the farther reaches of the solar system. The more visionary ones foresee a thriving space industry based on mining minerals from asteroids or planets and extracting gases from their atmospheres for energy and life support. K. R. Sridhar of the University of Arizona borrows the rhetoric of Mars enthusiasts when he says space pioneers will have to "live off the land": he has a developed an electrochemical cell that should be able to generate oxygen from the Martian atmosphere. Already one firm, SpaceDev, has talked about mining minerals from asteroids, earning a complaint from the Securities and Exchange Commission for its incautious enthusiasm. Some dreamers even devote themselves to finding ways of sending probes beyond the sun's domain into the vastness of interstellar space.

The clamor for a ticket to space is all the more remarkable in light of the extremely high cost of getting there. Conventional rockets, most developed by governments, cost around $20,000 per kilogram delivered to low-Earth orbit. The space shuttle, now operated privately by United Space Alliance, a joint venture of Boeing and Lockheed Martin, was intended to be an inexpensive ride to space, but its costs are no less than those of typical expendable rockets. In any event, the shuttle has been unavailable for commercial launches since the Challenger disaster in 1986. If a shuttle were outfitted today to take 50 passengers for a flight, they would have to pay $8.4 million a head for its operator to break even.

Getting into space is expensive today because boosters carry both the oxidizer and the fuel for their short ride and (with the exception of the partly reusable space shuttle) are abandoned to burn in the atmosphere after their few fiery minutes of glory. Engineers have long hoped to slash launch costs by building reusable craft that would need only refueling and some basic checks between flights, like today's commercial airliners. An energetic group of companies dedicated to reducing launch costs has sprung up in recent years, many of them populated with former NASA top brass. Most are adapting existing technology to gain a commercial edge for launching small payloads into low-Earth orbit.

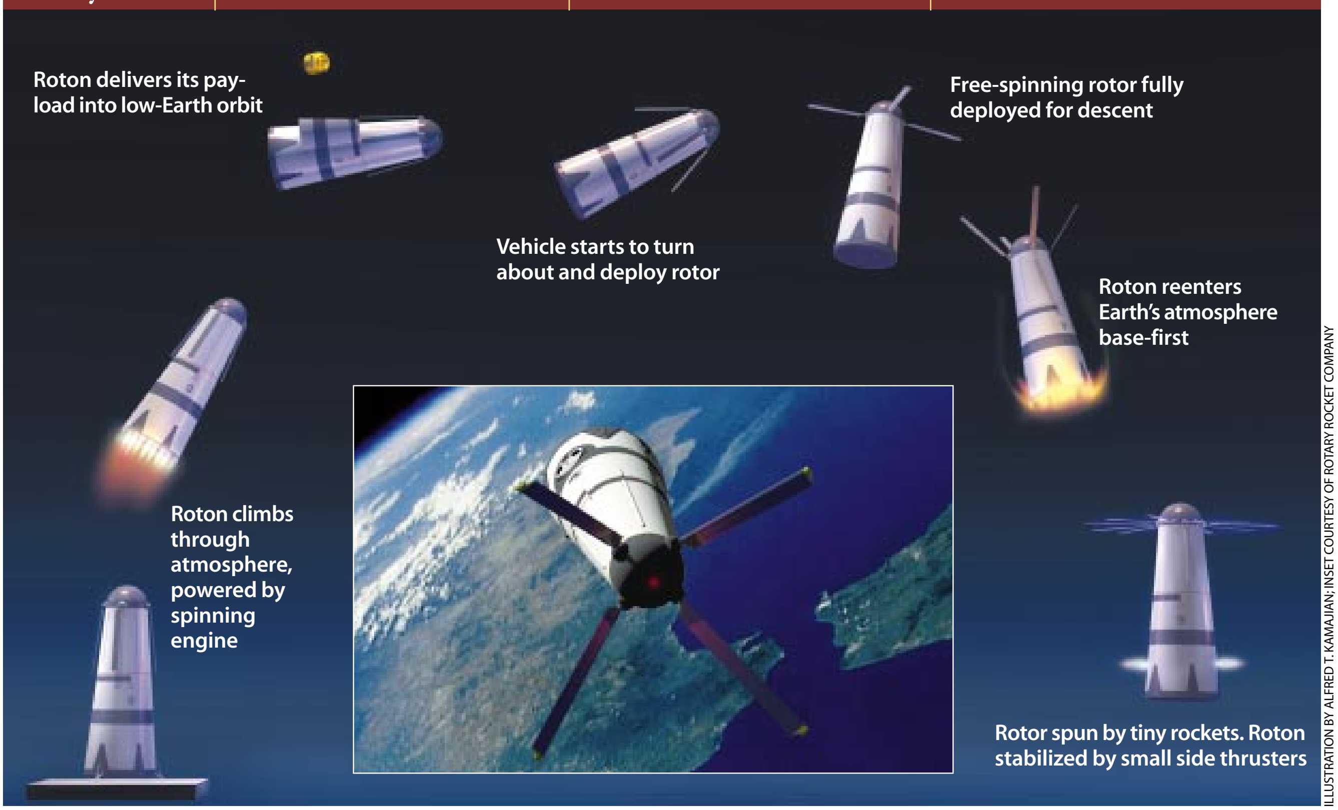
Buck Rogers Rides Again

Nobody should underestimate the risks of building rockets, even ones based on conventional designs. The very first Boeing Delta 3, which was the first large booster developed privately in decades, exploded shortly after liftoff from Cape Canaveral last August, setting back Boeing's plans. A U.S. Air Force/Lockheed Martin Titan 4A had detonated over the cape two weeks earlier, and European Arianespace had a costly failure of a new launcher in 1996. In the U.S., disagreements over costs and demand have led to the cancellation of several government-sponsored efforts to develop new expendable rockets in the past decade.

The entrepreneurs are not easily deterred. One of the farthest along and best financed of this new breed is Kistler Aerospace in Kirkland, Wash., which is building the first two of five planned launchers that will employ Russian-built engines. The first stage of each vehicle would fly back to the launch site; the second would orbit Earth before returning. Both stages would descend by parachute and land on inflatable air bags. The company has raised $440 million and seeks hundreds of millions more; it says that despite world financial turmoil, flights should start this year. Privately financed Beal Aerospace Technologies in Texas is developing a three-stage launcher that is scheduled to fly in the third quarter of 2000. A reusable version may be developed later, says Beal vice president David Spoede.

Several firms plan to increase their advantage by using oxygen in the atmosphere, thereby reducing the amount of it that their rockets have to carry. This can be done most easily with a vehicle that

Roton Rotary Rocket	*Approximate launch year:* 2000	*Approximate cost:* $100 million	*Power source:* Rotary rocket engine



ROTON VEHICLE is being constructed by Rotary Rocket in Redwood City, Calif. The craft takes off vertically, powered by a lightweight rotary rocket engine. After delivering a payload to low-Earth orbit, the craft comes about and unfolds helicopter blades. It reenters the atmosphere base-first. The helicopter blades rotate passively at first but are spun by small rockets on their tips for the vertical landing.

takes off and lands horizontally. Pioneer Rocketplane in Vandenberg, Calif., is developing a lightweight, two-seater vehicle powered by a rocket engine as well as conventional turbofan engines. The plane, with a payload and attached second stage in its small shuttle-style cargo bay, takes off from a runway with its turbofans and climbs to 6,100 meters (20,000 feet). There it meets a fuel tanker that supplies it with 64,000 kilograms (140,000 pounds) of liquid oxygen. After the two planes separate, the oxygen is used to fire up the smaller plane's rocket engine and take it to Mach 15 and 113 kilometers' altitude, at which point it can release its payload and second stage. A fail-safe mechanism for the cryogenic oxygen transfer is the main technical challenge, says the company's vice president for business development, Charles J. Lauer.

Kelly Space and Technology is also developing a horizontal takeoff plane for satellite launches, but one that can handle larger payloads, up to 32,000 kilograms. Kelly's Astroliner, which looks like a smaller version of the shuttle, has to be towed to 6,100 meters. At that altitude, its rocket engines are tested, and a decision is made either to zip up to 122,000

Air-Breathing Engines

by Charles R. McClinton

For years, engineers have dreamed of building an aircraft that could reach hypersonic speeds, greater than Mach 5, or five times the speed of sound. Propelled by a special type of air-breathing jet engine, a high-performance hypersonic craft might even be able to "fly" into orbit—a possibility first considered more than four decades ago. Recently, as the technology has matured and as the demand for more efficient Earth-to-orbit propulsion grows, scientists have begun seriously considering such systems for access to space.

Air-breathing engines have several advantages over rockets. Because the former use oxygen from the atmosphere, they require less propellant—fuel, but no oxidizer—resulting in lighter, smaller and cheaper launch vehicles. To produce the same thrust, air-breathing engines require less than one seventh the propellant that rockets do. Furthermore, because air-breathing vehicles rely on aerodynamic forces rather than on rocket thrust, they have greater maneuverability, leading to higher safety: flights can be aborted, with the vehicle gliding back to Earth. Missions can also be more flexible.

But air-breathing engines for launch vehicles are relatively immature compared with rocket technology, which has continually evolved, with refinements and re-refinements, over the past 40 years. Hypersonic air-breathing propulsion is just now finally coming of age.

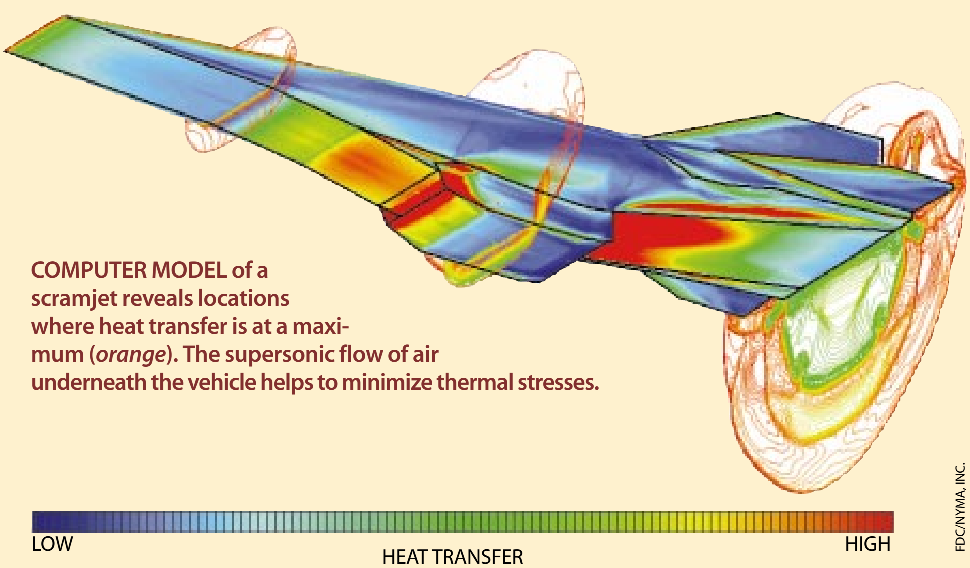
Of course, jet engines—which work by compressing atmospheric air, combining it with fuel, burning the mixture and expanding the combustion products to provide thrust—are nothing new. But turbojet engines, such as those found on commercial and fighter aircraft, are limited to Mach 3 or 4, above which the turbine and blades that compress the air suffer damage from overheating.

Fortunately, at such high supersonic speeds a turbine is not required if the engine is designed so that the air is "ram"-compressed. Such an engine has an air inlet that has been specially shaped to slow and compress the air when the vehicle is moving rapidly through the atmosphere. Because ramjets cannot work unless the vehicle is traveling at high speeds, they have been integrated in the same engine housing with turbojets, as in the French Griffon II experimental aircraft, which set a speed record of 1,640 kilometers per hour (1,020 miles per hour) around a course in 1959. Ramjets have also been combined with rockets in surface-to-air and air-to-surface missiles. But ramjets are limited to about Mach 6, above which the combustion chamber becomes so hot that the combustion products (water) decompose.

To obtain higher speeds, supersonic-combustion ramjets, or scramjets, reduce the compression of the airflow at the inlet so that it is not slowed nearly as much. Because the flow remains supersonic, its temperature does not increase as dramatically as it does in ramjets. Fuel is injected into the supersonic airflow, where it mixes and must burn within a millisecond. The upper speed limit of scramjets has yet to be determined, but theoretically it is above the range required for orbital velocity (Mach 20 to 25). But at such extreme speeds, the benefits of scramjets over rockets become small and possibly moot because of the resulting severe structural stresses.

Hypersonic air-breathing engines can operate with a variety of fuel sources, including both hydrogen and hydrocarbons. Liquid hydrogen, which powers the U.S. space shuttle, is the choice for space launch because it can be used to cool the engine and vehicle before being burned. Hydrocarbons cannot be utilized so efficiently and are limited to speeds less than about Mach 8.

For a scramjet-powered craft, which must be designed to capture large quantities of air, the



COMPUTER MODEL of a scramjet reveals locations where heat transfer is at a maximum (*orange*). The supersonic flow of air underneath the vehicle helps to minimize thermal stresses.

FDC/NYMA, INC.

meters or to fly back to the launch site. The first two vehicles should cost close to $500 million, and Kelly is now lining up investors.

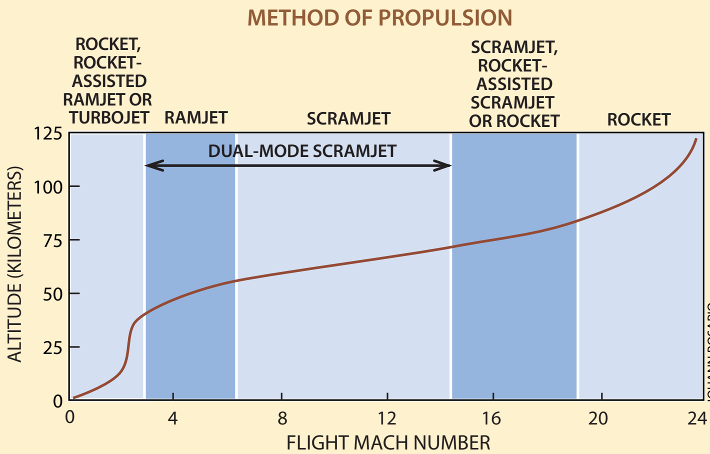
Other companies are being more technologically adventurous. One of the most intriguing is Rotary Rocket in Redwood City, Calif., which is building a crewed rocket that would take off and land vertically. The most innovative feature of the design, called the Roton, is its engine. Oxidizer and fuel are fed into 96 combustors inside a horizontal disk seven meters in diameter that is spun at 720 revolutions per minute before launch. Centrifugal force provides the pressure for combustion, thereby eliminating the need for massive, expensive turbo pumps and allowing the vehicle's single stage to go all the way to orbit. The Roton descends with the aid of foldaway helicopter blades that are spun by tiny rockets on their tips, like a Catherine wheel. Rotary Rocket says it will be able to deliver payloads to low-Earth orbit for a tenth of today's typical launch price. The first orbital flight is scheduled for 2000; the company has already tested individual combustors, and atmospheric flights are supposed to take place this year. The de-

distinction between engine and vehicle blurs. The oncoming flow is deflected mainly by the underside of the craft, which increases the pressure of the diverted air. Generally, the change is great enough to cause a pressure discontinuity, called a shock wave, which originates at the ship's nose and then propagates through the atmosphere. Most of the compressed air between the bottom of the vehicle and the shock wave is directed into the engine. The air gets hotter as its flow is slowed and as fuel is burned in the combustion region. The end product of the reaction expands through both an internal and an external nozzle, generating thrust. The high pressures on the underside of the vehicle also provide lift.

NASA LANGLEY

To broaden the scramjet's operating range, engineers have designed vehicles that can fly in either scram or ram mode. The dual-mode operation can be achieved either by constructing a combustor of variable geometry or by shifting the fuel flow between injectors at different locations.

Because neither scramjets nor ramjets can operate efficiently when they are traveling below Mach 2 or 3, a third type of propulsion (perhaps turbojet or rocket) is required for takeoff. So-called rocket-based combined-cycle engines, which could be used in a space vehicle, rely on a rocket that is integrated within the scramjet combustor to provide thrust from takeoff through subsonic, low-supersonic and then ramjet speeds. Ramjet operation is then followed by scramjet propulsion to at least Mach 10 or 12, after which the rocket is utilized again to supplement the scramjet thrust. Above Mach 18, the rocket by itself propels the vehicle into orbit and enables it to maneuver in space. The National Aeronautics and Space Administration is currently testing several variations of such a system.



JOHANN ROSARIO

SCRAMJETS (*top*) are designed to capture large quantities of air underneath the craft for burning with a fuel source, such as liquid hydrogen. Dual-mode scramjet engines could be combined with rockets (*graph*) in a vehicle that would, in essence, "fly" into space.

First, though, much work remains to validate scramjets. Sophisticated computational fluid-dynamic and engineering design methods have made it possible to develop a launch vehicle that has a scramjet built into its structure. Challenges remaining include developing lightweight, high-temperature materials, ensuring rapid and efficient fuel mixing and combustion, and minimizing the buildup of undesirable heat.

In the 1970s the NASA Langley Research Center demonstrated basic scramjet technology with models of hypersonic vehicles and a wind tunnel. Additional ground tests of prototype engines have been performed elsewhere in the U.S. as well as in England, France, Germany, Russia, Japan and Australia, with other related research under way in countries such as China, Italy and India. Today scientists routinely conduct ground tests of scramjet engines at simulated speeds up to Mach 15. In flight tests the Russians have demonstrated ramjet operation of a dual-mode scramjet up to Mach 6.4.

To date, though, no vehicle has flown under scramjet power. But this ultimate test is nearing reality. Through its Hyper-X research program at Langley and Dryden Flight Research Center, NASA is currently building the X-43A, a 3.6-meter-long aircraft that will demonstrate scramjet flight at Mach 7 and Mach 10 within the next three years. If all goes well, the tests will pave the way for future uses of scramjet propulsion, possibly in a vehicle designed for hypersonic flight into space.

CHARLES R. MCCLINTON, technology manager of the Hyper-X Program at the NASA Langley Research Center in Hampton, Va., has been intrigued and captivated by the technical challenges of hypersonic air-breathing propulsion since the 1960s.

sign “has got a lot of challenges,” observes Mark R. Oderman, managing director of CSP Associates in Cambridge, Mass., who has surveyed new rocket technologies. Oderman says the Roton has many features “that imply high levels of technical or financial risk.”

Space Access in Palmdale, Calif., is designing an altogether different but equally daring craft. Its heavy space plane would take off and land horizontally under the power of a proprietary engine design called an ejector ramjet. This novel engine, which has been tested on the ground, will propel the craft from a standstill to Mach 6, according to Space Access’s Ronald K. Rosepink—a performance well beyond anything in service today. Rosepink says the engine is almost 10 times more efficient than existing engines.

At Mach 6, the plane will fire up two

Space Tethers

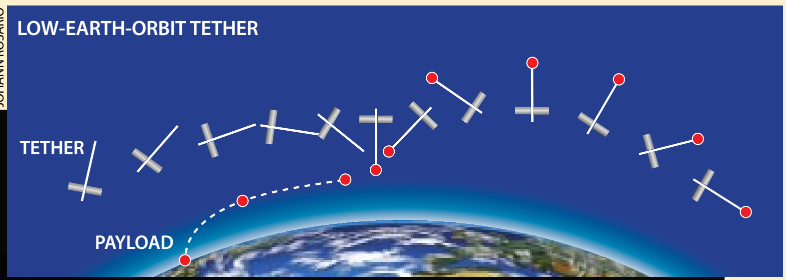
by Robert L. Forward and Robert P. Hoyt

When humans begin to inhabit the moon and planets other than Earth, they may not use the modern technology of rockets. Instead space travel and settlement may depend on an ancient technology invented long before recorded history—string.

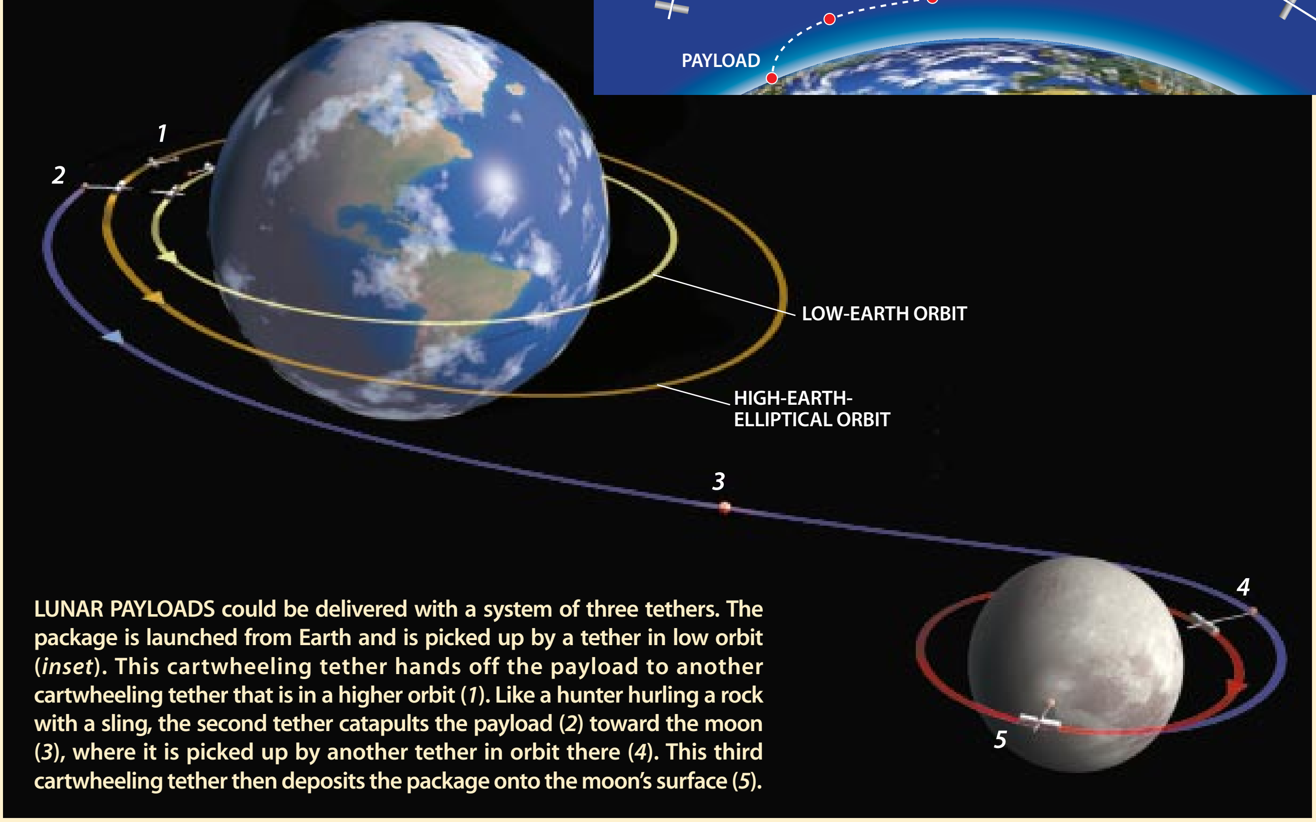
How can mere string propel objects through space? Consider two scenarios. First, a thick strand connecting two satellites can enable one to “throw” the other into a different orbit, much like a hunter casting a stone with a sling. Such a concept could be adapted for transporting payloads to the moon and beyond. Second, if the string is a conductive wire, electricity flowing through it will interact with Earth’s magnetic field to generate propulsive forces. The great advantage of both types of tethers—momentum transfer and electrodynamic—is their economical operation. Instead of consuming huge quantities of propellant, they work by simply draining a little momentum from a body already in orbit or by using electrical energy supplied from solar panels.

To date, 17 space missions have involved tethers. Most of these missions have been successful, but the general public has heard mainly about two failures. In 1992 a satellite built by the Italian Space Agency was to be released upward, away from Earth, from the space shuttle *Atlantis* at the end of a long tether made of insulated copper wire. But the spool mechanism jammed, halting the experiment.

Four years later the National Aeronautics and Space Administration tried again. In that mission, as the tether approached its full 20-kilometer (12-mile) length, the motion of the shuttle through Earth’s magnetic field generated 3,500 volts in the tether.



JOHANN ROSARIO



LUNAR PAYLOADS could be delivered with a system of three tethers. The package is launched from Earth and is picked up by a tether in low orbit (*inset*). This cartwheeling tether hands off the payload to another cartwheeling tether that is in a higher orbit (*1*). Like a hunter hurling a rock with a sling, the second tether catapults the payload (*2*) toward the moon (*3*), where it is picked up by another tether in orbit there (*4*). This third cartwheeling tether then deposits the package onto the moon’s surface (*5*).

ALFRED T. KAMAJIAN

liquid-hydrogen-fueled rockets. At Mach 9, its nose will open like the jaws of a crocodile to release the second and third stages plus the payload. All the stages have wings and will fly back and land horizontally at the launch strip. Space Access's plane will handle payloads of around 14,000 kilograms, as big as those carried by the shuttle. Commercial service could start in 2003, Rosepink claims.

The most prominent launch vehicle in development, the X-33, is under construction at Lockheed Martin's Skunk Works in Palmdale, Calif., as part of a joint industry-NASA effort to reduce launch costs 10-fold. The X-33 is a roughly half-size experimental craft intended to test a type of rocket engine known as a linear aerospike, as well as various other technologies. On paper the linear aerospike can power a fully reusable, vertical takeoff

Electronic devices on the shuttle and the Italian satellite provided an electrical conduit to the ionosphere, allowing ampere-level currents to flow through the tether. The experiment demonstrated that such electrodynamic tethers can convert shuttle momentum into kilowatts of electrical power, and vice versa.

Unfortunately, a flaw in the insulation allowed a high-power electric arc to jump from the tether to the deployment boom, and the arc burned through the tether. But although the break aborted the electrodynamic part of the project, it inadvertently triggered a spectacular display of momentum transfer. At the time, the Italian satellite was 20 kilometers above the shuttle and was being pulled along faster than the orbital speed for that higher altitude. Consequently, when the tether broke, the excess momentum made the satellite soar to seven times the tether length, or 140 kilometers, above the shuttle.

Other work has had greater success. In 1993, to test an idea proposed by Joseph A. Carroll of Tether Applications in San Diego, a payload attached to a 20-kilometer tether was deployed downward from a large satellite. Because the speed of the payload was then slower than that required for an object at that reduced orbital altitude, cutting the tether at the right moment caused the package to descend toward a predetermined point on Earth's surface. Tether Applications is now developing a reentry capsule and tether that the International Space Station could use to send urgent deliveries to Earth, including scientific payloads that cannot wait for the next shuttle pickup.

In a related mission in 1994, a payload was left hanging at the end of a 20-kilometer tether to see how long the connection—as thick as a kite string—would survive collisions with micrometeors and space debris. The expected lifetime of the tether, which could readily be cut by a particle the size of a sand grain traveling at high speed, was a meager 12 days. As things turned out, it was severed after only four.

The experiment demonstrated the need to make tethers out of many lines, separated so that they cannot all be cut by the same particle yet joined periodically so that when one line fails, the others take up the load. With that in mind, the Naval Research Laboratory (NRL) and the National Reconnaissance Office (NRO) fabricated a 2.5-millimeter-diameter hollow braid of Spectra fiber (a high-strength polymer used in fishing lines) loosely packed with yarn. A four-kilometer length linking two satellites that was launched in June 1996 has remained orbiting in space uncut for almost three years.

In a follow-up experiment last October, NRL and NRO tested a tether with a different design: a thin plastic tape three centimeters wide with strong fiber strands running along its length. The six-kilometer tether should survive for many years in space, but the tape makes it heavy. Our company, Tethers Unlimited in Clinton, Wash., is working with Culzean Fabrics and Flemings Textiles, both in Kilmarnock, Scotland, to fabricate multiline tethers with an open, fishnetlike pattern that will weigh less and should last in space for many decades.

Other tether demonstrations are scheduled. The Michigan Technic Corporation in Holland, Mich., has plans in 2000 for a shuttle to release two science packages joined by a two-kilometer tether.

In addition, the NASA Marshall Space Flight Center is investigating the use of electrodynamic tethers for propellantless space propulsion. In mid-2000 a mission will demonstrate that a conducting tether can lower the orbit of a Delta 2 upper stage. At Tethers Unlimited, we are developing a commercial version of the NASA concept: a small package that would be attached to a satellite or upper stage before launch. When the spacecraft completed its mission or malfunctioned, the conducting tether would unfurl and drag against Earth's magnetic field, causing the craft to lose altitude rapidly until it burned up in the upper atmosphere. We will test such a tether de-orbit device in late 2000 on an upper stage built by the Lavochkin Association of Russia.

NASA is also considering such electrodynamic tethers for upward propulsion. In the system, solar panels would supply a flow of electricity through the tether to push against Earth's magnetic field. The resulting force could haul payloads around Earth indefinitely. This approach might be used to keep the International Space Station in orbit without refueling.

How far can tethers take humankind in the future? We and others have analyzed a system of rapidly cartwheeling, orbiting tethers up to hundreds of kilometers long for delivering payloads to the moon and ever farther. The idea is simple—think of Tarzan swinging from one vine to the next. First, a low-Earth-orbit tether picks up a payload from a reusable launch vehicle and hands the delivery to another tether in a more distant elliptical-Earth orbit. The second tether then tosses the object to the moon, where it is caught by a Lunavator tether in orbit there.

The Lunavator would be cartwheeling around the moon at just the right velocity so that, after catching the payload, it could gently deposit the object onto the lunar surface a half-rotation later. Simultaneously, the tether could pick up a return load. No propellant would be required if the amount of mass being delivered and picked up were balanced. Such a transportation mechanism could become a highway to the moon that might make frequent lunar travel commonplace.

Obviously, there are many technological challenges that must be overcome before such a system becomes a reality, but its potential for opening up an economical expressway in space is tremendous. Perhaps someday there will be numerous cartwheeling tethers around many of the planets and their moons, carrying the hustle and bustle of interplanetary commerce. And it all will have begun with a piece of string.

ROBERT L. FORWARD and ROBERT P. HOYT are the founders of Tethers Unlimited, a start-up aerospace company based in Clinton, Wash., that specializes in developing space tether systems for commercial applications.

vehicle to orbit with a single stage of engines that would automatically adapt to changing atmospheric pressure. But the X-33, which will not itself achieve orbit, pushes the limits of current construction techniques. And some observers now doubt whether it will be able to provide NASA with enough information for a promised year 2000 decision on whether the agency should continue to rely on current shuttles until after 2020 or instead phase out those expensive workhorses around 2012.

Difficulties in building the engines have delayed the first flight of the X-33 by six months, until the end of this year. And Daniel R. Mulville, NASA's chief engineer, maintains that a further "year or two" of development will most likely be needed after flight tests are completed in late 2000 before a decision on building a full-

Highways of Light

by Leik N. Myrabo

Today's spacecraft carry their source of power. The cost of space travel could be drastically reduced by leaving the fuel and massive components behind and beaming high-intensity laser light or microwave energy to the vehicles. Experiments sponsored over the past year by the National Aeronautics and Space Administration and the U.S. Air Force have demonstrated what I call a lightcraft, which rides along a pulsed infrared laser beam from the ground. Reflective surfaces in the craft focus the beam into a ring, where it heats air to a temperature nearly five times hotter than the surface of the sun, causing the air to expand explosively for thrust.

Using an army 10-kilowatt carbon dioxide laser pulsing 28 times per second, Franklin B. Mead of the U.S. Air Force Research Laboratory and I have successfully propelled spin-stabilized miniature lightcraft measuring 10 to 15 centimeters (four to six inches) in diameter to altitudes of up to 30 meters (99 feet) in roughly three seconds. We have funding to increase the laser power to 100 kilowatts, which will enable flights up to a 30-kilometer altitude. Although today's models weigh less than 50 grams (two ounces), our five-year goal is to accelerate a one-kilogram microsatellite into low-Earth orbit using a custom-built, one-megawatt ground-based laser—expending just a few hundred dollars' worth of electricity.

Current lightcraft demonstration vehicles are made of ordinary aircraft-grade aluminum and consist of a forward aeroshell, or covering, an annular (ring-shaped) cowl and an aft part consisting of an optic and expansion nozzle. During atmospheric flight, the forward section compresses the air and directs it to the engine inlet. The annular cowl takes the brunt of the thrust. The aft section serves as a parabolic collection mirror that concentrates the infrared laser light into an annular focus, while providing another surface against which the hot-air exhaust can press. The design offers automatic steering: if the craft starts to move outside the beam, the thrust inclines and pushes the vehicle back.

A one-kilogram lightcraft will accelerate this way to about Mach 5 and reach 30 kilometers' altitude, then switch to onboard liquid hydrogen for propellant as air becomes scarce. One kilogram of hydrogen should suffice to take the craft to orbit. A version 1.4 meters in diameter should be able to orbit microsatellites of up to 100 kilograms by riding a 100-megawatt laser beam. Because the beams we use are pulsed, this power might be achieved fairly easily by combining the output from a group of lasers. Such lasers could launch communications satellites and de-orbit them when their electronics become obsolete.

Lightcraft with different geometries can move toward their energy source rather than away from it—or even sideways. These variant vehicles have potential for moving cargo economically around the planet. Lightcraft could also be powered by microwaves. Microwaves cannot achieve such high power densities as lasers, so the vehicles would have to be larger. But microwave sources are considerably less expensive and easier to scale to very high powers.

I have also designed more sophisticated beamed-energy craft, operating on a different principle, that could transport passengers. These craft would be better for carrying larger cargoes because they can produce thrust more efficiently.

LEIK N. MYRABO

MINIATURE LIGHTCRAFT demonstration vehicle has already flown to a height of 30 meters in tests, powered by a 10-kilowatt laser. Larger designs should be able to accelerate to orbit.

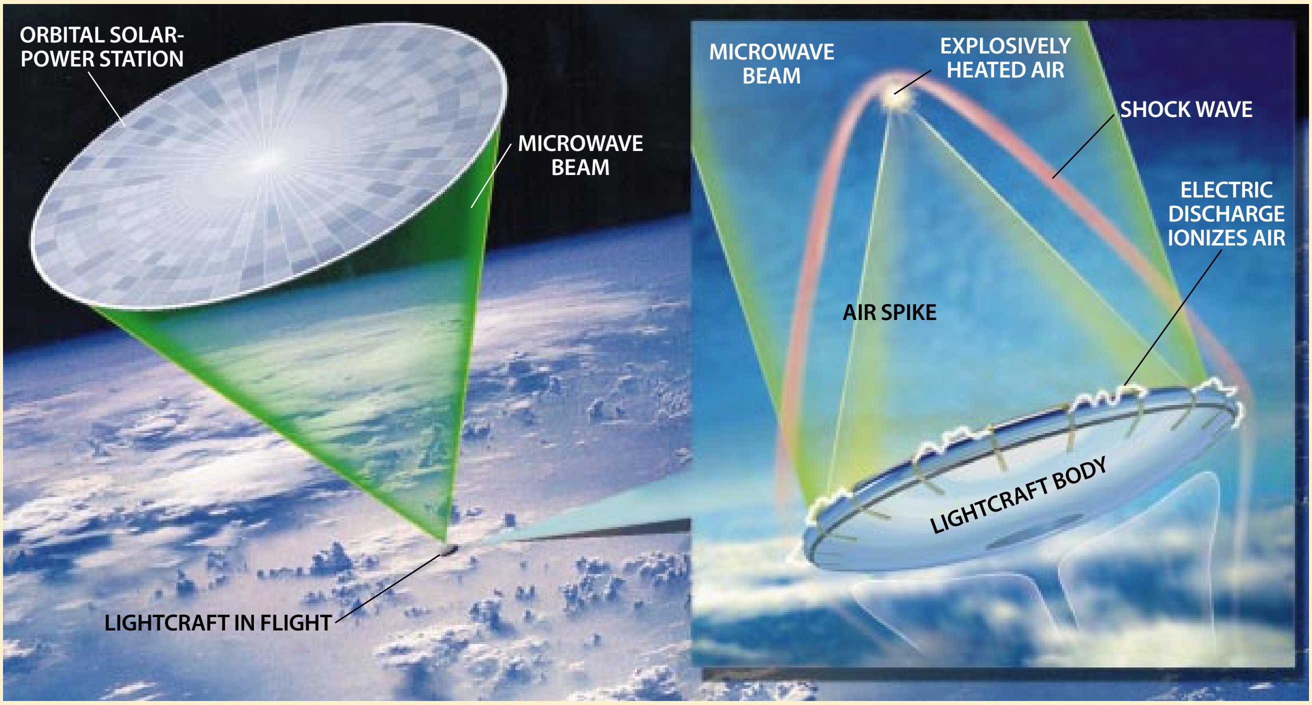
A mirror in the craft focuses some of the incoming beamed energy at a point one vehicle-diameter ahead of the vehicle. The intense heat creates an "air spike" that diverts oncoming air past the vehicle, decreasing drag and reducing the heating of the craft.

This craft taps some additional beamed energy to generate powerful electric fields around the rim, which ionizes air. It also uses superconducting magnets to create strong magnetic fields in that region. When ionized air moves through electric and magnetic fields in this configuration, magnetohydrodynamic forces come into play that accelerate the slipstream to create thrust.

By varying the amount of energy it reflects forward, the lightcraft can control the airflow around the vehicle. I demonstrated reduction of drag by an air spike in April 1995 in a hypersonic shock tunnel at Rensselaer Polytechnic Institute, though with an electrically heated plasma torch rather than with laser power. Tests aimed at generating magnetohydrodynamic thrust, using a 15-centimeter-diameter device, have just begun. A person-size lightcraft of this type driven by microwaves or by a 1,000-megawatt pulsed laser should be able to operate at altitudes up to 50 kilometers and to accelerate easily to orbital velocities.

Lightcraft could revolutionize transportation if they are driven from orbiting solar-power stations. But the cost of assembling the orbital infrastructure eventually must be reduced below a few hundred dollars per kilogram. It now costs about size single-stage-to-orbit vehicle. (Lockheed Martin, however, which calls its design the VentureStar, says it will be ready to commit by the end of 2000.) One problem: the world does not have a large enough autoclave to cure the VentureStar's all-composite liquid-hydrogen tank. More effort is also needed on the metallic tiles that will protect the craft from the heat of reentry.

The VentureStar was billed as a potential national launch system, notes Marcia S. Smith of the Congressional Research Service. Yet the timing could be awkward, as the first VentureStar would not carry humans. NASA has recently asked industry to study the options for carrying to orbit both human and nonhuman cargo early next century. Some potentially useful tricks are being explored with a smaller experimental vehicle known as



ORBITING solar-power station (*upper left*) could beam microwave energy to an ascending lightcraft (*right*) powered by magnetohydrodynamic thrust. The lightcraft focuses the microwave energy to create an "air spike" that deflects oncoming air. Electrodes on the vehicle's rim ionize air and form part of the thrust-generating system.

$20,000 to put a kilogram of payload in orbit by means of the space shuttle, about 100 times too much.

I think we can bridge the gap by making the first orbital power station one that is specialized for enabling cheap access to space. Imagine a one-kilometer-diameter structure built like a giant bicycle wheel and orbiting at an altitude of 500 kilometers. Its mass would be about 1,010 metric tons, and it would slowly spin to gain gyroscopic stability. Besides the structural "spokes," the wheel would have a disk made from 55 large, pie-slice segments of 0.32-millimeter-thick silicon carbide. Completely covering one side of the silicon carbide would be 30 percent efficient, thin-film solar photovoltaic cells capable of supplying 320 megawatts of electricity. (Such devices are expected within a decade.) On the other side would be 13.2 billion miniature solid-state transmitters, each just 8.5 millimeters across and delivering 1.5 watts of microwave power.

Today's heavy-lift chemical rockets could loft this entire structure over about 55 launches, at an affordable cost of perhaps $5.5 billion. The station would be ringed by an energy storage device consisting of two superconducting cables, each with a mass of 100 metric tons, that could be charged up with counterflowing electric currents. (This arrangement would eliminate the titanic magnetic torque that would be produced by a single cable.)

During two orbits of Earth, the station would completely charge this system with 1,800 gigajoules of energy. It would then beam down 4.3 gigawatts of microwave power onto a lightcraft at a range of about 1,170 kilometers. Torquing forces produced by shifting small amounts of current from one cable to the other would crudely point the power station, but fine control would come from a beacon mounted on the lightcraft. It would send a signal that would coordinate the individual transmitters on the power station to create a spot 10 meters in diameter at the launch site. The vehicle could reach orbit in less than five minutes, subjecting occupants to no more than three g's of acceleration, about the same that shuttle astronauts experience. Or the solar-power station could unload all its energy in a 54-second burst that should offer a nearly vertical 20-g boost to geostationary orbit or even to escape velocity.

The first orbital solar-power station will pave the way for a whole industry of orbital stations, launched and assembled from specialized lightcraft. Within decades, a fleet of these will make feasible rapid, low-cost travel around the globe, to the moon and beyond.

LEIK N. MYRABO is associate professor of engineering physics at Rensselaer Polytechnic Institute. His research interests focus on advanced propulsion and power technology, energy conversion, hypersonic gas dynamics and directed energy.

the X-34. It will test two-stage-to-orbit technologies, including a new type of reusable ceramic tile, starting this year.

Looking beyond X-33 and X-34 technology, the agency recently beefed up work on hypersonic jet engines, which had taken a back seat since the National Aerospace Plane program was canceled in November 1994. Variants on jet engines called scramjets—which breathe air like conventional jets but can operate at speeds over Mach 6—could help bring the goal of single stage to orbit within reach. Several unpiloted scramjets, designated X-43, will fly at speeds of up to Mach 10 and then crash-land in the Pacific Ocean, starting in the year 2000 [*see box on page 62*].

The difficulty faced by such efforts, explains NASA's Gary E. Payton, is in slowing the incoming air enough so that fuel can be burned in it for thrust without generating excess heat. In principle, it can be done with a shock wave created at the air inlet. But the process wastes a lot of energy.

One potentially pathbreaking launch technology is an air-breathing engine that also operates as a rocket both when at low velocities and when the air becomes too thin to be worth taking in. At that altitude, a vehicle heading for space would most likely be traveling at about Mach 10. Such rocket-based combined-cycle engines have yet to advance beyond tests in wind tunnels, and they have to be de-

Light Sails

by Henry M. Harris

Science-fiction dreams of worlds beyond our own solar system have taken on a more realistic aspect since astronomers discovered that the universe contains planets in unexpectedly large numbers. Studying those distant planets might show how special Earth really is and tell us more about our place in the universe. This perspective is prompting the National Aeronautics and Space Administration to turn its gaze toward the stars.

Gazing is one thing, but for actual exploration the engineering reality is harsh. It would take tens of thousands of years to reach even the nearest stars with today's technologies. In 1998 I coordinated for NASA a survey of propulsion concepts that might enable an exploratory vehicle to travel to another star fast enough to accomplish its mission within 40 years, the professional lifetime of a scientist. We came up with only three that now seem plausible: fusion [*see box on page 72*], antimatter and beamed energy. Of these, only beamed energy is understood sufficiently to be part of any realistic near-term research program.

It is easy to see why beamed energy is attractive. When you take your car on a long trip, you rely on gas stations for fuel and on mechanics to keep it running. Current spacecraft, in contrast, have to transport all the fuel they will need and must operate without human intervention. But could the engine somehow be kept on Earth, along with the fuel? Besides making in-flight repairs possible, the arrangement would make the spacecraft less massive and therefore easier to accelerate.

Beamed energy might offer a way. Engineering analyses suggest that the best approach for long-duration spaceflight is to shine a powerful optical laser at a large, thin "sail." This idea was first proposed by Robert L. Forward as long ago as 1984. Lasers can project energy over vast distances, and the large area of a sail allows it to receive a lot of energy in relation to its mass. Other types of beamed energy, such as microwaves, could also be used. Some investigators have even considered beaming charged particles at a spacecraft. The particles, on reaching the craft, would pass through a superconducting magnetic loop, thereby creating a Lorentz force that would provide thrust. But for now, laser light aimed at sails seems to be the most practical option.

When a photon from a laser hits a sail, one of two things can happen. It can collide elastically with the electromagnetic field surrounding the atoms in the sail and be reflected. Alternatively, the photon can simply be absorbed by the sail material, a process that heats the sail a minuscule amount. Both processes impart an acceleration, but reflection imparts twice as much as absorption. Thus, the most efficient sail is a reflective one.

The acceleration that a laser provides is proportional to the force it transmits to the sail and inversely proportional to the spacecraft's mass. Like other propulsion methods, then, light sails are limited in their performance by the thermal properties and the strength of materials—as well as by our ability to design low-mass structures. The sail designs that have been proposed consist of a polished, thin metal film, most with some kind of backing for structural strength.

SLIM FILMS

The power that can be transmitted is constrained by heating of the sail: as the metal surface gets hotter, it becomes less reflective. The temperature a sail attains can be lowered, and so its acceleration increased, by coating its reverse side with materials that efficiently radiate heat.

To reach very high velocities, a spacecraft must sustain its acceleration. The ultimate velocity achievable by a light sail is determined by how long the Earth-bound laser can illuminate its target efficiently. Laser light has an important property known as coherence. It means that the energy it can impart is undiminished by distance, up to a critical value known as the diffraction distance. Beyond it, the power delivered quickly becomes insignificant.

The diffraction distance of a laser, and thus the ultimate velocity of a spacecraft it powers, is governed by the size of the laser's aperture. Very powerful lasers would probably consist of hundreds of smaller ones ganged together in an array. The effective aperture size is roughly the diameter of the entire array. Maximum power is transferred when the array is packed as densely as possible. We have a tessellated design that approaches 100 percent packing density.

At the Jet Propulsion Laboratory in Pasadena, Calif., my team has studied the trade-offs in mission cost between the power of individual lasers and the size of an array. The aperture size required for an interstellar mission is enormous. A phased laser array we have designed to send a probe in 40 years to the nearby star Alpha Centauri would be 1,000 kilometers (621 miles) in diameter. Fortunately, planetary missions require much smaller apertures. A 46-gigawatt laser illuminating a 50-meter-diameter, gold-plated sail would require only a 15-meter aperture to send signed as part of the body of a craft to achieve adequate thrust. NASA recently awarded Boeing a cost-shared contract under its new Future-X program to develop an Advanced Technology Vehicle that will test a variety of hypersonic flight technologies. Payton says that "if things go well" flight tests of rocket-based combined-cycle engines could occur between 2004 and 2006.

As soon as a vehicle has left the atmosphere and reached orbital velocity—around Mach 25, or 18,000 miles per hour—the engineering challenges change completely. Large thrusts are no longer needed, because the craft is not fighting Earth's gravity and air resistance. Several new approaches are being explored, including, notably, the ion engine now flying on NASA's Deep Space 1 spacecraft. Ion engines work by accelerating charged atoms (ions) of a propellant with electrical grids charged to high voltage. As the ions leave the engine, they impart thrust. Xenon is the currently favored propellant.

Power on Deep Space 1 comes from solar panels, but theoretically any means of generating electricity could be used to drive an ion engine, which can produce almost 10 times more thrust per kilogram of propellant than chemical rockets can. As a result, even though ion engines generate only a few grams of force, they can in principle operate for years nonstop, allowing a spacecraft to reach extremely high velocities. Ion engines could feasibly

a 10-kilogram payload to Mars in 10 days. This system could send a probe to the boundary between the solar wind and the interstellar medium in three to four years.

Light-sail craft can be designed to follow a beam automatically, so steering can be done from Earth. A sail might even be built incorporating a reflective outer ring that could be detached on reaching the destination. The ring would continue onward as before and reflect laser light back onto the separated central part of the sail, thus propelling it back home.

A good deal of work relevant to light sails has already been done. The Department of Defense has developed high-powered lasers and precision-pointing capability as part of its research into ballistic-missile defenses and possible antisatellite weaponry. And saillike structures whose purpose is to reflect sunlight have already been tested. Russian scientists have flown a spinning 20-meter-diameter, polymer solar reflector, Znamya 2, as part of a scheme to provide extra winter illumination in northern Russian cities; a 25-meter-diameter version is scheduled for testing in February.

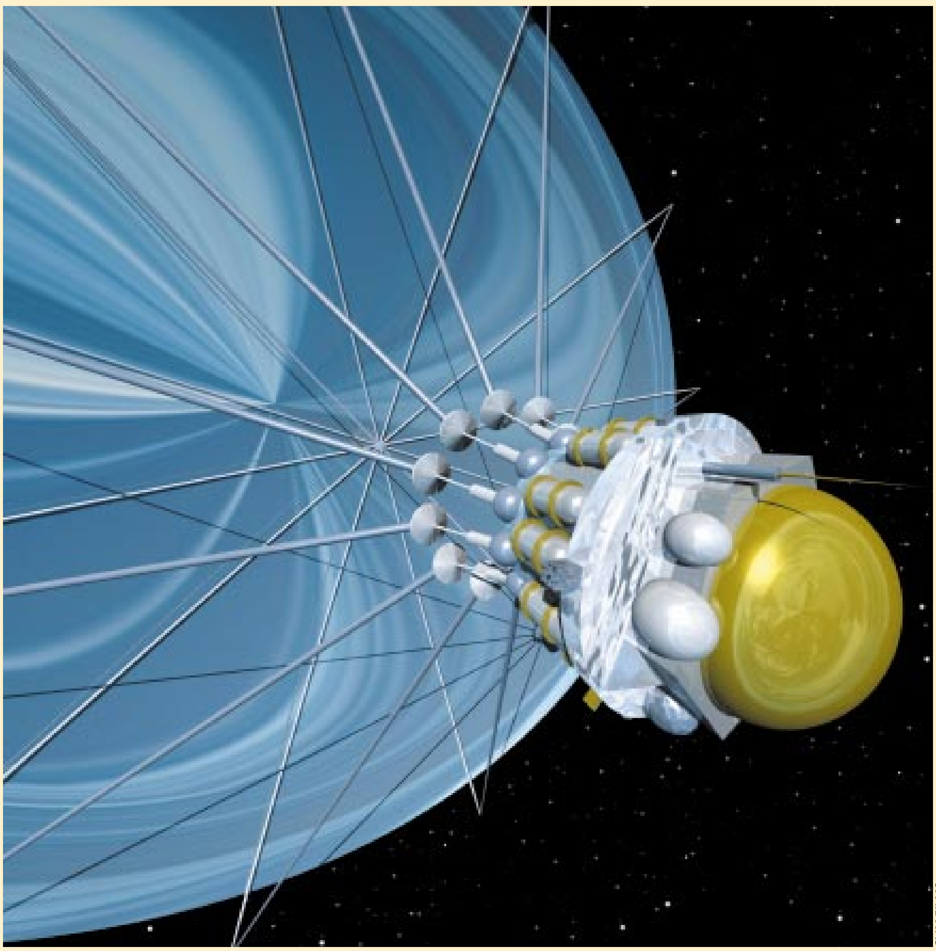
Closer to home, the U.S. National Oceanic and Atmospheric Administration is planning to launch within four years a spacecraft powered by a solar sail. The craft would hover at an orbitally unstable location between Earth and the sun, from where it could provide about an hour's advance warning of particles emanating from solar storms.

NASA is now evaluating plans to develop laser light sails as a possible low-cost alternative to conventional rockets. Missions being considered range from a demonstration of a 100-meter-diameter sail in Earth orbit to a journey through the shock wave at the edge of our planetary system.

In the immediate future, laboratory tests could measure the properties of candidate laser-sail materials for missions to Mars, the Kuiper belt and the interstellar medium. A military megawatt-class chemical laser at White Sands Missile Range in New Mexico may be used to illuminate sails deployed from spacecraft so that the resulting accelerations can be verified. And planned megawatt-class lasers that can run inexpensively off the power grid could within five years be able to boost light sails between orbits. I estimate that such lasers could power scientific missions to the moon within a decade.

We see in light sails a possible glimpse of the future, a vision of rapid, inexpensive access to the remote solar system and beyond. In time they could make travel to distant stars a reality.

HENRY M. HARRIS is a physicist who studies interstellar exploration at the Jet Propulsion Laboratory in Pasadena, Calif. He has also designed space shuttle and other experiments. Harris has worked as a jazz musician and has written a novel about science and spirituality.



SLIM FILMS

THEORIZED LIGHT-SAIL craft (*far left*) driven from Earth by a laser could one day convey sensors to distant reaches of the solar system and even to other stars. The sail's reflective surface maximizes velocity. The low-mass structure might carry a light payload (*near left*).

Compact Nuclear Rockets

by James R. Powell

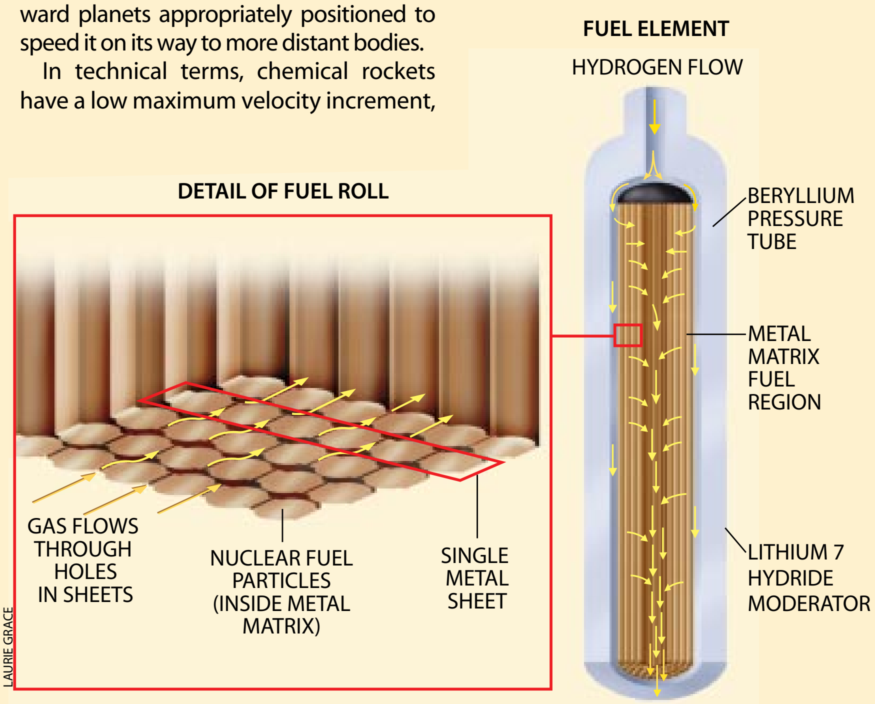
Someday, in exploring the outer planets of our solar system, humankind will want to do more than send diminutive probes that merely fly rapidly by them. In time, we will want to send spacecraft that go into orbit around these gaseous giants, land robots on their moons and even return rock and soil samples back to Earth. Eventually, we will want to send astronauts to their intriguing moons, on at least a couple of which liquid water—the fundamental requirement for life as we know it—is believed to be abundant.

For missions such as these, we will need rockets powered by nuclear fission rather than chemical combustion. Chemical rockets have served us well. But the relatively low amount of energy that they can deliver for a given mass of fuel imposes severe restrictions on spacecraft. To reach the outer planets, for example, a chemically powered space vehicle must have very limited mass and make extensive use of planetary gravitational "assists," in which the craft maneuvers close enough to a planet for the planet's gravitational field to act like a slingshot, boosting the speed of the craft. To take advantage of these assists, mission planners must wait for "windows"—short periods within which a craft can be launched toward planets appropriately positioned to speed it on its way to more distant bodies.

In technical terms, chemical rockets have a low maximum velocity increment, which means that their exhaust velocities are not high enough to impart very high speeds to the rocket. The best chemical rockets, which are based on the reaction between hydrogen and oxygen, impart a maximum velocity increment of about 10 kilometers (six miles) a second to spacecraft departing from Earth orbit.

Nuclear rockets, in contrast, could impart a maximum velocity increment of up to about 22 kilometers a second. Such a high value would make possible a direct path to, say, Saturn, reducing travel time from about seven years to as little as three. A nuclear rocket such as this would be inherently safe and environmentally benign: contrary to popular belief, a nuclear rocket need not be strongly radioactive when launched. The spacecraft, with its nuclear thrusters, would be launched as a payload atop a conventional chemical rocket. Then, once the payload was in high-Earth orbit, above about 800 kilometers, the nuclear reactor would start up.

The technology required to build a rocket motor powered by nuclear fission is not far beyond current capabilities. In fact, my colleagues and I have designed a compact nuclear rocket engine, which we call Mitee (deriving the letters loosely from the words "miniature reactor engine"), that could be built in about six or seven years at a cost of $600 million to $800 million—actually quite modest in the context of space launches. In fact, the costs of developing the engine would be offset by savings in future launch costs. The reason is that nuclear spacecraft powered by the engine would not need to haul along a large mass of chemical propellant, meaning that launching it would not require a Titan IV vehicle costing $250 million to $325 million. Instead a lower-priced rocket, such as a Delta or an Atlas in the range of $50 million to $125 million, could be used.



FUEL ELEMENT would be one of 37 in a compact nuclear rocket engine. Liquid hydrogen flowing into the element would convert to a gas and flow through the nuclear fuel roll (*light brown*). Five of the roll's metal matrix sheet layers are shown in the detail at the left. The superheated gas would then shoot down a center channel and out the bottom of the element, providing thrust.

In our design, the reactor's nuclear fuel would be in the form of perforated metal sheets in an annular roll, in a configuration similar to a jelly roll with a hollow center [*see illustration below*]. A jacket of lithium 7 hydride around the outside of the fuel roll would act as a moderator, reducing the speed of the neutrons emitted by the nuclear fission occurring inside the fuel. The coolant—liquid hydrogen—would flow from the outside of the roll inward, quickly turning into a gas as it heated up and flowed toward the center. The superheated gas, at about 2,700 degrees Celsius (4,900 degrees Fahrenheit), would flow at a high velocity along a channel at the center axis of the roll and then out through a small nozzle at the end.

A key attraction of nuclear propulsion is that its propellant—hydrogen—is widely available in gaseous form in the giant planets of the outer solar system and in the water ice of distant moons and planets. Thus, because the nuclear fuel would be relatively long-lasting, a nuclear-powered craft could in theory tour the outer solar system for 10 or 15 years, replenishing its hydrogen propellant as necessary. A vehicle could fly for months in the atmospheres of Jupiter, Saturn, Uranus and Neptune, gathering detailed data on their composition, weather patterns and other characteristics. Alternatively, a craft could fly to Europa, Pluto or Titan to collect rock samples and also accumulate hydrogen, by electrolyzing water from melted ice, for the trip back to Earth.

Because its reactor would start up well away from Earth, a nuclear-powered spacecraft could actually be made safer than some deep-space probes that are powered by chemical thrusters. In the outer reaches of the solar system, the sun's rays are too feeble to provide energy for a spacecraft's instruments. So they generally run on plutonium 238 power sources, which are highly radioactive even during launch. In a probe with nuclear thrusters, on the other hand, the instruments would be run off the same reactor that provides thrust. Moreover, the amount of radioactive waste produced would be negligible—amounting to about a gram of fission products for a deep-space mission—and in any event the material would never come back to Earth.

Nuclear rockets are not new. Among the U.S. Department of Defense's projects in this area was the Space Nuclear Thermal Propulsion program in the late 1980s. Its goal was to develop a compact, lightweight nuclear engine for defense applications, such as launching heavy payloads into high-Earth orbit. The cornerstone of the design was a particle bed reactor (PBR), in which the fuel consisted of small, packed particles of uranium carbide coated with zirconium carbide. Although the PBR work ended before a full-scale nuclear engine was built, engineers did successfully build and operate low-power reactors based on the concept and demonstrated that high-power densities could be achieved.

Indeed, our Mitee engine owes much to the PBR effort, on which my colleagues and I worked for nearly a decade at Brookhaven National Laboratory. In addition to the same basic annular configuration of fuel elements, the Mitee also would use lightweight, thermally stable lithium 7 hydride as a moderator. To be conservative, however, we designed the Mitee's fuel assembly to have a power density of about 10 megawatts per liter instead of the PBR's 30.

It is an easily provable fact that with only chemical rockets, our ability to explore the outer planets and their moons is meager. In the near term, only nuclear rockets could give us the kind of power, reliability and flexibility that we would need to improve dramatically our understanding of the still largely mysterious worlds at the far edges of our solar system.

JAMES R. POWELL is president of Plus Ultra Technologies in Shoreham, N.Y., which conceived and designed the Mitee reactor for space propulsion. He worked for Brookhaven National Laboratory from 1956 to 1996 and was head of its reactor systems division. The author wishes to thank his co-workers George Maise and John Paniagua for their help in the preparation of this article.

make long-term exploratory missions to Uranus and Neptune that would return far more data than the simple flybys that Voyager 2 made in the 1980s, according to James S. Sovey of the NASA Lewis Research Center.

Other Thrusters

Ion engines are not the only futuristic space drive being considered for solar system exploration. Hall thrusters also accelerate ions, but without grids. They employ radial magnetic fields, in part, to direct the ions, and they can deliver larger thrusts: a 50-kilowatt version has been tested, and research models are as propellant-efficient as an ion engine, according to Robert S. Jankovsky of the NASA Lewis center. The devices are attractive for now mainly for near-Earth space applications, although that could change if performance improves. The U.S. government has already flown one on a classified payload, and Teledesic, which plans to offer a broadband, global telecommunications service, will use Hall thrusters on its fleet of satellites.

Photovoltaic cells are now used to power almost all satellites in near-Earth orbit. And their performance is expected to improve: NASA has developed advanced designs that incorporate myriad small lenses that focus sunlight on the photovoltaic material. Deep Space 1 is now testing this type.

But solar power can be used to provide thrust more directly. The U.S. Air Force has committed $48 million to a four-year program to develop a solar-powered final rocket stage that would move satellites from low-Earth orbit to geostationary orbit at a fraction of the cost of chemical rockets. The Solar Orbit Transfer Vehicle uses a lightweight mirror to direct the sun's light onto a graphite block, which reaches 2,100 degrees Celsius (3,800 degrees Fahrenheit) and vaporizes stored liquid hydrogen. The expanding gas provides the thrust.

An operational version would take three to eight weeks to boost a typical payload to geostationary orbit, but its light weight means that a satellite will be able to go on a smaller rocket than it would otherwise. The savings amount to tens of millions of dollars for each launch, notes deputy program manager Thomas L. Kessler of Boeing.

The sun, however, can only do so much, and it is difficult to exploit solar power for journeys to planets more distant than Jupiter. The Galileo mission to Jupiter and the Cassini mission to Saturn both employed radioisotope thermal generators, which utilize the heat generated by the decay of plutonium 238 to generate modest amounts of electricity. But this technique

Space Access		
	Approximate launch year:	2003
	Approximate cost:	$4 billion to $6 billion
	Power source:	Air-breathing engines, rockets

COURTESY OF SPACE ACCESS

HEAVY SPACE PLANE is being developed by Space Access in Palmdale, Calif. The craft will utilize innovative ejector ramjet engines to accelerate to Mach 6, then switch to rocket engines. Separated stages will individually fly back to the launch strip.

cannot readily be scaled up to provide larger amounts.

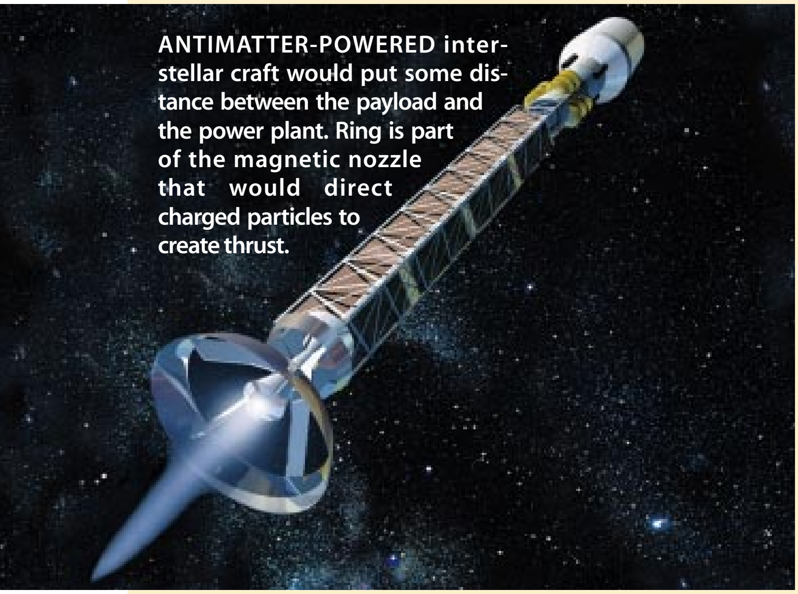
Many space buffs believe nuclear reactors designed to operate in space could be the answer. Because operating a reactor generates some radioactive waste, proponents of space nuclear power now envisage designs that would be launched on chemical rockets in an inactive state. They would be energized only after attaining a safe distance from Earth, so they would present no threat in the event of a launch accident. Some estimates indicate that a nuclear-powered journey to Mars might last just 100 days, about half the estimated trip time for a chemical rocket. A reactor could also be valuable to provide power to support a base on Mars,

Reaching for the Stars

by Stephanie D. Leifer

The notion of traveling to the stars is a concept compelling enough to recur in countless cultural artifacts, from Roman poetry to 20th-century popular music. So ingrained has the concept become that when novelists, poets or lyricists write of reaching for the stars, it is instantly understood as a kind of cultural shorthand for striving for the unattainable.

Although interstellar travel remains a glorious if futuristic dream, a small group of engineers and scientists is already exploring concepts and conducting experiments that may lead to technologies capable of propelling spacecraft to speeds high enough to travel far beyond the edge of our solar system. A propulsion system based on nuclear fusion could carry humans to the outer planets and could propel robotic spacecraft thousands of astronomical units into interstellar space (an astronomical unit, at 150 million kilometers, or 93 million miles, is the average distance from Earth to the sun). Such a system might be built in the next several decades. Eventually, even more powerful engines fueled by the mutual annihilation of matter and antimatter might carry spacecraft to nearby stars, the closest of which is Proxima Centauri, some 270,000 astronomical units distant.



ANTIMATTER-POWERED interstellar craft would put some distance between the payload and the power plant. Ring is part of the magnetic nozzle that would direct charged particles to create thrust.

BOB SAULS *John Frassanito & Associates*

The attraction of these exotic modes of propulsion lies in the fantastic amounts of energy they could release from a given mass of fuel. A fusion-based propulsion system, for example, could in theory produce about 100 trillion joules per kilogram of fuel—an energy density that is more than 10 million times greater than the corresponding figure for the chemical rockets that propel today's spacecraft. Matter-antimatter reactions would be even more difficult to exploit but would be capable of generating an astounding 20 quadrillion joules from a single kilogram of fuel—enough to supply the entire energy needs of the world for about 26 minutes.

In nuclear fusion, very light atoms are brought together at temperatures and pressures high enough, and for long enough, to fuse them into more massive atoms. The difference in mass between the reactants and the products of the reaction corresponds to the amount of energy released, according to Albert Einstein's famous formula $E = mc^2$.

The obstacles to exploiting fusion, much less antimatter, are daunting. Controlled fusion concepts, whether for rocket propulsion or terrestrial power generation, can be divided into two general classes. These categories indicate the technique used to confine the extremely hot, electrically charged gas, called a plasma, within which fusion occurs. In magnetic confinement fusion, strong magnetic fields contain the plasma. Inertial confinement fusion, on the other hand, relies on laser or ion beams to heat and compress a tiny pellet of fusion fuel.

In November 1997 researchers exploiting the magnetic confinement approach created a fusion reaction that produced 65 percent as much energy as was fed into it to initiate the reaction. This milestone was achieved in England at the Joint European Torus, a tokamak facility—a doughnut-shaped vessel in which the plasma is magnetically confined. A commercial fusion reactor would have to produce far more energy than went into it to start or maintain the reaction.

But even if commercial fusion power becomes a reality here on Earth, there will be several problems unique to developing fusion rockets. A key one will be directing the energetic charged particles created by the reaction to produce usable thrust. Other important challenges include acquiring and storing enough fusion fuel and maximizing the amount of power produced in relation to the mass of the spacecraft.

Since the late 1950s, scientists have proposed dozens of fusion rocket concepts. Although fusion produces enormous amounts of very energetic particles, the reaction will accelerate a spacecraft only if these particles can be directed so as to produce thrust. In fusion systems based on magnetic confinement, the strategy would be to feed in fuel to sustain the reaction while allowing a portion of the plasma to escape to generate thrust. Because the plasma would destroy any material vessel it touched, strong magnetic fields, generated by an assembly that researchers call a magnetic nozzle, would direct the charged particles out of the rocket.

In an engine based on the inertial confinement approach, high-power lasers or ion beams would ignite tiny fusion fuel capsules at a rate of perhaps 30 per second. A magnetic nozzle might also suffice to direct the plasma out of the engine to create thrust.

The particles created in a fusion reaction depend on the fuels used. The easiest reaction to initiate is between deuterium and tritium, two heavy isotopes of hydrogen whose atomic nuclei include one and two neutrons, respectively, besides a proton. The reaction products are neutrons and helium nuclei (also known as alpha particles). For thrust, the positively charged alpha particles are desirable, whereas the neutrons are not. Neutrons cannot be directed; they carry no charge. Their kinetic energy can be harnessed for propulsion, but not directly—to do so would involve stopping them says Samuel L. Venneri, NASA's chief technologist.

Reactors could be used for propulsion in various ways. One that generates thrust directly and operates for a short intense burst is described by James R. Powell on page 70. Such a design might make it possible to return rock samples to Earth from Pluto, Powell maintains. But there are other possibilities. A reactor could be designed to generate heat over long periods. Several different schemes then would be available to convert the heat to electricity to power ion drives, Hall thrusters or a new type of electric propulsion in early development known as a magnetoplasmodynamic thruster. "You can mix and match different reactor and thrust

in a material and making use of the heat generated by their capture. Neutron radiation also poses a danger to a human crew and would necessitate a large amount of shielding for piloted missions.

These facts lead to a key difficulty in fusion fuel selection. Although it is easiest to initiate fusion between deuterium and tritium, for many propulsion concepts it would be more desirable to use deuterium and the isotope helium 3 (two protons, one neutron). Fusion of these nuclei produces an alpha particle and a proton, both of which can be manipulated by magnetic fields.

The problem is that helium 3 is exceedingly rare on Earth. In addition, the deuterium–helium 3 reaction is more difficult to ignite than the deuterium-tritium reaction. But regardless of the fusion fuel selected, a spacecraft of thousands of tons—much of it fuel—would be necessary to carry humans to the outer reaches of the solar system or deep into interstellar space (for comparison, the International Space Station will have a mass of about 500 tons).

Even individually, the key obstacles to fusion propulsion—getting higher levels of power out of a controlled reaction, building effective containment devices and magnetic nozzles, and finding enough fuel—seem overwhelming. Still, for each of them, there is at least a glimmer of a future solution.

In the first place, there is every reason to believe that fusion reactors will go far beyond the break-even point, at which a reactor produces as much energy as is fed into it. Inertial confinement work in the U.S. is enjoying robust funding as part of the stockpile stewardship program, in which researchers are working on methods of assuring the safety and reliability of thermonuclear weapons without actually test-firing them. The research is centered at the National Ignition Facility, now under construction at Lawrence Livermore National Laboratory. The facility is expected to start up in 2001, with full laser energy of 1.8 million joules—for four billionths of a second—available in 2003. With that kind of power, researchers anticipate liberating up to 10 times the energy required to initiate the reaction.

There are indications, too, that the tokamak, which has dominated magnetic confinement research, may someday be supplanted by more compact technologies more amenable to rocket propulsion. In 1996 the Fusion Energy Sciences Advisory Committee of the U.S. Department of Energy endorsed investigation of such promising magnetic confinement schemes as reverse-field pinches, the field-reversed configuration and the spherical tokamak.

In the meantime, workers have begun preliminary work on magnetic nozzles. The largest research effort at present is a collaboration among the National Aeronautics and Space Administration, Ohio State University and Los Alamos National Laboratory. Researchers from the three organizations are using extremely high electric currents to create a plasma, which in the experiments stands in for a fusion plasma, and to study its interactions with a magnetic field.

Even the fusion fuel problem may be tractable. Although there is very little helium 3 on Earth, there are larger quantities of it in the lunar soil and in Jupiter's atmosphere as well. Also, other elements found on Earth, such as boron, may figure in alternative fusion reactions that are difficult to ignite but that yield alpha particles.

For all the promise of fusion propulsion, there is one known physical phenomenon—matter-antimatter annihilation—that releases far more energy for a given mass of reactants. A space propulsion system based on this principle would exploit the mutual annihilation of protons and antiprotons.

This annihilation results in a succession of reactions. The first of these is the production of pions—short-lived particles, some of which may be manipulated by magnetic fields to produce thrust. The pions resulting from matter-antimatter annihilation move at speeds close to that of light.

Here again, though, one of the key problems is scarcity: the number of antiprotons produced at high-energy particle accelerators all over the world adds up to only a few tens of nanograms a year. To carry humans on a rendezvous mission to the nearest star, Proxima Centauri, a matter-antimatter drive system would need tons of antiprotons. Trapping, storing and manipulating antiprotons present other major challenges because the particles annihilate on contact with ordinary protons.

Nevertheless, it may be possible to exploit, albeit to a lesser extent, antimatter's high energy content while requiring much smaller numbers of antiprotons—amounts that are most likely to be available in the next decade. Such a system would use antiprotons to trigger inertial confinement fusion. The antiprotons would penetrate the nuclei of heavy atoms, annihilating with protons and causing the heavy nuclei to fission. The energetic fission fragments would heat the fusion fuel, initiating the fusion reaction. The first steps toward determining the feasibility of such a propulsion system are already being taken under NASA sponsorship. One research activity is the design and construction, at Pennsylvania State University, of a device in which antiprotons could be trapped and transported.

DANA BERRY (*spaceship*); ROBERT O'DELL (*Orion nebula*)

HUMAN-PILOTED interstellar spaceship would have a rotating structure in front, to simulate gravity in four compartments.

At this very early stage, the challenges to building fusion—let alone antimatter—propulsion systems may seem insurmountable. Yet humankind has achieved the seemingly impossible in the past. The Apollo program and the Manhattan Project, among other large undertakings, demonstrated what can be accomplished when focused, concerted efforts and plenty of capital are brought to bear. With fusion and antimatter propulsion, the stakes could not be higher. For these will be the technologies with which humanity will finally and truly reach for the stars.

STEPHANIE D. LEIFER is manager of advanced propulsion concepts in the Advanced Propulsion Technology Group at the Jet Propulsion Laboratory in Pasadena, Calif. At JPL she has also studied solar sails and electric and micropropulsion systems.

concepts," observes Gary L. Bennett, NASA's former manager of advanced space propulsion systems. Yet strong public distaste for anything nuclear means that space reactors face enormous political obstacles, and NASA's effort in that area is now dormant.

Beam Me Up

Whether space nuclear power is eventually developed or not, inventive engineers and scientists are optimistic about the prospects for further solar system exploration. Ivan Bekey, a former top NASA official and now a consultant, believes that a sustained effort could reduce launch costs from $20,000 a kilogram to as low as $2 a kilogram over the next 40 years. Fully reusable single-stage-to-orbit launchers should achieve the first factor of 10 within a decade, he predicts.

Engines that combine hypersonic technology and rocket propulsion, together with new high-energy propellants, should achieve another factor of 10. (Reusable single-stage-to-orbit vehicles that could each fly 1,000 flights a year would be another way of bringing launch costs down to $200 per kilogram, Bekey estimates.) Bekey is impressed, too, with the potential of magnetically levitated catapults, devices that would suspend a rocket craft above a track like a maglev train. The track would have an upward curve at one end—built, perhaps, on the side of a mountain. The rocket-powered vehicle would accelerate along the track and leave it skyward at a 30- to 40-degree angle and about the speed of sound.

Beyond 20 years from now, Bekey envisages microwave-powered vehicles like the designs described by Leik N. Myrabo of Rensselaer Polytechnic Institute [*see box on page 66*]. These craft would create thrust by means of what are termed magnetohydrodynamic forces, which arise when a conductive fluid or gas moves through crossed electric and magnetic fields. The engineering obstacles are substantial—but many of those who have examined the principle believe it could be made to work. Because beamed energy means that neither oxidizer nor fuel has to be carried out of Earth's gravitational potential well, laser- or microwave-driven craft should reduce launch costs to $20 a kilogram, Bekey asserts.

Myrabo and others believe beamed-energy craft could be supported by a network of orbital solar-power stations. In principle, power stations in space have many advantages: for the part of their orbit when they are illuminated by the sun, they are assured of receiving plenty of photons. NASA, spurred by an enthusiastic Dana Rohrabacher, representative from California and chairman of the House of Representatives's subcommittee on space and aeronautics, is studying the idea for supplying power to users on the ground. But Venneri says that "in the past the economics have not been there" to support that application. Using inflatable structures in low-Earth orbit could bring costs down somewhat, he adds.

Orbital solar-power stations, which could resemble the alien saucers in the movie *Independence Day,* might however make more economic sense if their energy were used by craft in transit through Earth's atmospheric veil. That, at any rate, is Myrabo's contention.

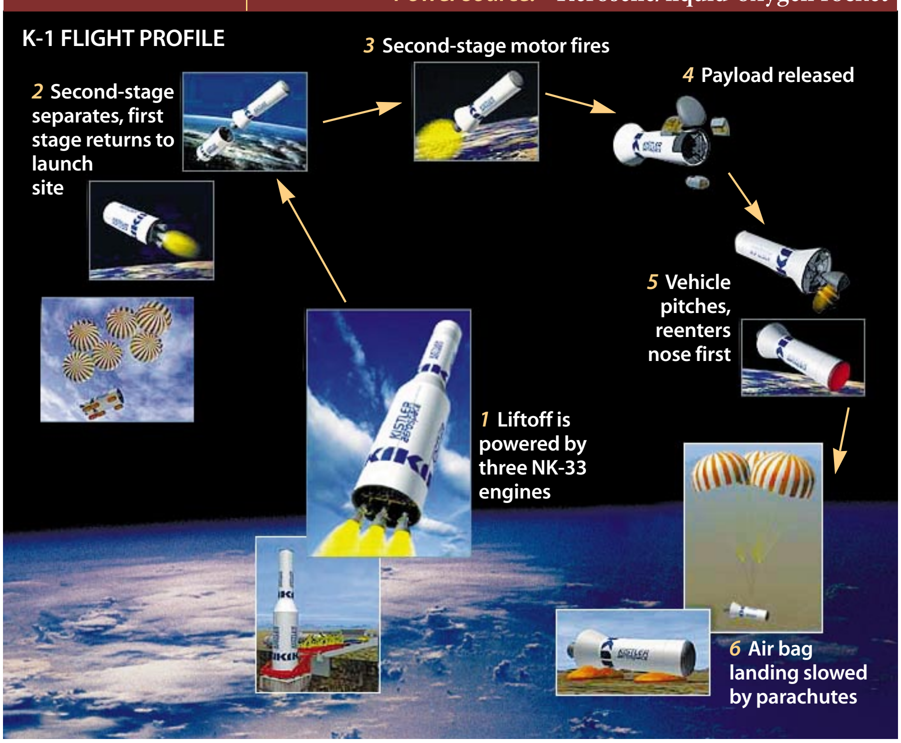
Space enthusiasts are also gung-ho about the potential of tethers, long connecting cables that in orbit acquire astonishing properties nearly qualifying them as a means of propulsion. Their bizarre behavior arises because to stay in orbit, objects farther from Earth's center must maintain a slightly slower horizontal velocity than closer objects. As a result, when objects at different altitudes are connected by a tether more than a few hundred meters long, powerful forces keep it in tension.

Other physical principles, notably the conservation of angular momentum, can then operate on the tethered bodies. The upshot, via some counterintuitive mechanics, is that a tether can be used like a giant slingshot to transfer momentum efficiently between payloads and so quickly propel satellites between orbits. Electrically conducting versions can even be used to generate electricity or contribute lift [*see box on page 64*]. Yet predicting and controlling the dynamics of large, multibody systems in orbit remains a difficult challenge, Venneri cautions.

Tethers even open up the startling possibility of connecting the whole Earth to a satellite in geostationary orbit by a fixed line attached at a point on the planet's

Kistler Reusable Rocket

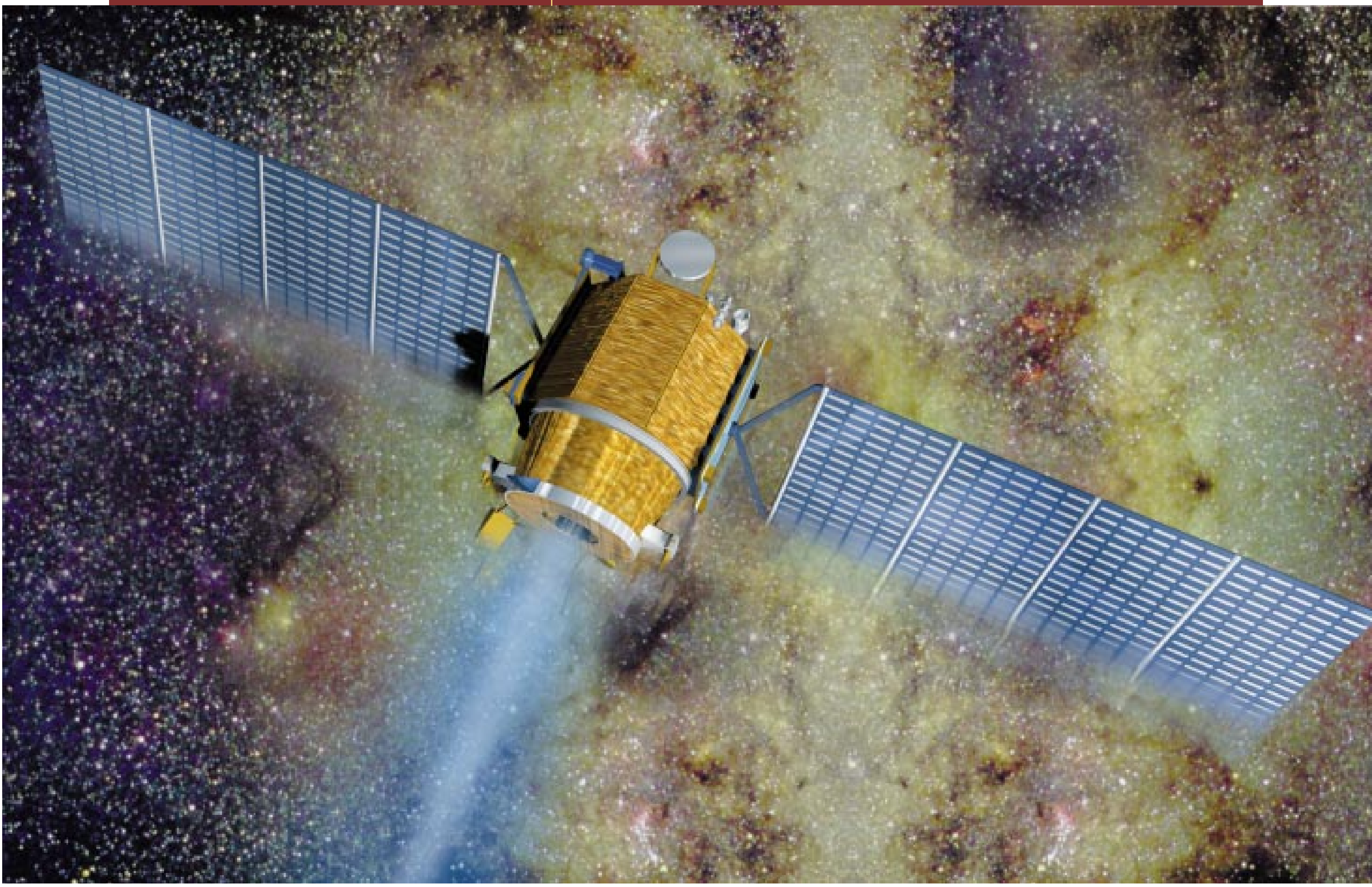
Approximate launch year:	1999
Approximate cost:	Undisclosed
Power source:	Kerosene/liquid-oxygen rocket



COURTESY OF KISTLER AEROSPACE

"WORLD'S FIRST FULLY REUSABLE LAUNCH VEHICLE" is how Kistler Aerospace in Kirkland, Wash., describes its K-1 rocket, scheduled to fly late this year. The two-stage rocket utilizes Russian-built engines that run on kerosene and liquid oxygen. The separated stages return to Earth by parachute.

Ion Propulsion System		
	Launch year:	1998
	Approximate cost:	$150 million
	Power source:	Photovoltaics



DON FOLEY

ION ENGINE is flying now on the Deep Space 1 spacecraft, which is scheduled to visit an asteroid. The system uses solar panels to generate electric fields that accelerate charged atoms of xenon. The engine can operate for weeks at a time and so reach high velocities.

equator. Climbing devices could then ascend the tether to reach any desired altitude up to 36,000 kilometers, with very little expenditure of energy.

Such a tether could not be built today, because the forces it would experience mean it would have to be made from a material far stronger for its weight than Kevlar, the polymer used for some small-scale tethers. But Bekey notes that buckytubes, which are microscopic fibers made of carbon atoms assembled into tubes just a few nanometers in diameter, might fit the bill. "When we learn how to grow them into long ropes and work and tie them, we'll be able to make a tether 600 times stronger than with current materials," he predicts, with airy confidence. That would be more than strong enough. A geostationary tether system could reduce launch costs to $2 a kilogram, Bekey says.

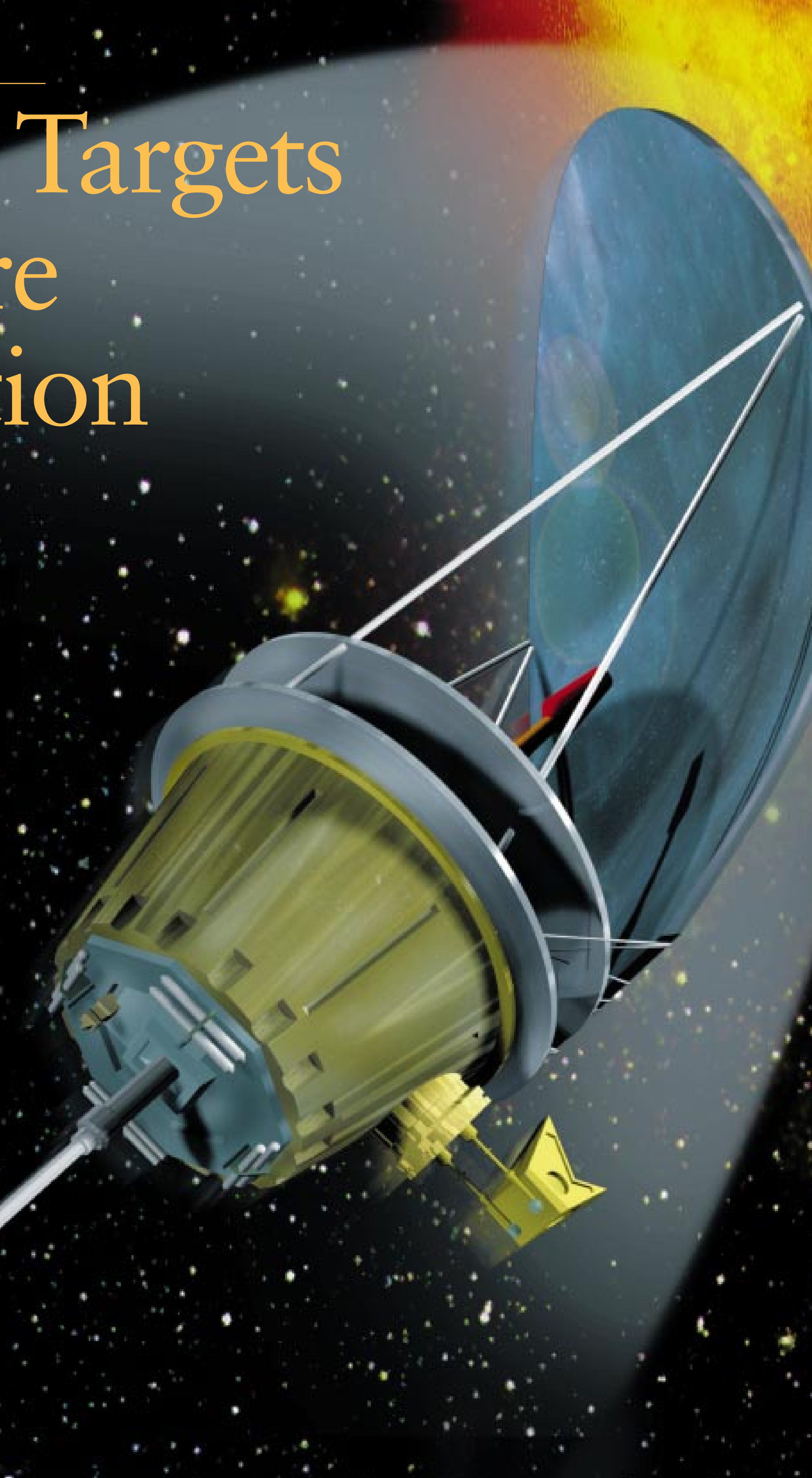
As if such schemes were not ambitious enough, long-term thinkers are even now studying concepts that might one day allow humans to send a spacecraft to another star. The most promising approach at present seems to be light sails [*see box on page 68*]. Such devices might well also be employed to move cargo around the solar system.

Tapping the huge theoretical power of fusion to propel spacecraft has its devotees, too. Although controlled production of useful energy from fusion has not yet been demonstrated even on Earth, hope springs eternal, and a fusion reactor in space would be able to provide enough energy to reach any solar system destination with ease [*see box on page 72*].

Other notions for propulsion technologies are even more far-out and have been floated as possible means for making interstellar journeys: quantum teleportation, wormholes and the elimination of momentum. These mind-boggling ideas seem to require entirely new understandings of physics; the steps for making them feasible cannot even be listed today. Even so, serious investigators continue to look for ways to turn each of these concepts into reality. If they work, they will change radically our ideas about the universe. And who is to say that any of them will prove forever impossible? SA

Further reading for this article is available at www.sciam.com/1999/0299issue/0299beardsleybox1.html on the World Wide Web. This article also appeared in Scientific American *in February 1999.*

The Best Targets for Future Exploration



So much to see, so little money. That is the problem faced by the National Aeronautics and Space Administration as it tries to determine which space missions it can afford to fund. The agency must choose among dozens of worthy proposals, balancing the cost and risk of each mission against its potential for new discoveries.

In the following pages, SCIENTIFIC AMERICAN presents some of the best targets for future exploration as well as the missions that have been proposed for studying them (for planned Mars missions, see "What's Next for Mars," on page 40). All plans and launch dates are subject to change. *—The Editors*

The Sun

Upcoming missions will investigate the sun and the powerful solar wind that it hurls toward the planets

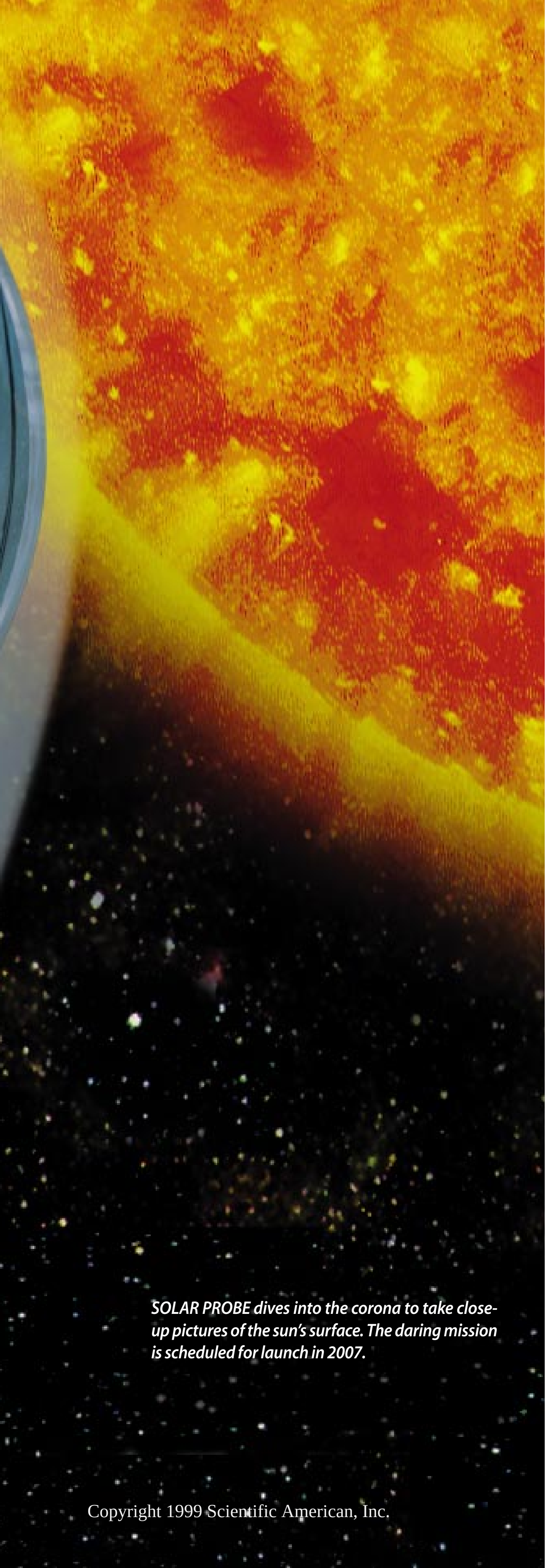
Like an ill-tempered king, the sun is prone to violent outbursts. Shifts in the sun's intense magnetic fields send monstrous streams of charged particles hurtling through space. This solar wind buffets the planets and sparks the aurora borealis in Earth's Northern Hemisphere. Occasional surges in the solar wind can also silence communications satellites and cause power blackouts on Earth. In the next decade, space agencies in the U.S., Europe and Asia expect to launch a small fleet of spacecraft to study the sun and its fierce flare-ups. One of those probes will even venture into the corona, the sun's fiery outer atmosphere.

Recent solar missions have paved the way. For the past three years, the Solar and Heliospheric Observatory (SOHO) has provided breathtaking images of the sun and its corona. And the Ulysses probe has measured the solar wind and the sun's magnetic field while moving in a distant orbit that allows it to view the sun's north and south poles. These missions suggest that the fastest solar winds, flowing at up to 800 kilometers (500 miles) per second, may arise all over the sun's surface and not just from its poles, as astronomers had previously thought. But scientists still don't understand the physical processes that produce the solar wind, and they cannot predict the occurrence of the solar storms that wreak such havoc on Earth.

In 2001 NASA plans to launch Genesis, a spacecraft that will collect solar-wind particles from a near-Earth orbit. After a three-year mission, the probe will return the samples to Earth, where scientists can measure the abundance of various elements and isotopes. Russia, Japan and Germany are also developing spacecraft that will study the sun from a variety of vantage points. But the most ambitious mission is NASA's Solar Probe, scheduled for launch in 2007. This spacecraft will go into an eccentric orbit that in 2010 will send it through the corona, less than three million kilometers from the sun's surface—about one-twentieth the distance between the sun and Mercury.

During its first flyby of the sun, 14 hours from pole to pole, Solar Probe's heat shields will have to withstand temperatures of up to 2,000 degrees Celsius (3,600 degrees Fahrenheit). The spacecraft will measure the sun's magnetic fields and take high-resolution photographs of the sun's surface. The probe will also carry several spectrometers and an instrument to measure the sun's plasma waves. "It's the first mission to a star—our star," says Bruce Tsurutani, Solar Probe project scientist at the Jet Propulsion Laboratory in Pasadena, Calif. The spacecraft will return for a second flyby in 2015, when it will speed through the coronal holes where the fastest solar winds appear to originate.

Scientists hope the spacecraft will help explain how the solar wind is accelerated to such incredible speeds. The mission may also illuminate the most puzzling paradox of solar physics: why the sun's outer atmosphere is hundreds of times hotter than the sun's surface. And David Hathaway, head of solar physics at the NASA Marshall Space Flight Center, says the new data may help scientists forecast potentially damaging solar storms. "These scientific mysteries aren't just intellectual curiosities," Hathaway remarks.



***SOLAR PROBE** dives into the corona to take close-up pictures of the sun's surface. The daring mission is scheduled for launch in 2007.*

DON FOLEY

U.S. GEOLOGICAL SURVEY

MERCURY, the innermost planet, has a rocky and cratered surface (above left). *An artist's conception shows the Discovery scarp, a 500-kilometer- long fault, at daybreak* (above right).

SURFACE OF VENUS is obscured by clouds (right), *but the Magellan orbiter used radar to map the planet. The radar data were processed to create a perspective of Maat Mons* (below), *a six-kilometer-high volcano.*

DAVID P. ANDERSON *Southern Methodist University*

Venus and Mercury

DON DIXON

The inner planets are full of intriguing mysteries. Studying the atmosphere of Venus may teach scientists about global warming. And the surface of Mercury may hold secrets about the early history of the solar system. NASA is considering missions to both planets

Venus provides a good example of the horrific effects of runaway global warming. The planet is a hellish place, with a carbon dioxide–choked atmosphere, clouds of sulfuric acid and a surface hot enough to melt lead. But planetary scientists believe that Venus started out much like Earth and simply evolved differently, like a twin gone bad. Venus offers researchers a unique opportunity to compare the planet with Earth and perhaps discover why the histories of the two bodies diverged.

In 2002 a proposed mission called the Venus Sounder for Planetary Exploration (VESPER) may travel to Earth's closest neighbor, following the trail blazed by the Mariner, Pioneer and Magellan spacecraft. VESPER is expected to orbit Venus for two and a half years, measuring atmospheric gases, wind speeds, air pressure and temperature—in short, recording the planet's weather. Mounted on a three-axis platform, VESPER's spectrometers, cameras and other instruments will pivot their fields of view to study Venus's environment from every angle.

VESPER will focus its instruments on Venus's middle atmosphere, 60 to 120 kilometers above the surface. It is here that yellow clouds of sulfuric acid form, causing the greenhouse effect that heats up the planet. Gordon Chin, VESPER's principal investigator at the NASA Goddard Space Flight Center, says the spacecraft could help scientists understand how to prevent such disastrous global warming on Earth. "For that, Venus is a wonderful laboratory," Chin observes.

Mercury, the planet closest to the sun, also intrigues scientists. It is the second densest planet in the solar system, next to Earth, and contains a much higher proportion of iron than any other planet or satellite does. Astronomers have developed several hypotheses to explain Mercury's unusual density. Some scientists speculate that early in the solar system's history, the sun vaporized the outer part of the planet, leaving only the metallic core intact. Others believe that a comet or asteroid impact may have blasted away Mercury's outer crust and mantle.

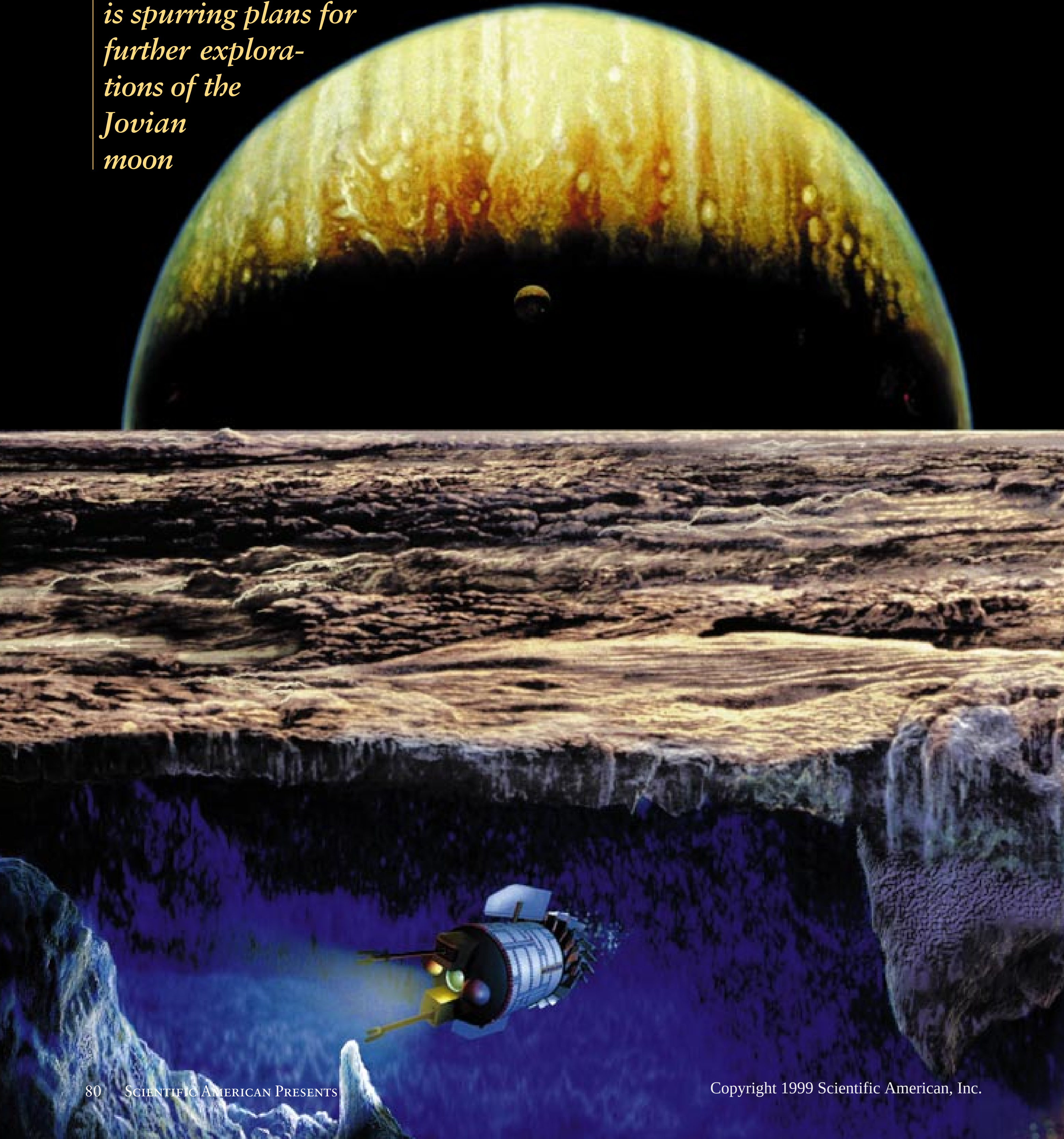
Only one spacecraft has ever visited Mercury: Mariner 10, which flew by the planet three times in 1974 and 1975. But NASA is now considering the Mercury Surface, Space Environment, Geochemistry and Ranging mission (MESSENGER), which is scheduled for launch in 2004. After flying by Venus and Mercury twice, the 300-kilogram spacecraft would go into orbit around Mercury in 2009. For the next year, MESSENGER would use its instruments—including an imaging system, a magnetometer and four spectrometers—to gather data on Mercury's surface features, magnetic field and tenuous atmosphere.

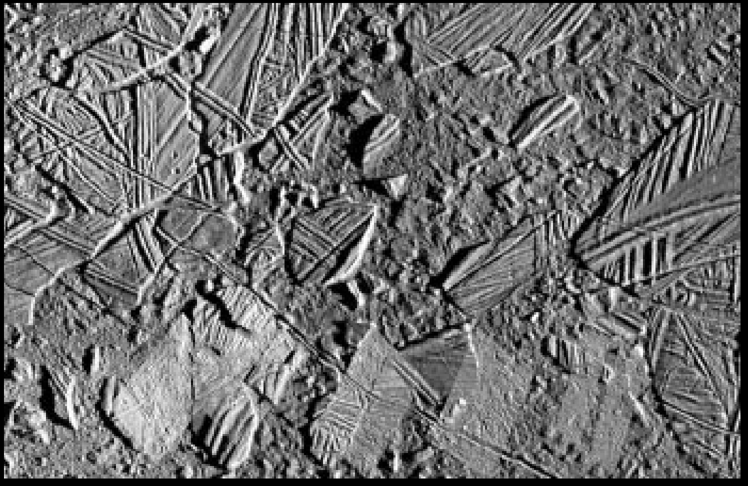
Because Mercury is so close to the sun—about one third as far from it as Earth—MESSENGER will carry a huge sunshade to protect the spacecraft's instruments from the intense solar radiation. Scientists hope that the probe can solve the mystery of Mercury's geologic past by determining the abundance of elements in the planet's crust. "It's just one example of the formation and evolution questions we can ask about terrestrial planets in the inner solar system," explains Sean Solomon, the Carnegie Institution of Washington geophysicist who is the mission's principal investigator. "And like so many questions, this one can only be answered in space."

NASA

Europa

The possible presence of an ocean under Europa's ice is spurring plans for further explorations of the Jovian moon





FRACTURED ICE
on the surface of Europa is shown in this mosaic of images (above) *taken by the Galileo spacecraft in 1997. This 1,750-square-kilometer area lies near Europa's equator, where tidal forces are most likely to disrupt the icy crust. If the presence of a subsurface ocean is confirmed, scientists plan to send a robotic probe beneath the ice to search for signs of life* (below). *Bubbles rise from a hydrothermal vent* (bottom right).

DON DIXON; NASA (*inset*)

Europa is no ordinary moon. The surface of Jupiter's fourth-largest satellite is sheathed with a layer of scarred and fractured ice. Many scientists believe that at one point in Europa's past—and possibly still today—a briny ocean roiled under the ice pack. If still present, the ocean could be the first found on another world. It could even be home to extraterrestrial life, which might thrive near undersea volcanic vents.

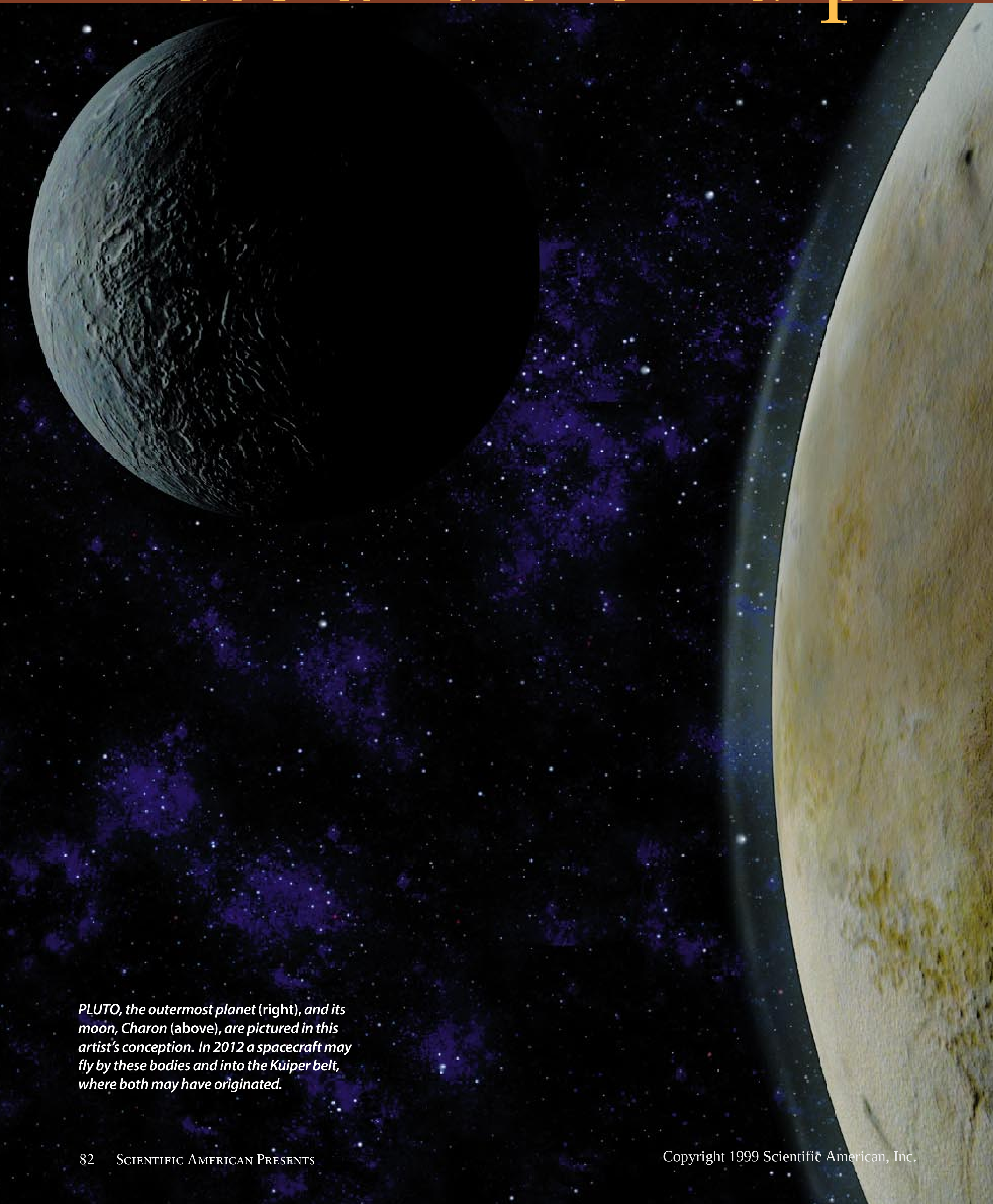
In 1979 NASA's Voyager 1 probe first glimpsed Europa's craggy surface. Over the past four years, the Galileo spacecraft has repeatedly flown by Europa during its orbits around Jupiter and transmitted clearer images of the moon's icy shell. The ice is streaked with stress cracks, ridges and salt deposits—all evidence, scientists say, of a turbulent ocean underneath the ice. Although the temperature at Europa's surface is a chilly –160 degrees Celsius (–256 degrees Fahrenheit), friction generated by Jupiter's enormous gravity—which causes Europa's surface to rise and fall in a kind of tide—may be warming the moon's interior. Unfortunately, scientists do not know for certain whether an ocean of liquid water or slush lies below Europa's surface. Galileo's cameras cannot peer through the ice to find out.

So NASA is going diving. In 2003 the agency plans to launch a spacecraft called Europa Orbiter that will aim ice-penetrating radar at the moon. After the probe goes into orbit around Europa, a three-antenna radar array will beam signals of various frequencies toward the moon's surface. By recording the reflections of the signals, the instrument will measure the thickness of the ice layer and determine whether an ocean lies below it. If an ocean exists, the radar will provide a three-dimensional map of its distribution. In addition, a laser altimeter on board the spacecraft will measure the tidal deformation of Europa's surface caused by Jupiter's gravity. The tidal bulge should be much larger if there is an ocean beneath the ice.

Here on Earth, oceans mean life. Researchers have found hardy microbes, dubbed extremophiles, lurking in even the most punishing oceanic environments, from Antarctic sea ice to deep-sea hydrothermal vents. Could organisms do the same on a moon that is 780 million kilometers from the sun? Probably, says Torrence Johnson, project scientist for Europa Orbiter at the Jet Propulsion Laboratory. "Europa may be the only place where we can find extraterrestrial life in an ocean."

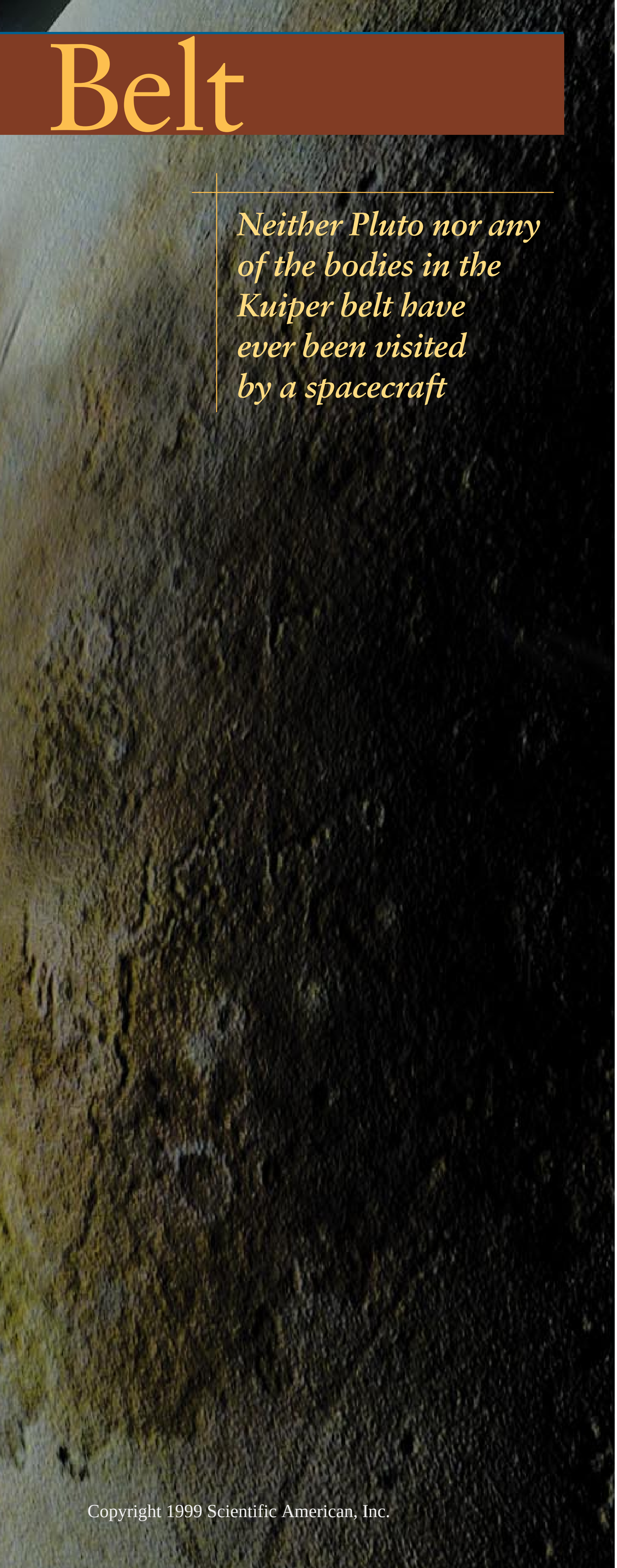
Europa Orbiter, slated to arrive at the moon in 2007, will stop short of looking for life. It will, however, identify prime landing spots for future missions. One idea for a follow-up mission is to use hydrobots, or remote-controlled underwater probes, that would penetrate the ice, possibly by melting their way through, and look for signs of life in the water below. JPL scientists have already designed a prototype, a 20-centimeter-wide cylinder equipped with a camera. They recently tested the probe at an undersea volcano off the coast of Hawaii. A research submersible lowered the probe to a depth of nearly 1.3 kilometers, then inserted it into a hydrothermal vent so that it could search for microbes in the superheated water. The scientists hope to test a similar hydrobot in Antarctica and finally on Europa. "If life is there," Johnson states, "we'd like to find it."

Pluto and the Kuiper



PLUTO, the outermost planet (right), *and its moon, Charon* (above), *are pictured in this artist's conception. In 2012 a spacecraft may fly by these bodies and into the Kuiper belt, where both may have originated.*

Belt



Neither Pluto nor any of the bodies in the Kuiper belt have ever been visited by a spacecraft

SAIC; PAT RAWLINGS

Pluto may be the smallest planet, but to astronomers it is Mount Everest. On the solar system's fringe, Pluto is the one planet that has never been observed up close by a spacecraft. For two decades, NASA scientists have been proposing missions to Pluto. Around 2012, a spacecraft called Pluto-Kuiper Express may finally get the chance. Shooting in a straight trajectory past Pluto, the probe will map the planet and its moon, Charon, in zoom-lens detail.

Discovered in 1930, Pluto is unusual inside and out. The planet's surface is a shell of frozen methane, carbon monoxide, nitrogen and oxygen. Underneath, its rock-and-ice body may be more similar to a comet's nucleus than to that of a typical planet. Pluto orbits near the edge of the Kuiper belt, a disorderly gang of comets and other objects too small to be considered planets. Pluto's distance from the sun varies from 4.4 billion to 7.4 billion kilometers during its eccentric 248-year orbit. Pluto's diameter of 2,340 kilometers is only twice as large as Charon's diameter, leading some astronomers to consider the pair a double planet.

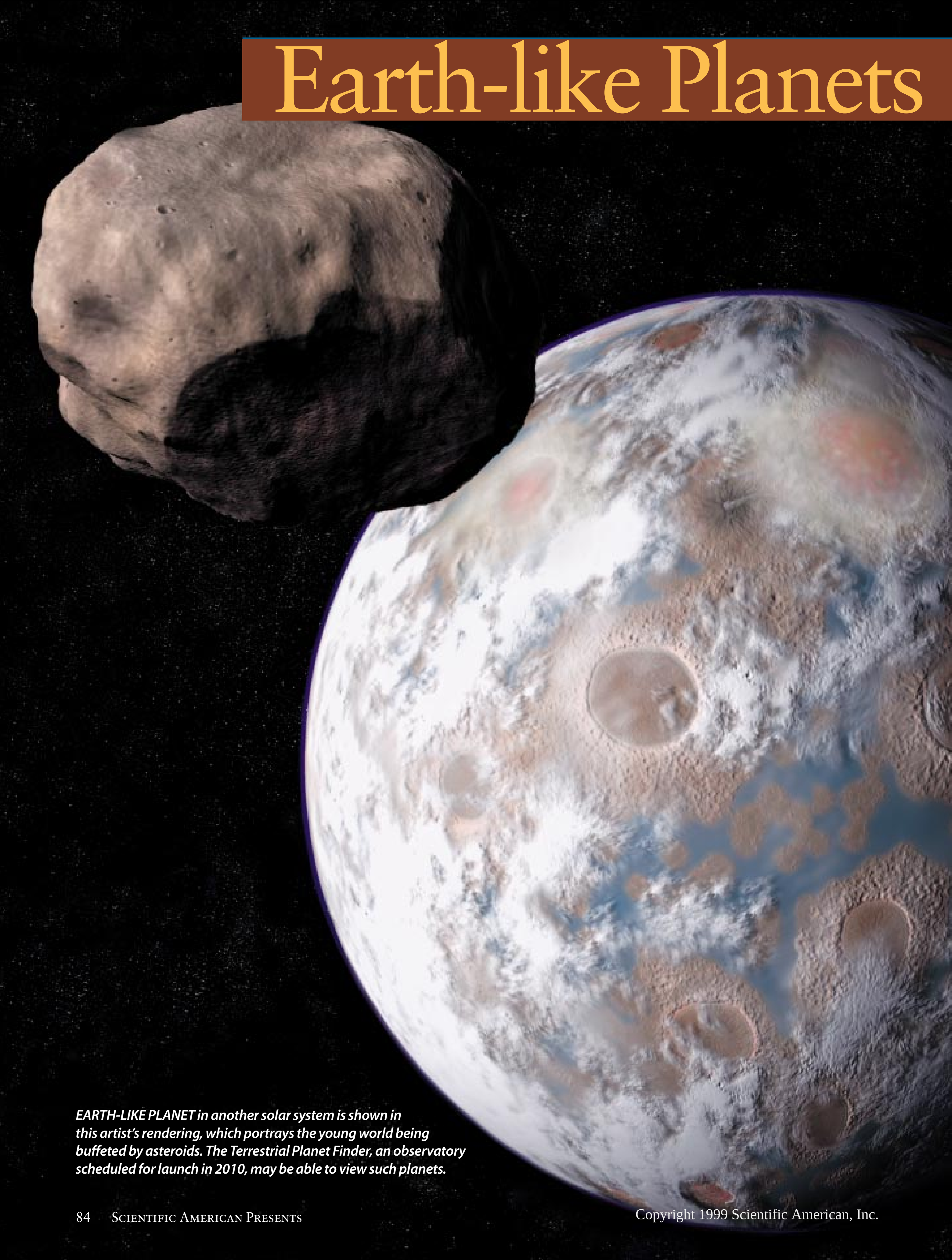
Because Pluto is so far from Earth, the best images of the planet—taken by the Hubble Space Telescope—have very low resolution. But Pluto-Kuiper Express will whiz within 15,000 kilometers of the planet's surface, snapping photographs that will show features smaller than a kilometer across. According to Robert Staehle, the mission's deputy project manager, NASA plans to launch the probe in 2004, and it will travel at roughly 18 kilometers per second for almost a decade to make the five-billion-kilometer trek to Pluto. After its long journey, the spacecraft will spend only a few hours actually gleaning details from the farthest planet.

In keeping with NASA's focus on "faster, better, cheaper" missions, Pluto-Kuiper Express will be relatively lightweight—around 135 kilograms—and cost some $250 million. About a meter wide, the spacecraft will carry an instrument package barely heavier than a backpack of books. Cameras and spectrometers will photograph landforms on both Pluto and Charon as well as characterize surface chemicals and take temperature and pressure readings. The probe will also measure Pluto's gravitational pull. And as the spacecraft flies past the planet, an ultraviolet spectrometer will determine the composition of its thin atmosphere by measuring the absorption of the sunlight passing through it.

Pluto's atmosphere captivates scientists because it is so variable. When Pluto is closer to the sun, the light causes some of the frozen chemicals on the planet's surface to sublimate into gases. Because the planet is so small, however, its meager gravity cannot hold the gases for long, and the atmosphere escapes into space almost as quickly as it forms. Some scientists suggest that as Pluto moves away from the sun into colder territory, the atmospheric gases refreeze and fall in chunks to the planet's surface. Pluto-Kuiper Express may help determine whether this theory is correct.

After passing Pluto, the spacecraft will continue on its trajectory into the Kuiper belt, where its cameras and infrared spectrometer will turn toward any icy bodies nearby and analyze their chemical makeup. If the Kuiper bodies have the same composition as Pluto, the similarity will corroborate suggestions that the planet may have emerged from the belt. Further analyses could help explain the mystery of Pluto's birth and perhaps shed some light on Earth's beginnings.

Earth-like Planets



***EARTH-LIKE PLANET** in another solar system is shown in this artist's rendering, which portrays the young world being buffeted by asteroids. The Terrestrial Planet Finder, an observatory scheduled for launch in 2010, may be able to view such planets.*

in Other Solar Systems

A squadron of space observatories may help scientists identify a life-bearing planet orbiting another star

SAIC; PAT RAWLINGS

Perhaps the most exciting astronomical discovery would be the sighting of an Earth-like planet orbiting another star. If a futuristic telescope could find such a planet and analyze its atmosphere, it might be able to determine whether the planet is home to extraterrestrial life.

Ground-based telescopes have recently detected evidence of a handful of planets circling stars outside our solar system. But these observations have been indirect—the astronomers inferred a planet's presence based on the gravity-induced wobble of the star being observed. And because a planet must be very massive to produce a discernible wobble, all the planets detected so far are closer in size to Jupiter than to Earth.

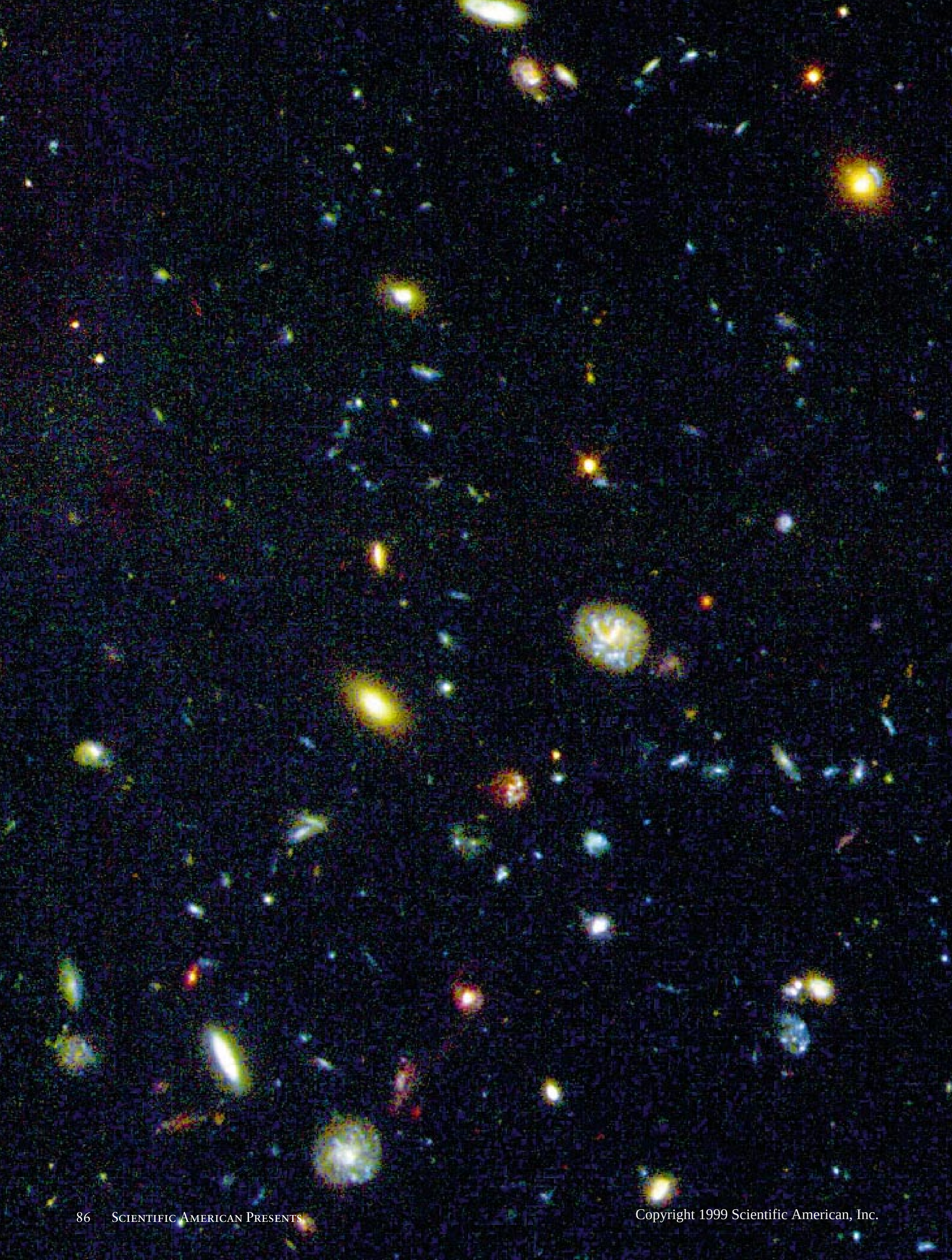
In 2005 NASA plans to improve its searching ability with the Space Interferometry Mission (SIM), an observatory that would travel around the sun in a near-Earth orbit. SIM would capture images of unprecedented resolution by combining the light from two telescopes that are 10 meters apart. The observatory would be able to measure star positions so precisely that astronomers could detect the wobble caused by an Earth-like planet orbiting a nearby star.

SIM would set the stage for the Terrestrial Planet Finder (TPF), an instrument that could directly observe the light reflected off Earth-like planets in other solar systems. The main challenge facing TPF is glare. A nearby star would shine one million times brighter than its surrounding planets, even in the infrared range of the spectrum, where planets are brightest. According to Charles Beichman, co-chair of the TPF science team, observing a planet in another solar system would be like trying to spot a firefly that is sitting on the rim of a searchlight. What is more, interstellar dust tends to scatter starlight, adding extra glare and making it harder to isolate a planet's faint glow.

Fortunately, TPF has a way to block the stars' glare. The observatory would consist of five spacecraft flying in formation in a near-Earth orbit around the sun. Four of the spacecraft would carry 3.5-meter-wide telescope mirrors that would be aimed at the target star. Each of the mirrors would reflect the star's infrared light toward the fifth spacecraft, a vessel flying in the middle of the group, where the image would be focused. The four beams would be combined so that the light waves interfered with one another, canceling out the starlight in the center of the image but preserving the light from any planets on the periphery.

NASA hopes to launch TPF in 2010, after SIM has identified the solar systems most likely to have Earth-like planets. TPF would observe several hundred stars up to 50 light-years away, spending a few hours at each star. After completing the survey, the group of spacecraft would pay closer attention to any discovered planet that is about the size of Earth. The observatory would then use spectrographic instruments to try to determine the chemical composition of the planet's atmosphere.

Carbon dioxide, water vapor and ozone are all promising signs of life that can be detected in the infrared spectrum. Ozone, for example, forms when light reacts with oxygen, which can be made by plants. "If you have ozone in the atmosphere, that's circumstantial evidence for primitive life on the planet," Beichman says. TPF will get about five years in space to conduct its search. Mission scientists believe that if they focus on the right stars and planets, they are bound to discover whether there is evidence of life in other solar systems.



The First Galaxies

With the help of an enormous space telescope, astronomers hope to observe the very first stars and galaxies

Can astronomers observe the birth of the universe? In 2003 NASA plans to begin building the Next Generation Space Telescope (NGST), a deep-space observatory that will allow scientists to peer into the farthest reaches of the cosmos, nearly 12 billion light-years from Earth. The new telescope would use an eight-meter-wide mirror to capture images of the very first galaxies, which astronomers believe started generating their light just a few hundred million years after the big bang.

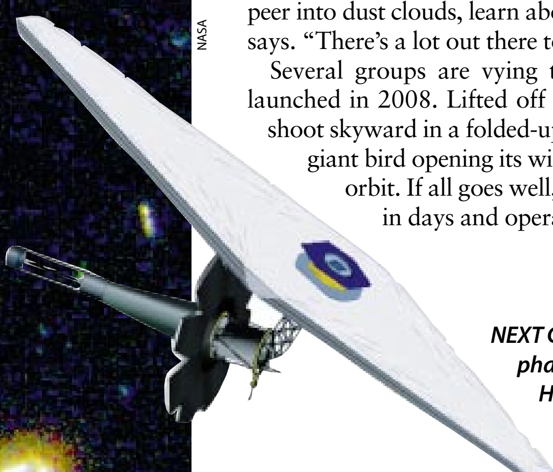
The Hubble Space Telescope, which has been orbiting Earth since 1990, has revealed some tantalizing hints about the early history of the universe. Hubble has observed fully formed galaxies dating as far back as a billion years after the big bang. Astronomers want to know how those first galaxies coalesced from the dark primordial nebula. “Hubble whetted our appetite for the cosmic dark ages,” says John Mather, the NGST project scientist at the NASA Goddard Space Flight Center. “NGST will help us see farther and sharper to learn about the history and shape of the universe.”

Because the universe is expanding, the light from distant objects is redshifted—that is, converted to longer wavelengths. The amount of redshift is measured as the ratio of the change in wavelength to the original wavelength. The farthest galaxies have the greatest redshifts. The best current telescopes have spotted galaxies with redshifts of about five, but NGST will be able to observe objects with redshifts of 10 to 20. To see such objects, the new telescope will be designed to scan from the far visible to the mid-infrared range of the spectrum. (Hubble detects light in the visible to near-infrared range.)

NGST’s lightweight, flexible mirror will be at least twice as wide as Hubble’s and will gather 10 times more light. Because the new telescope will operate in the infrared range, the optics and cameras must be kept as cold as possible to prevent background heat from obscuring the images. The spacecraft will carry a massive sunshade to prevent overheating and will be located far from Earth to avoid the sunlight reflected from the planet’s surface. Most likely, the telescope will orbit the sun near the L2 Lagrange point, one of five points where the sun’s and Earth’s gravity are in equilibrium. L2 is about 1.5 million kilometers farther from the sun than Earth is.

The images from NGST may help unravel the mystery of how density fluctuations left over from the big bang evolved into the large-scale structure of the universe. Astronomers are not sure whether galaxies formed from the contraction of larger clouds of matter or from the aggregation of smaller star clusters. The telescope may also provide new observations of stellar and planetary formation, which take place inside massive clouds of dust. Because dust does not absorb infrared light as much as it absorbs light of other wavelengths, NGST will be able to see deeper inside the clouds. “With the infrared, we can peer into dust clouds, learn about dark matter and find faint planets,” Mather says. “There’s a lot out there to discover.”

Several groups are vying to construct NGST, which is expected to be launched in 2008. Lifted off Earth by an expendable rocket, NGST would shoot skyward in a folded-up position. Once in space, it would unfold like a giant bird opening its wings, pop up its sunshade and settle into its frigid orbit. If all goes well, the telescope will begin collecting images within days and operate for about a decade.



NASA

NEXT GENERATION SPACE TELESCOPE, ***now in the design phase*** **(near left),** ***will be even more powerful than the Hubble telescope, which has observed ancient galaxies in its Deep Field South survey*** **(far left).**

Interstellar

Can We Travel to Other Stars?

Small self-replicating probes could be launched on interstellar journeys. Creating a galactic Internet may yield even greater benefits

by Timothy Ferris

Living as we do in technologically triumphant times, we are inclined to view interstellar spaceflight as a technical challenge, like breaking the sound barrier or climbing Mount Everest—something that will no doubt be difficult but feasible, given the right resources and resourcefulness.

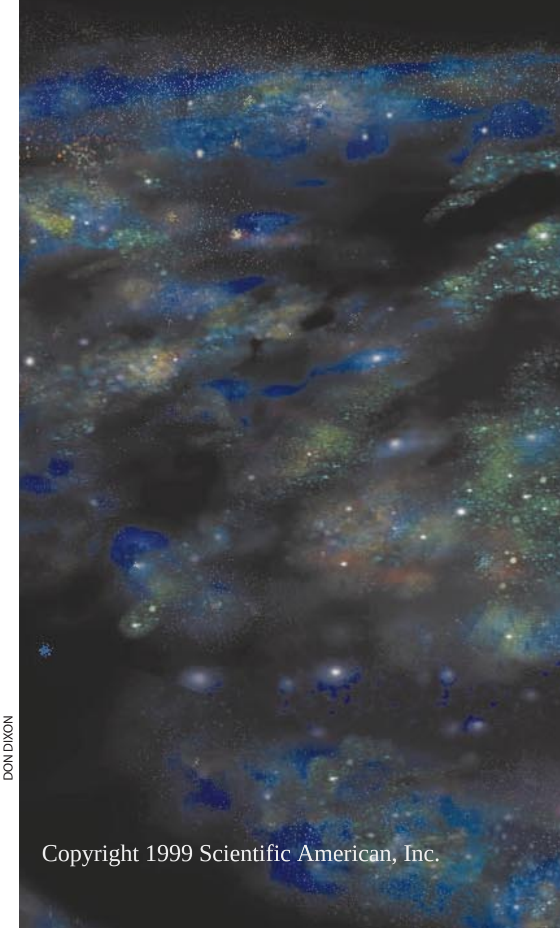
This view has much to recommend it. Unmanned interstellar travel has, in a sense, already been achieved, by the Pioneer 10 and 11 and Voyager 1 and 2 probes, which were accelerated by their close encounters with Jupiter to speeds in excess of the sun's escape velocity and are outward-bound forever. By interstellar standards, these spacecraft are slow: Voyager 1, the speediest of the four at 62,000 kilometers per hour (39,000 miles per hour), will wander for several tens of thousands of years before it encounters another star. But the Wright brothers' first airplane wasn't particularly speedy either. A manned interstellar spacecraft that improved on Voyager's velocity by the same 1,000-fold increment by which Voyager improved on the Kitty Hawk flights could reach nearby stars in a matter of decades, if a way could be found to pay its exorbitant fuel bill.

But that's a big "if," and there is another way of looking at the question: Rather than scaling a mountain, one can always scout a pass. In other words, the technical problems involved in traveling to the stars need not be regarded solely as obstacles to be overcome but can instead be viewed as clues, or signposts, that point toward other ways to explore the universe.

Three such clues loom large. First, interstellar space travel appears to be extremely, if not prohibitively, expensive. All the propulsion systems proposed so far for interstellar voyages—fusion rockets, antimatter engines, laser-light sails and so on—would require huge amounts of energy, either in the manufacturing of fusion or antimatter fuel or in the powering of a laser beam for light sails [see "The Way to Go in Space," page 58]. Second, there is no compelling evidence that alien spacefarers have ever visited Earth. Third, radio waves offer a fast and inexpensive mode of *communication* that could compete effectively with interstellar *travel*. What might these clues imply?

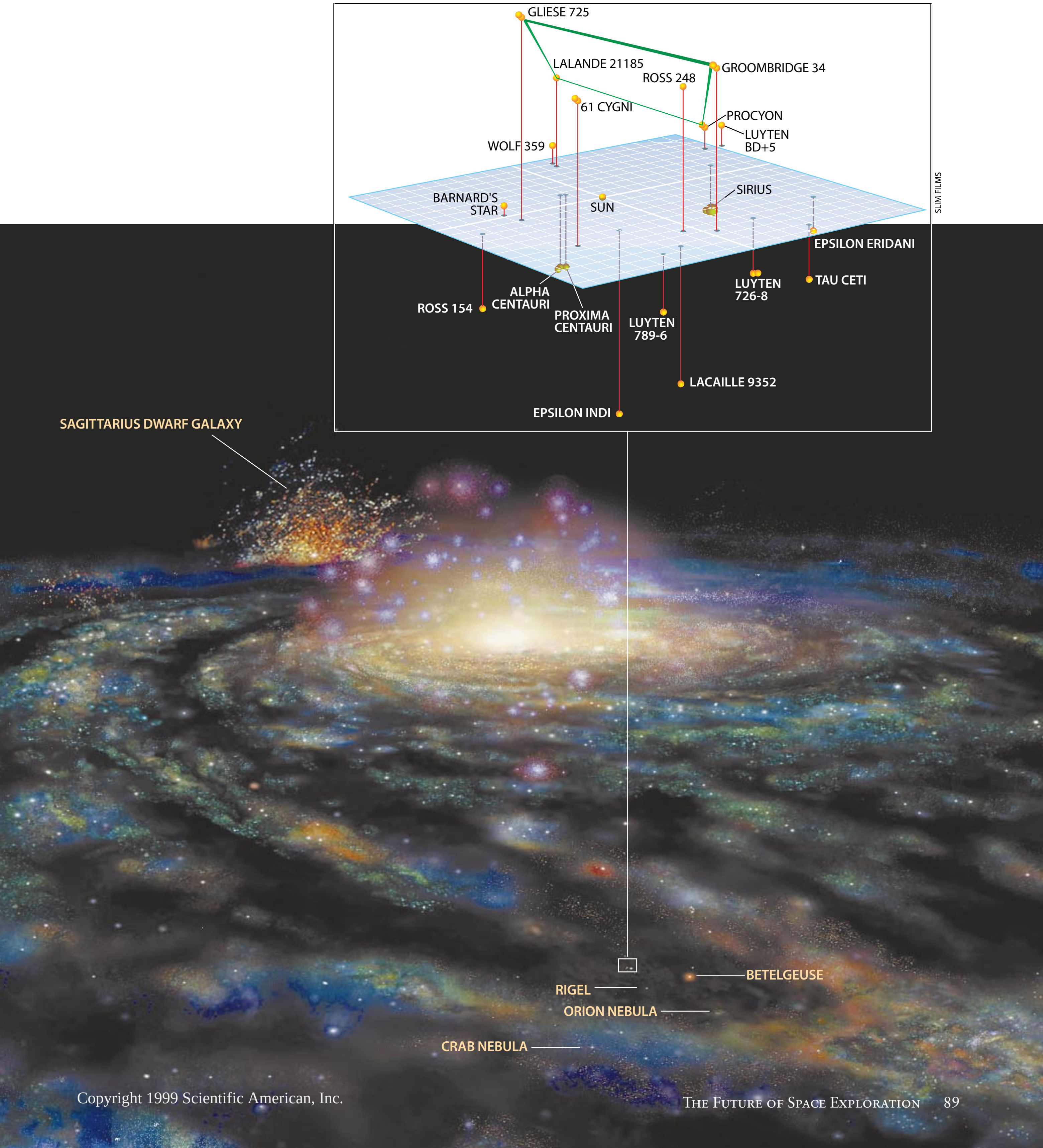
The high cost of interstellar spaceflight suggests that the payloads carried between stars—whether dispatched by humans in the future or by alien spacefarers in the past—are most likely, as a rule, to be small. It is much more affordable to send a grapefruit-size probe than the starship *Enterprise*. Consider spacecraft equipped with laser-light sails, which could be pushed through interstellar space by the beams of powerful lasers based in our solar system. To propel a manned spacecraft to Proxima Centauri, the nearest star, in 40 years, the laser system would need thousands of gigawatts of power, more than the output of all the electricity-generating plants on Earth. But sending a 10-kilogram unmanned payload on the same voyage would require only about 50 gigawatts—still a tremendous amount of power but less than 15 percent of the total U.S. output.

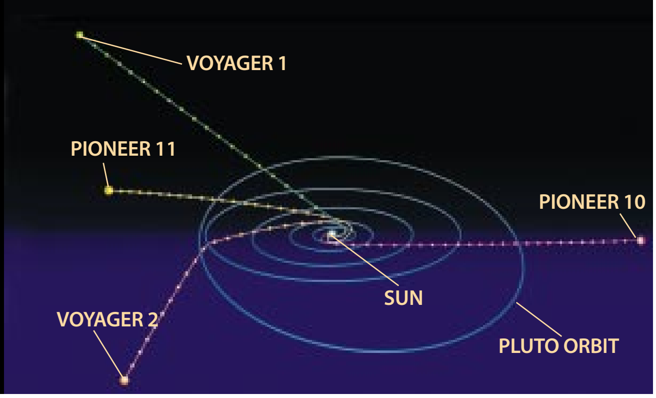
NEAREST STARS to the solar system are depicted in this view of the Milky Way galaxy as seen from 500 light-years above the galactic plane. The green lines between the stars (*inset*) represent high-bandwidth radio beams in a hypothetical communications network linking alien civilizations. Such an interstellar network would allow intelligent species to share knowledge without incurring the tremendous expense of traveling to other stars.



DON DIXON

Spaceflight:





SLIM FILMS

FIRST STARSHIPS are the Pioneer 10 and 11 and Voyager 1 and 2 probes, all launched in the 1970s. Voyager 1 has traveled the farthest of the four spacecraft; it is now 10.8 billion kilometers from the sun.

What can be accomplished by a grapefruit-size probe? Quite a lot, actually, especially if such probes have the capacity to replicate themselves, using materials garnered at their landing sites. The concept of self-replicating systems was first studied by mathematician John von Neumann in the 1940s, and now scientists in the field of nanotechnology are investigating how to build them. If the goal is exploring other planetary systems, one could manufacture a few small self-replicating probes and send them to nearby stars at an affordable cost. Once each probe arrived at its destination, it would set up long-term housekeeping on a metallic asteroid. The probe would mine the asteroid and use the ore to construct a base of operations, including a radio transmitter to relay its data back to Earth. The probe could also fashion other probes, which would in turn be sent to other stars. Such a strategy can eventually yield an enormous payoff from a relatively modest investment by providing eyes and ears on an ever increasing number of outposts.

If colonization is the goal, the probes could carry the biological materials required to seed hospitable but lifeless planets. This effort seems feasible whether our aim is simply to promote the spread of life itself or to prepare the way for future human habitation. Of course, there are serious ethical concerns about the legitimacy of homesteading planets that are already endowed with indigenous life. But such worlds may be outnumbered by "near-miss" planets that lack life but could bloom with a bit of tinkering.

One of the intriguing things about small interstellar probes is that they are inconspicuous. A tiny probe built by an alien civilization could be orbiting the sun right now, faithfully phoning home, and we might never learn of its existence. This would be especially true if the probe were engineered to keep a low profile—for instance, if its radio antenna were aimed well away from the ecliptic, or if it were programmed to turn off its transmitters whenever the beam came near a planet. And that is just how such probes would presumably be designed, to discourage emerging species like ours from hunting them down, dismantling them and putting them on display in the Smithsonian National Air and Space Museum. Similarly, a biological probe could have seeded Earth with life in the first place. The fact that life appeared quite early in Earth's history argues against the hypothesis that it was artificially implanted (unless somebody out there was keeping a close eye out for newborn planets), but such an origin for terrestrial life is consistent with the evidence currently in hand.

Where Are the Aliens?

From the second clue—that aliens have not yet landed on the White House lawn—we can posit that our immediate celestial neighborhood is probably not home to a multitude of technologically advanced civilizations that spend their time boldly venturing to other star systems on board big, imposing spacecraft. If that were the case, they would have shown up here already, as they evidently have not. (I am, of course, discounting reports of UFO sightings and alien abductions, the evidence for which is unpersuasive.) By similar reasoning we can reach the tentative conclusion that wormholes, stargates and the other faster-than-light transit systems favored by science-fiction writers are not widely in use, at least out here in the galactic suburbs.

Admittedly, one can poke holes in this argument. Perhaps the aliens know we exist but are courteous enough not to bother us. Maybe they visited Earth during the more than three billion years when terrestrial life was all bugs and bacteria and quietly departed after taking a few snapshots and carefully bagging their trash. In any event, it seems reasonable to conclude that if interstellar interstates exist, we are not living near an exit ramp.

The third clue—that radio can convey information much faster and more cheaply than starships can carry cargo—has become well known thanks to SETI, the search for extraterrestrial intelligence. SETI researchers use radio telescopes to listen for signals broadcast by alien civilizations. The SETI literature is therefore concerned mostly with how we can detect such signals and has little to say about how electromagnetic communications might be employed among advanced civilizations as an alternative to interstellar travel. Yet just such a path of speculation can help explain how intelligent life could have emerged in our galaxy without interstellar travel becoming commonplace.

When SETI was first proposed, in a paper published in *Nature* by Giuseppe Cocconi and Philip Morrison in 1959, the main method of electronic communication on Earth was the telephone, and the objection most frequently raised to the idea of interstellar conversation was that it would take too long. A single exchange—"How are you?" "Fine"—would consume 2,000 years if conducted between planets 1,000 light-years apart. But, as Morrison himself has noted, conversation is not essential to communication; one can also learn from a monologue. Eighteenth-century England, for instance, was deeply influenced by the ancient Greeks, although no English subject ever had a conversation with an ancient Greek. We learn from Socrates and Herodotus, although we cannot speak with them. So interstellar communication makes sense even if using it as a telephone does not.

In 1975, when I first proposed that long-term interstellar communications traffic among advanced civilizations would best be handled by an automated network, there was no model of such a system that was familiar to the public. But today the Internet provides a good example of what a monologue-dominated interstellar network might be like and helps us appreciate why extraterrestrials might prefer it to the arduous and expensive business of actually traveling to other stars.

Experientially, the Internet tends to collapse space and time. One looks for things on the Net and makes use of them as one pleases. It does not necessarily matter whether the information came from next door or from the other side of the planet, or whether the items were placed on-line last night or last year. E-mail aside, the Internet is mostly monologue.

Suppose the Internet had been invented several thousand years ago, so that we had access not only to the books of Aristotle and Archimedes but also to their sites on the World Wide Web. What a boon it would be to surf such a web, downloading the lost plays of Sophocles and gazing at the vivid mosaics of Pompeii in colors undimmed by time. Few, I think, would trade that experience for a halting phone conversation with someone from the past.

The same may also be true of communications between alien worlds. The most profound gulf separating intelligent species on various star systems is not space but time, and the best way to bridge that gulf is not with starships but with networked interstellar communications.

The gulf of time is of two kinds. The first is the amount of time it takes signals to travel between contemporaneous civilizations. If, as some of the more optimistic SETI scientists estimate, there are 10,000 communicative worlds in the Milky Way galaxy today, the average time required to send a one-way message to one's nearest neighbor—across the back fence, so to speak—is on the order of 1,000 years. Therefore, it makes sense to send long, fact-filled messages rather than "How are you?"

ROLF EBELING

INTERSTELLAR INTERNET might include informational sites similar to the hypothetical home page shown above. Alien civilizations could archive their histories, scientific discoveries and literatures on the network, leaving a permanent record of their existence.

The Interstellar Internet

The other gulf arises if, as it seems reasonable to assume, communicative civilizations generally have lifetimes that are brief by comparison with the age of the universe. Obviously, we do not even know whether alien societies exist, much less how long they normally stay on the air before succumbing to decay, disaster or waning interest. But they would have to last a very long time indeed to approach the age of the Milky Way galaxy, which is more than 10 billion years old. Here on Earth, species survive for a couple of million years on average. The Neanderthals lasted about 200,000 years, *Homo erectus* about 1.4 million years. Our species, *H. sapiens,* is about 200,000 years old, so if we are typical, we may expect to endure for another million or so years. The crucial point about any such tenure is that it is cosmologically insignificant. Even if we manage to survive for a robust 10 million years to come, that is still less than a tenth of 1 percent of the age of our galaxy.

Any other intelligent species that learns how to determine the ages of stars and galaxies will come to the same sobering conclusion—that even if communicative civilizations typically stay on the air for fully 10 million years, *only one in 1,000 of all that have inhabited our galaxy is still in existence.* The vast majority belong to the past. Is theirs a silent majority, or have they found a way to leave a record of themselves, their thoughts and their achievements?

That is where an interstellar Internet comes into play. Such a network could be deployed by small robotic probes like the ones described earlier, each of which would set up antennae that connect it to the civilizations of nearby stars and to other network nodes. The network would handle the interstellar radio traffic of all the worlds that know about it. That would be the immediate payoff: one could get in touch with many civilizations, without the need to establish contact with each individually. More important, each node would keep and distribute a record of the data it handled. Those records would vastly enrich the network's value to every civilization that uses it. With so many data constantly circulated and archived among its nodes, the interstellar Internet would give each inhabited planet relatively easy access to a wealth of information about the civilizations that currently exist and the many more worlds that were in touch with the network in the past.

Intelligence brings knowledge of one's own mortality—and at the same time, provides a means to transcend it—so the desire for some kind of immortality is, I suspect, widespread among intelligent beings. Although some species may have limited themselves to physical monuments, such as the one erected by Percy Bysshe Shelley's Ozymandias, these must eventually weather away and would in any event require long journeys to be seen and appreciated. Surely most species would elect to contribute to the interstellar Internet, where their thoughts and stories could career around the galaxy forever.

If there were any truth in this fancy, what would our galaxy look like? Well, we would find that interstellar voyages by starships of the *Enterprise* class would be rare, because most intelligent beings would prefer to explore the galaxy and to plumb its long history through the more efficient method of cruising the Net. When interstellar travel did occur, it would usually take the form of small, inconspicuous probes, designed to expand the network, quietly conduct research and seed infertile planets. Radio traffic on the Net would be difficult for technologically emerging worlds to intercept, because nearly all of it would be locked into high-bandwidth, pencil-thin beams linking established planets with automated nodes. Our hopes for SETI would rest principally on the extent to which the Net bothers to maintain omnidirectional broadcast antennae, which are economically draining but could from time to time bring in a fresh, naive species—perhaps even one way out here beyond the Milky Way's Sagittarius Arm. The galaxy would look quiet and serene, although in fact it would be alive with thought.

In short, it would look just as it does. SA

Timothy Ferris is the author of *The Whole Shebang: A State-of-the-Universe(s) Report, Galaxies, Coming of Age in the Milky Way* and other best-selling books. In 1977 he produced the archival phonograph record carried on the Voyager probes. He is currently emeritus professor of journalism at the University of California, Berkeley.

Making Money in Space

Exploring the solar system turns out to be the easy part. The next great challenge will be creating profitable space enterprises

by Mark Alpert, *issue editor*

MARK MAXWELL *LunaCorp*

In 1975 the National Aeronautics and Space Administration sponsored a study to design a commercially viable space station. A team of scientists and engineers proposed the construction of a giant wheel, nearly two kilometers in diameter, orbiting Earth at the same distance as the moon. The station would hold 10,000 colonists in a habitat tube running along the rim of the wheel, which would revolve once a minute to simulate Earth's gravity. The colonists would breathe oxygen derived from moon rocks and eat food grown on the station's 63 hectares of farmland. The study estimated that the station would cost nearly $200 billion in 1975 dollars, which is equivalent to some $500 billion today. But the authors of the study confidently predicted that the station could pay for itself in 30 years through the assembly of enormous solar-power satellites.

Needless to say, the development of space has not lived up to this ambitious plan. The International Space Station, if it is ever completed, will hold only seven crew members and generate negligible income, certainly not enough to cover its $40-billion construction cost. NASA still hopes to strike partnerships with companies interested in manufacturing in zero gravity; the agency is trying to sell research modules on the space station to pharmaceutical, biotechnology and electronics companies. But even NASA officials admit that commercial interest has been cool. So far the only space industry that has proved to be a rousing success is the satellite communications business. Driven by the strong demand for cellular telephone service, companies such as Motorola and Loral Space and Communications are investing billions of dollars in new networks of satellites flying in low-Earth orbit [see "New Satellites for Personal Communications," on page 96].

LUNAR POLAR LANDING of a spacecraft proposed by LunaCorp, a 10-year-old private company. The unmanned probe could be the first commercial spacecraft on the moon, landing in Peary Crater near the moon's north pole in 2002. LunaCorp plans to finance the mission by selling the data collected by the probe's robotic rover.

In recent years, however, there has been a quiet revolution in the space industry. A new generation of entrepreneurs has arisen, many of them scientists or former astronauts. Despite a severe shortage of capital, they have founded small, scrappy companies such as Universal Space Lines, Pioneer Rocketplane, SpaceDev and LunaCorp. Some of these companies are trying to develop low-cost launch vehicles; others are planning lunar and deep-space missions intended to turn a profit. What they all share is a strict allegiance to the bottom line. Their oft-repeated motto is: "To go to space to *stay,* we have to make space *pay*."

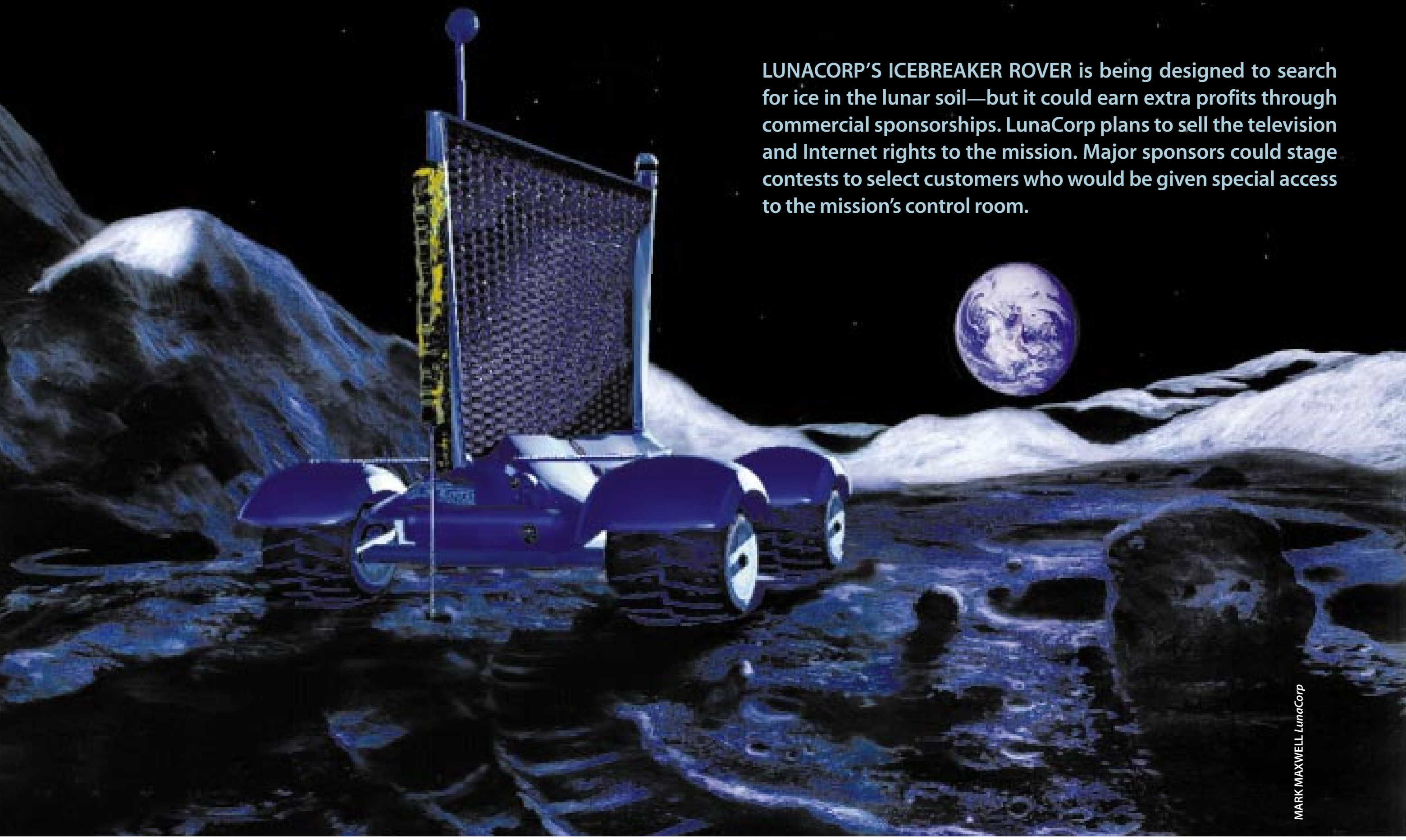
Economics in Orbit

The primary constraint on space enterprises is the high cost of escaping Earth's gravity. Lofting a payload into low-Earth orbit using expendable rockets or the space shuttle costs between $10,000 and $20,000 per kilogram. The pressing need for cheaper launches has led NASA to invest in the X-33, a prototype for a lightweight, fully reusable space plane. Lockheed Martin is building the X-33 and plans to follow it with a commercial vehicle called VentureStar, but smaller companies such as Rotary Rocket and Kistler Aerospace are rushing to build their own reusable launch vehicles [see "The Way to Go in Space," on page 58].

To stimulate the competition, the X Prize Foundation has offered a $10-million award to the first privately funded team to fly a reusable three-person spaceship on two consecutive suborbital flights. Sponsored by the St. Louis business community, the X Prize is modeled after the prizes offered to pioneer aviators early in the century, which promoted the growth of the aircraft industry. The launch vehicle companies want to follow the same growth curve; they hope to decrease their operating costs by flying their vehicles as often as possible, like commercial airliners. But is there a need for so many spaceflights? Currently there are about 90 launches a year, most of them carrying communications satellites into orbit using expendable boosters, such as the Ariane, Delta and Atlas rockets. A single reusable launch vehicle that could blast off into space twice a week could conceivably loft every commercial payload planned for the next 10 years.

The space industry obviously needs to do more than boost communications, navigation and weather satellites. For many years, NASA promoted the idea of space-based manufacturing, claiming that certain pharmaceuticals, semiconductor materials and other products could be manufactured with better quality in an orbital station than in an Earth-based factory. Unfortunately, high launch costs have prevented most companies from considering the idea. But even if cheaper vehicles became available, very few products could be manufactured in orbit and sold profitably on Earth. Most products made in space simply would not be competitive with products made on the ground—in part because Earth-based manufacturing techniques are continually improving.

The assembly of solar-power satellites—the main



LUNACORP'S ICEBREAKER ROVER is being designed to search for ice in the lunar soil—but it could earn extra profits through commercial sponsorships. LunaCorp plans to sell the television and Internet rights to the mission. Major sponsors could stage contests to select customers who would be given special access to the mission's control room.

MARK MAXWELL *LunaCorp*

purpose of the giant space colony conceived in 1975—seems more promising, given the expected growth in worldwide energy consumption. Because a solar collector in a geostationary orbit would not be subject to the day/night cycle or to atmospheric interference, it would receive about eight times as much light as a solar collector on the ground. The power could be transmitted by microwave beams from the satellites to antenna arrays on Earth. A large solar-power satellite, with a collector three to six kilometers in diameter, could conceivably generate five billion watts of electricity, about five times the output of a conventional power plant.

In 1997 NASA released the "Fresh Look" study, which reexamined the costs and benefits of solar-power satellites. The study noted that solar power from space could become a competitive energy source, but only if launch costs declined to less than $400 a kilogram, a more than 20-fold reduction from current levels. The idea also faces technical hurdles—scientists must improve the efficiency of microwave-power transmission—and billions of dollars would have to be invested in the project before the first watt of electricity could be generated. Solar-power satellites will probably not be seriously considered by the private sector until the next energy crunch.

In the near future the best way to make money in space may be to take paying passengers there. One of the strongest advocates of space tourism is former Apollo astronaut Buzz Aldrin, Jr., the second man to walk on the moon. Aldrin has founded a company called ShareSpace to promote mass-market space travel. "People have come up to me and asked, 'When do *we* get a chance to go?'" Aldrin says. A 1997 survey of 1,500 Americans showed that 42 percent were interested in flying on a space cruise. Two travel companies, Space Adventures and Zegrahm Space Voyages, are already taking advance reservations for seats on suborbital flights, even though the launch vehicles have not yet been built. Tickets for the first flights are expected to cost between $50,000 and $100,000.

A 1998 NASA study endorsed the concept of space tourism, concluding that it may grow into a $10-billion-a-year industry in a few decades. John Spencer, director of the Space Tourism Society, predicts that by 2040 there will be orbital hotels carrying hundreds of travelers. "The romance of space will be a key selling point," he says. These projections, however, are based on the assumption that the next generation of vehicles will be more reliable than the space shuttle or expendable rockets. In the satellite launch industry, a failure rate of 1 percent—one loss for every 100 launches—is considered remarkably good. But such a failure rate would doom the space tourism business.

Staking Claims in the Asteroid Belt

Space entrepreneurs are also eyeing Earth's moon and the asteroid belt. The recent discovery of signs of ice at the lunar poles has revived talk of a manned base on the moon. But the near-Earth asteroids, which travel in orbits that cross or graze Earth's orbit, may be better sites for commercial development. Many of these asteroids are easier to reach than the moon, and they are rich in iron, nickel, cobalt and platinum-group metals. In fact, a two-kilometer-wide asteroid holds more metal than all the ore mined on Earth since the beginning of civilization.

Of course, it would be difficult to transport so much metal from the asteroids to Earth's surface. Dropping large quantities of ore into the atmosphere would be impractical, not to mention dangerous. Asteroid resources could be more profitably used to support other space enterprises—for example, to construct space hotels or solar-power satellites in Earth orbit. The most precious resource from the asteroids is actually not a metal—it is water ice, which could provide propellants for spacecraft at one-thousandth the cost of launching the fuel from Earth [see "Tapping the Waters of Space," on page 100].

An asteroid-prospecting mission is already in the works. SpaceDev, a fast-growing publicly held company, plans to send a $50-million spacecraft, the Near Earth Asteroid Prospector (NEAP), to the asteroid 4660 Nereus by 2002. It would be the first commercial deep-space mission; SpaceDev hopes to make a profit by selling the data sets from NEAP's scientific instruments and by offering payload space on the probe to university researchers. For $10 million, SpaceDev will deliver an ejectable payload that could land on Nereus's surface. NASA has recognized NEAP as a Mission of Opportunity, meaning that research groups can receive NASA funding for scientific instruments carried on board the spacecraft.

Jim Benson, SpaceDev's chief executive, says that once NEAP lands its first instrument on Nereus, he will declare his ownership of the asteroid. "If I take the risk to go there, by God I'm going to claim it," he states. Whether such a claim would be legal is an open question. Although the United Nations's Outer Space Treaty of 1967 prohibits nations from claiming sovereignty over celestial bodies, it does not disallow property rights. Benson hopes his claim will set a precedent. But NEAP may yield a more immediate payback: if SpaceDev can make a profit on the research mission, it will serve as a model for other commercial spacecraft.

A similar mission has been proposed by LunaCorp, which plans to send an unmanned rover to the moon's north pole to determine how much ice is buried there. The rover is being developed by the Robotics Institute of Carnegie Mellon University. If all goes as planned, in 2002 the rover will land in a sunlit part of Peary Crater near the north pole, then travel to the permanently shadowed area where ice is believed to lie below the surface. The rover will be able to drill more than a meter into the lunar soil to test for the presence of subsurface ice.

Like SpaceDev, LunaCorp intends to finance its mission by selling the research results to NASA and other space agencies. The company is also trying to raise funds by offering a variety of sponsorship opportunities. For example, an entertainment company could pay for the television rights to the mission. "Because it's a private project, we can offer exclusive rights," says David Gump, LunaCorp's chief executive.

Another company, Applied Space Resources, plans to underwrite a lunar mission by selling moon dust. Denise Norris, the company's founder, wants to land a probe in the Mare Nectaris, just south of the moon's equator, where it will scoop up 10 kilograms of lunar soil and then return the sample to Earth. The company will give away five kilograms to scientists and sell the remaining moon dust to retailers at $6,000 a gram. It seems a fanciful way to pay for a space mission, but Norris points to a historical precedent from the 17th century: the colonization of North America was financed in large part by the sale of exotic items such as tobacco and beaver pelts.

The Space Enterprise Zone

Perhaps the biggest problem facing these companies is a lack of capital. Wall Street does not understand the space industry, and most investors are unwilling to bet on companies building new launch vehicles or planning commercial missions. Even the risk-taking, venture-capital firms have steered clear of the space business. The scarcity of capital has inspired a reworking of an old adage: if God had wanted people to go to space, He would've given them more money.

To stimulate extraterrestrial business activity, interest groups such as ProSpace and the Space Frontier Foundation have called for a rethinking of the government's role in space. They believe NASA should privatize the space shuttle and the International Space Station. The space agency, they argue, should buy launch services from competing companies rather than fund the development of a single vehicle. Rick Tumlinson, the president of the Space Frontier Foundation, says NASA should focus on the exploration of the solar system and leave its operations in low-Earth orbit to the private sector. "NASA astronauts shouldn't be driving the space trucks," he remarks. "They should be going to Mars!"

NASA *is* slowly moving in this direction. In 1998 Congress passed the Commercial Space Act, which requires NASA to draft a plan for the privatization of the space shuttle. The law also establishes a regulatory framework for licensing the next generation of reusable launch vehicles. But space entrepreneurs say more incentives are needed. Some executives advocate the creation of a space enterprise zone similar to the enterprise zones in inner cities. Under the proposal, the federal government would not tax any profits from new space businesses such as launch vehicle companies. Other executives believe, however, that the proposal would do little to encourage investment, because high-tech companies typically do not turn a profit during their first years of operation.

Despite the stumbling blocks, most people in the space industry remain optimistic. They are convinced that in the long run commercial outposts will be established in Earth orbit, on the moon, in the asteroid belt and beyond. Some long-term thinkers have even contemplated the ultimate space project: the transformation of Mars into a habitable planet [see "Bringing Life to Mars," on page 52]. The proposal may seem outrageously ambitious, but ambition is one attribute that today's space capitalists possess in abundance. SA

ZEGRAHM SPACE VOYAGES

SPACE TOURISTS are already booking reservations for suborbital flights planned by Zegrahm Space Voyages, an adventure travel company. A reusable launch vehicle (*left*) that could take six passengers to an altitude of 100 kilometers is in development. Passenger flight suits (*right*) are also being designed.

New Satellites for Personal

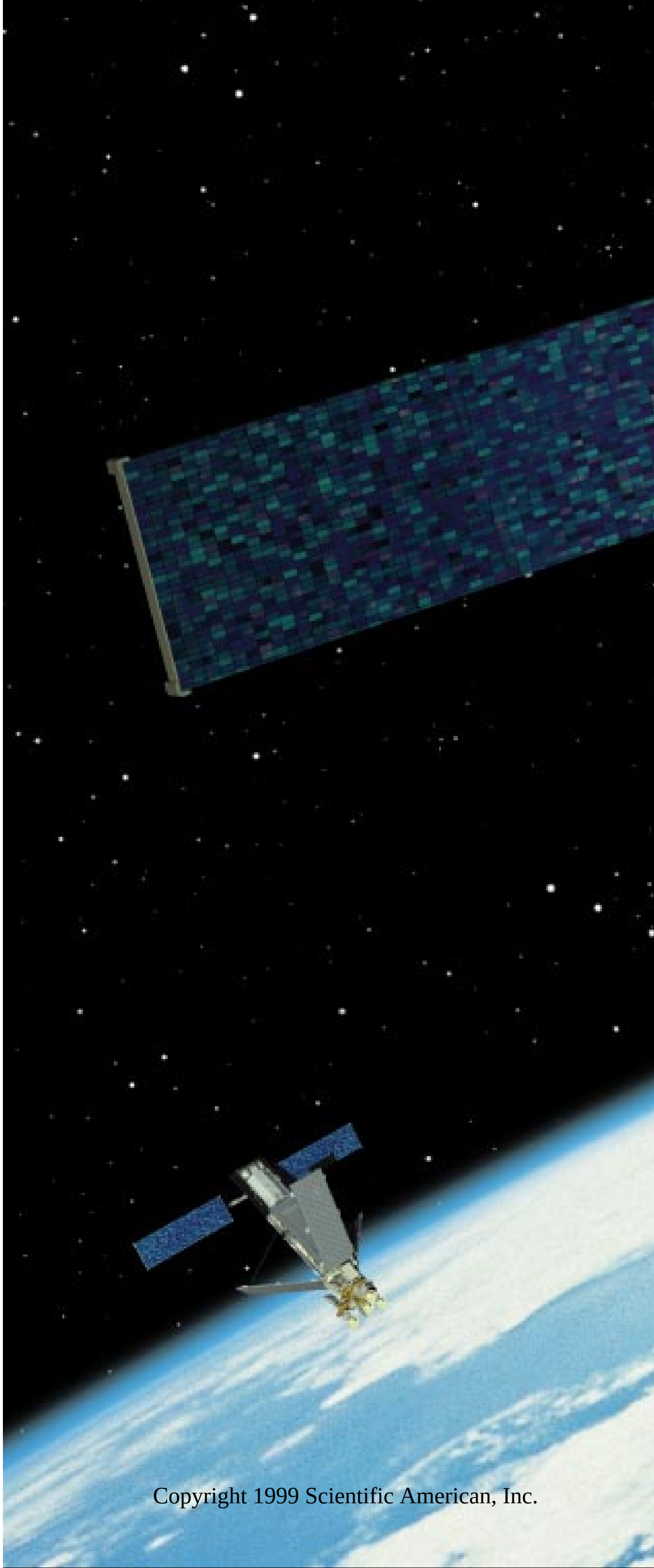
by John V. Evans

Since the first commercial model was launched into orbit in 1965, the communications satellite has become a linchpin of global communications. From modest beginnings—that first satellite could handle only 240 voice circuits at a time—the technology has blossomed to the extent that satellites now carry about one third of the voice traffic between countries and essentially all the television signals between countries.

Much of the voice traffic handled by satellites, however, is to countries that have no access to fiber-optic cables, which are the preferred medium for carrying telephone calls. Because large communications satellites are typically put into geostationary orbits, where they are roughly 36,000 kilometers (22,300 miles) above the same spot on Earth at all times, it takes a quarter of a second for signals to travel to and from the satellite, delaying the responses received during a conversation. Although not all users find this delay irritating, communications satellites are increasingly being used to carry television signals and data rather than voice traffic.

All of that is about to change. In November 1998 the first of a completely new type of satellite communications system began operation. Called Iridium, it is a network of 66 satellites, each capable of handling as many as 1,100 simultaneous calls. Iridium and the other networks expected to follow will provide cellular telephone service via satellite. Among other unique characteristics, these new systems will be based on a relatively large number of satellites in orbits considerably lower than geostationary ones; they will therefore introduce less delay into telephone conversations. A second type of system will be designed primarily for handling data, such as connections to the Internet. Over the next six or seven years, three to five of the voice-type systems and possibly upward of a dozen of the data-oriented satellite systems could go into operation.

How fast and big this market may grow is difficult if not impossible to say. Nevertheless, several groups have already invested billions in projects that are well along. The technical challenges and risks are significant; some of the enterprises, for example, would be unthinkable if not for the availability of a new generation of powerful communications satellites capable not only of amplifying and retransmitting

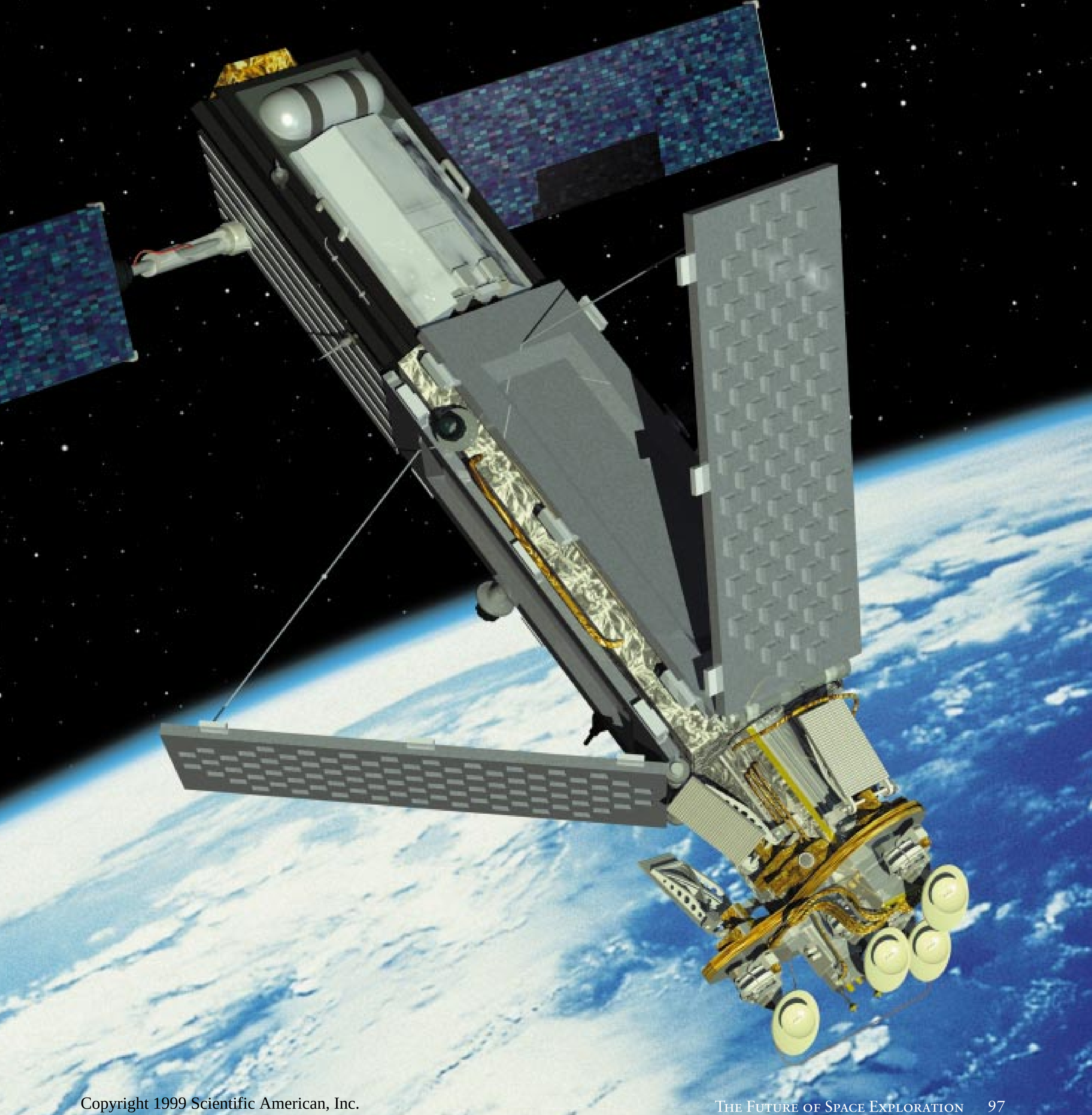


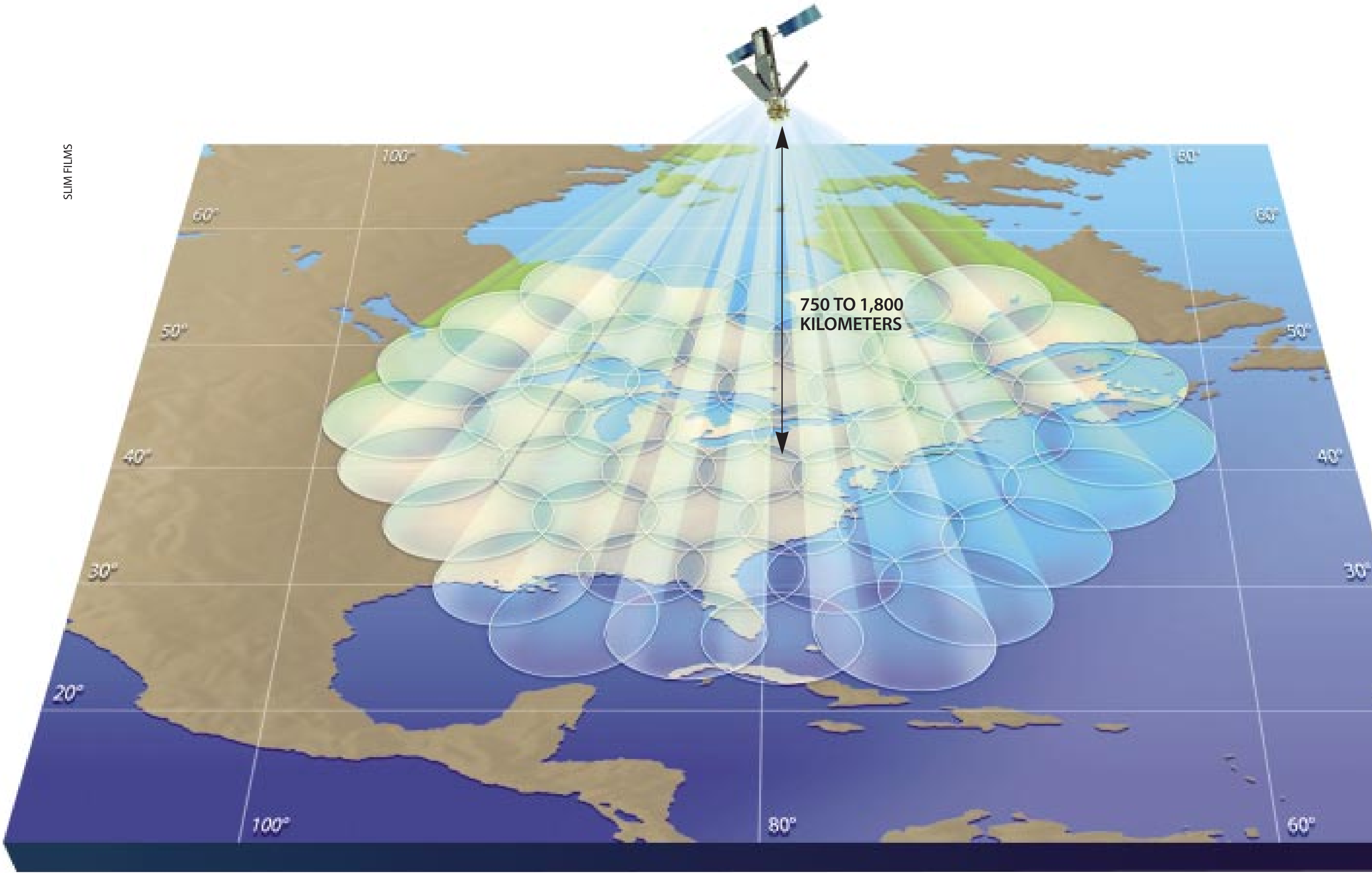
SLIM FILMS

COMMUNICATIONS SATELLITES shown here are typical of a new generation of craft capable of switching and routing calls. Visible in this scene are two of the Iridium system's 66 satellites, which are in low-Earth orbits.

Fleets of satellites will soon make it possible to reach someone anywhere on Earth, using nothing more than a small handset

Communications





SPOT BEAMS of an Iridium satellite each cover a "cell" on Earth perhaps 150 kilometers across. A cluster of four dozen of these relatively narrow beams provides coverage of a larger region—the eastern U.S., say. Use of the narrow beams is necessary because the signals from the handheld telephones are weak, placing most of the burden of connection on the satellite.

signals but also switching and routing them. In addition, some of the proposed systems will operate at very high frequencies in radio bands not previously used for satellite communications.

Satellites as Base Stations

The new personal communications satellite systems are striving to incorporate the advantages of both satellite and cellular systems into a single global network. In these new systems the satellites will be, in effect, orbiting cellular base stations, with which the handheld or mobile phones will communicate directly. Moreover, like conventional satellite systems, the new networks will be capable of serving large areas—including ones where no service is currently available.

Advantages such as these will be achievable only with some rather sophisticated technologies, however. One of the fundamental challenges results from the fact that a handheld phone can be equipped only with a very small antenna. It is impossible to design such an antenna so that it beams signals in a highly directional manner. Moreover, because the phones are held against the head when they are in use, the transmitted power must be kept below about one watt to allay concerns about the possible effects of radio-frequency radiation on biological tissue, such as the brain. (Low-power operation is also necessary to avoid draining the batteries too quickly.)

What these factors mean is that the signal transmitted from the phone is rather weak and that to "hear" it in geostationary orbit would require an antenna with a diameter of about 10 to 12 meters. Deploying such a huge antenna in space will be difficult, to say the least. To get around the need for such large dishes, the first of the new personal communications satellite systems have put satellites in orbits much closer to Earth. Because the required signal power falls with the square of the distance, bringing the orbit down from 36,000 kilometers to 10,000 kilometers, for example, causes a 13-fold increase in the strength of the signal received from the handheld phone. Such an increase permits the antenna on the lower-orbit satellite to be about the same size—two to three meters—as those now used on geostationary satellites.

Of course, there is a trade-off. In geostationary orbit, each satellite "sees" about a quarter of Earth, so only three or four satellites are needed for global coverage. At 10,000 kilometers, on the other hand, a satellite would have an orbital period of about six hours and would see less of Earth's surface. In fact, a fleet of about a dozen or more equally spaced satellites would be necessary to cover the planet.

In addition, because the signal from the handheld phone is weak, the entire burden of completing the link is placed on the satellite. The hookup can be achieved only if the satellite employs very narrow, searchlightlike spot beams on the order of one degree or so, each covering a "cell" on Earth perhaps 150 kilometers across. Many of these beams must be employed to provide coverage of the intended service area.

In general, satellites must orbit either above or below the Van Allen radiation belt, whose energetic ionized particles

would damage solar cells and perhaps other solid-state components. Thus, satellite altitudes must be above about 10,000 kilometers or below about 1,500 kilometers. For the latter option, however, the orbital period is roughly 100 minutes, and about 50 or more satellites are required to cover the globe, because each one sees only a small part. (Imagine trying to take a picture of an elephant from one meter away.) The high- and low-orbit choices have become known as intermediate circular orbit and low-Earth orbit.

Targeting Business Travelers

The designs of the announced satellite cellular phone systems differ considerably, reflecting different assumptions about the customers who might be attracted. The largest groups of potential users are two types of business travelers: those from the developed world who do business often in less developed countries, where the local phone service may be unreliable, and those who need mobile communications in their own countries but who travel beyond the reach of terrestrial cellular systems. Other potential markets include people living in very rural areas, where there is currently no service at all, and law-enforcement, fire, public-safety and other government officials who need access to a communications network that would survive a regional disaster, such as an earthquake or flood.

Many different global systems have been proposed, but only five appear to have some promise of being fielded. Four of them are U.S.-based and have received licenses from the Federal Communications Commission; the fifth is an enterprise spun off from the International Mobile Satellite Organization (Inmarsat), a treaty organization similar to Intelsat. The four U.S.-based projects are Iridium, which was constructed by Motorola with Lockheed Martin, Raytheon and other contractors; Globalstar, a joint effort in which Loral Space and Communications (a satellite manufacturer) and Qualcomm (a maker of cellular equipment) are the principal partners; ECCO, a proposal put forth by Constellation Communications in Reston, Va.; and Ellipso, to be built by Mobile Communications Holdings in Washington, D.C. In addition, several regional systems are being developed that will employ geostationary satellites and primarily serve Third World countries.

Deregulation of the telecommunications industry in various developed countries is speeding delivery of new services and prompting the investment of enormous amounts of capital in new facilities. A key factor in this activity is the explosion in the use of the Internet, which is expected to grow from 50 million households in 1998 to perhaps 150 million by 2000, representing a market of more than $10 billion. Corporate use of the Internet may grow even more spectacularly. Increasingly, corporations are using the Internet to create their own semiprivate "intranets." Some observers believe this market could expand from the less than $1 billion spent in 1996 to more than $30 billion by 2000.

To serve these markets, many new satellite systems are planned. Because of the congestion on the frequencies currently used for fixed (as distinct from mobile) satellite services, these systems will operate in a higher range of frequencies, known as Ka-band. The choice of Ka-band is driven largely by the absence of a suitable alternative; recent developments have made it almost impossible to secure orbital locations for satellites that would operate in other bands without interfering with neighboring satellites. Worldwide there are now believed to be more than 50 proposed Ka-band projects requiring approximately 170 geostationary-orbit locations. Most of these proposals appear to be for national or regional systems, and not much has been published about them thus far.

Data and Multimedia Services

A total of six U.S. systems have received licenses from the FCC to offer global service, although none has progressed beyond the design stage. One of the systems would be based on low-Earth-orbit satellites, the other five on constellations of geostationary-orbit spacecraft. In some sense, these projects are more risky than the voice-oriented satellite projects described earlier because the demand is less certain. This fact may aggravate the problem of raising capital—leaving the field open to those companies best able to commence their projects with their own resources. Those most committed at present, in terms of money spent on design studies, appear to be Lockheed Martin, Motorola and Teledesic.

In addition, success in a consumer market is believed to depend on terminals that cost less than about $1,000. These terminals will combine a small satellite dish antenna and a two-way radio, which may be mounted on the dish, with an indoor component that interfaces with the computer. Achieving such a low cost will most likely require the mass production of a million or more terminals, which is hardly a certainty. If, somehow, the price of the terminals can be brought down to this level, then satellites may take on another role—that of providing "last-mile" connections to homes and businesses for broadband data, multimedia and related services, because existing telephone lines do not afford this kind of data rate (although efforts are under way to change this situation).

The world will soon be a place where not just communications but also torrents of information will be available just about everywhere.

The development of the fleets of satellites described here will affect some of us profoundly. By 2000 it will be possible to call home from essentially anywhere on the planet using a handheld terminal similar to one of today's cellular phones. For better or worse, we need never be out of touch, no matter where we are.

Besides the obvious benefits to commerce and tourism, universal service will become possible, at least for those who can afford it, in countries where none now exists. Within a decade, it will probably be possible to live in a remote area and yet be connected to the worlds of commerce and entertainment via the Internet and other sources of multimedia at rates high enough to support movies-on-demand. The world will soon be a place where not just communications but also torrents of information will be available just about everywhere. Whether this world will seem smaller, larger or more interesting will probably depend on your point of view. SA

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Tapping the Waters of Space

by John S. Lewis

That space travel must be exorbitantly expensive is a modern myth. The high cost of today's space missions is partly because of the failure of governmental agencies to reduce the costs of launching spacecraft. For example, a one-way trip on the space shuttle to low orbit around Earth costs about $20,000 per kilogram. Soft-landing a ton of anything on the moon costs about $100 million. But the high price of space travel also reflects the fact that astronauts must take everything they will need on their journey with them, rather than putting the natural resources found in space to good use.

Ironically, most of what we launch into space is intrinsically cheap rocket propellant. To get a gallon of gasoline or liquid oxygen to the moon would cost $400,001—$1 to purchase it on Earth and $400,000 to deliver it to the moon. And whether it is a communications satellite bound for geostationary orbit, an Apollo flight to the moon or a manned Mars expedition, any ambitious spaceflight requires copious amounts of propellant.

The absurdity of such a logistical system is obvious. But how can we do better? Certainly any accessible reservoir of propellant on the moon or Mars would be enormously attractive. Even if it were to cost $400 to extract or manufacture a gallon of propellant on the surface of the moon or another planet, we would save 99.9 percent. Thus, we could reduce the cost of propellant on a particular mission 1,000-fold, or we could move 1,000 times as much payload. We only need a scientifically, technically and economically sound extraterrestrial source of propellants.

Although there are no oil wells on Mars or the moon, there are two abundant commodities—sunlight and water—that in combination can provide the propellant we need. An array of solar cells could capture sunlight and convert it into electricity, which would then be used to electrolyze water; this process breaks apart the water molecules into hydrogen and oxygen. Burning hydrogen in the presence of oxygen offers the best possible chemical rocket engine performance. And of course, water is the key to life-support systems—a crucial part of the astronauts' diets, a source of oxygen to breathe and an essential component of agriculture in space. Water is arguably the most important material resource we could hope to find in space.

Fortunately, water (in the form of ice) has been found recently in space in a number of surprising places. The Clementine mission in 1994 and the Lunar Prospector mission in 1998 identified and verified the presence of a billion or more tons of ice in the polar regions of the moon, thereby raising the prospect of establishing permanent, self-sufficient lunar bases or even lunar colonies. Just a few years earlier, in 1991, a team of radar astronomers found similar deposits of ice in the bottom of permanently shadowed craters near the poles of Mercury.

In addition, astronomers have known for many years about the presence of ice on Mars. The planet's polar caps are covered in water ice and, during the winter, carbon dioxide snow. Mars is so cold that permafrost exists over more than half the planet's surface. Water-bearing clay minerals and hydrated salts appear to be ubiquitous on the planet. Even the Martian atmosphere, which is 95 percent carbon dioxide, should not be ignored as a source of propellants and material for life-support systems: Kumar N. Ramohalli of the University of Arizona and his co-workers have demonstrated how to manufacture oxygen and carbon monoxide (a medium-performance propellant combination) out of carbon dioxide under conditions similar to those on Mars. Adding Martian water to the process would permit the manufacture on Mars of storable rocket propellants such as methanol.

And in what could prove to be the most promising development, evidence has accumulated that water is probably a common constituent of more than half of the so-called near-Earth asteroids, which revolve around the sun and frequently cross Earth's orbit. As it turns out, water is a widespread resource in the inner reaches of our solar system.

Getting to the Water

This water must be accessible to us, however, if we are to exploit any of the reservoirs profitably. Availability depends on how much energy it takes to get equipment to where the water is, how easy it is to extract the water and process it into useful products, and how much energy it takes to transport the products to where they are needed.

First, let us consider the moon. Because of the amount of energy required to escape from the moon's gravity, it is important to distinguish between water that might be used on the lunar surface and water that would be exported off the surface. Un-

DAVID EGGE

Space travel could be considerably cheaper if astronauts could produce their own food and propellants from the resources already out there

NEAR-EARTH ASTEROID could serve as a refueling station for interplanetary spacecraft. For the swarm of roughly 3,000 asteroids and comets that enter the inner solar system, roughly 25 percent of their mass is water, which translates to some 6,000 billion tons of water. Spacefarers could extract water from the asteroids and convert it to hydrogen and oxygen—important rocket propellants.

fortunately, both options may prove hard to implement.

A lunar base that could take full advantage of water from the polar-ice deposits would have to be located near one of the poles because of the difficult logistics of moving materials long distances over the moon's rugged terrain. Building a base at the poles would be extraordinarily challenging: to capitalize on the sun's energy, the base would have to be constructed high on a permanently illuminated mountaintop. Mining the permafrost for water is also a daunting prospect, requiring work in temperatures below 100 kelvins (–280 degrees Fahrenheit) in the permanent darkness of the valleys where the ice is found. Exporting water from the moon (or even flying a payload from the pole to the equator) requires overcoming the moon's substantial gravitational field, a feat that would dramatically lower the desired energy savings motivating the mission in the first place.

Another place to mine for water could be Mars. Mars has a substantial gravity field, requiring an escape velocity of 5,400 meters per second (around 18,000 feet per second). Lifting water or propellant off Mars would be somewhat easier than exporting these products from Earth (where the escape velocity is 11,200 meters per second). But we would still have to fight against Mars's gravity to deliver material generated there to anywhere else—which would eat up a large portion of the propellant that had been produced. Making propellant for a return trip from Mars to Earth is an attractive option, but exporting items from Mars for use elsewhere in the solar system is simply too costly.

Mars's two moons—Phobos and Deimos—have also been considered potential water sources. Indeed, as early as 1939 a British engineer named Arthur C. Clarke pointed out that these moons might be sufficiently rich in water to make them attractive way stations and refueling stops for missions to and from Mars. But Larry A. Lebofsky of the University of Arizona, working with Jeffrey F. Bell and his group at the University of Hawaii at Manoa, has searched for the telltale signal of water, an absorption band in the near infrared, and has failed to detect water on either Phobos or Deimos.

Although the Martian moons have not lived up to early expectations for them as extraterrestrial filling stations, their resemblance in size and appearance to a particular class of asteroids has pointed astronomers in a much more encouraging direction. Like the Martian moons, carbonaceous (or C-type) asteroids are dark, low-density stones containing carbon, magnetite, salts and abundant clay minerals. But whereas the surfaces of Phobos and Deimos have been baked free of water and other volatile compounds by repeated heating from impacts and reaccretion of dried materials, C-asteroids should still carry water-rich materials on the surface.

Under observational scrutiny, however, C-asteroids behave with a shocking disregard for theory. Lebofsky and Thomas D. Jones, a planetary scientist turned astronaut, have found that only about half of the C-asteroids in the main asteroid belt between Mars and Jupiter have prominent water absorption bands. Evidence bearing on the water content of these asteroids is sparse. The only C-asteroid yet visited by a spacecraft—the Near Earth Asteroid Rendezvous mission, or NEAR—is 253 Mathilde.

But even if we had overwhelming proof of the presence of ice or water in a C-asteroid in the main asteroid belt, it is far from clear that this source of water would have any practical significance. The main asteroid belt is simply too far away from Earth and too remote from any place where we might soon have a demand for materials produced in space. Fortunately for us, however, complex dynamic processes constantly shower the inner solar system with asteroids ejected from the main belt.

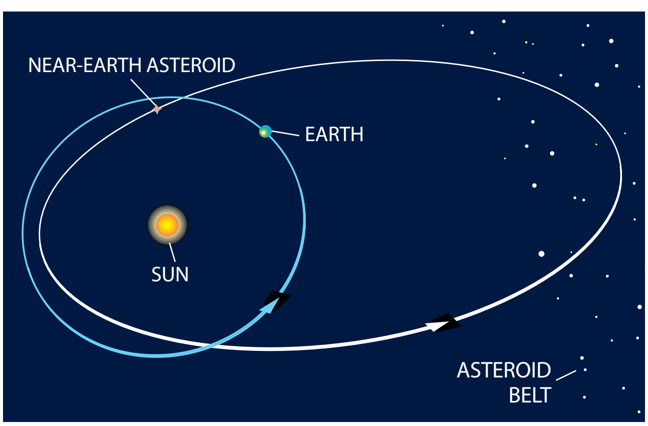
Near-Earth Objects

Such asteroids—along with the comets that travel into the inner solar system—are collectively termed near-Earth objects, or NEOs. These NEOs have relatively short life expectancies: most last only 30 million to 100 million years before being destroyed by collision with any of the planets whose orbits they cross or ejected from the solar system after a close encounter with Jupiter. Many even crash into the sun or come so close to the sun that they evaporate. Comets may dissipate completely, or their surfaces may dry out enough so that they start to resemble C-asteroids. Small pieces of debris knocked off these bodies by minor impacts can fall to Earth as meteorites. Indeed, the large majority of meteorites that strike Earth's upper atmosphere probably originate from NEOs. Meteorites are therefore powerful clues to whether the asteroids in the inner solar system (called near-Earth asteroids, or NEAs) carry any water.

Of the meteorites that reach Earth's surface and are recovered, only about 3 percent are water-bearing, carbonaceous types. But spectroscopic and photographic studies of fireballs in the upper atmosphere suggest that well over half of the meter-size objects that strike are carbonaceous bodies so weak that they disintegrate high in the atmosphere. Few of these fragile fireballs succeed in delivering meteorites to Earth's surface. So if the meteors seen in Earth's atmosphere provide an accurate representation of the different types of NEAs, then half or more of those asteroids should carry abundant supplies of water.

The best test of this hypothesis would be to analyze samples taken from asteroids. But because no spacecraft has yet to touch down on an asteroid, we must rely on astronomical spectral studies. The spectra of about 45 near-Earth asteroids have been published, and 60 others have been studied recently.

These data suggest that about 25 percent of the NEAs consist of some variant of C-type material that carries water. But this number is somewhat skewed. Astronomers detect NEAs by visible light, and carbonaceous asteroids are much darker than other types. Thus, the traditional method of discovering asteroids discriminates against C-asteroids simply because they are harder to see. As a result, astronomers know that at least 25 percent of NEAs are C-asteroids; in practice, most estimates put the figure as high as 50 to 60 percent. Each of these asteroids contains 5 to 20 percent water. In addition, dynamic studies suggest that about half of the NEAs are actually extinct comet cores,



GEORGE RETSECK

ORBITS of the near-Earth asteroids have been dislodged from the main asteroid belt between Mars and Jupiter. Experts estimate there are roughly 2,000 of these asteroids.

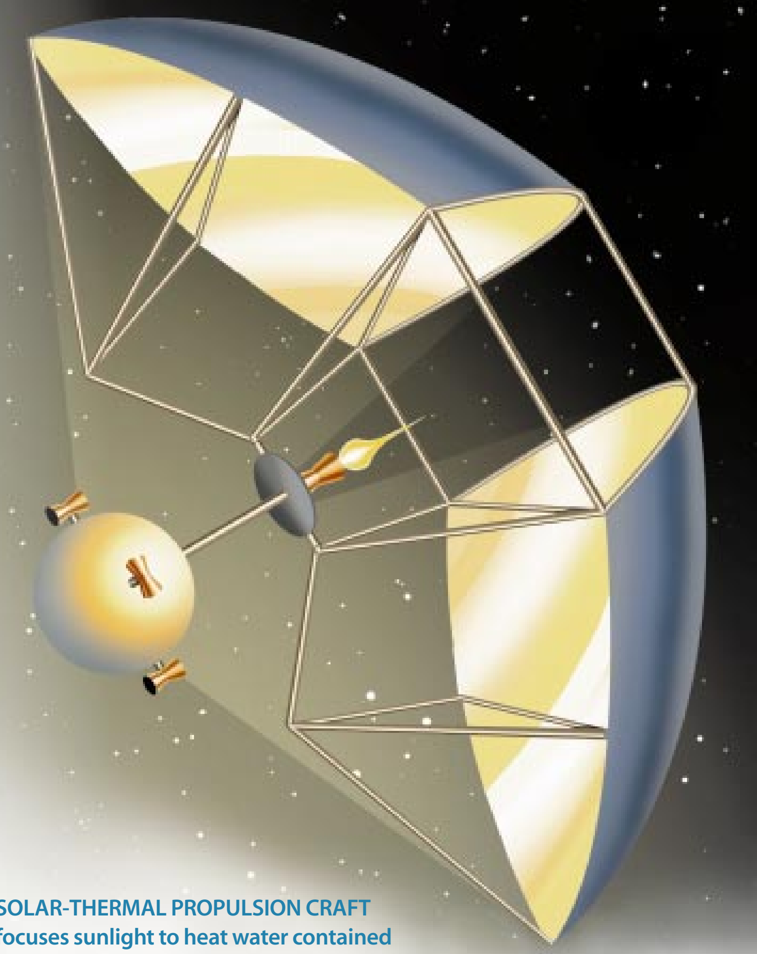
bearing up to 60 percent water. In total, for the swarm of roughly 3,000 asteroids and comets that enter the inner solar system, roughly 25 percent of the mass is water, which translates to some 6,000 billion tons of water. There is water, water everywhere in our solar system—but is there any drop we can afford to drink?

Mining an Asteroid

Fortunately, missions from Earth to the near-Earth asteroids are surprisingly straightforward. About 15 percent of the known NEAs are easier to reach than the moon. Because of the moon's gravity, a large amount of propellant is required to slow the descent of a rocket vehicle to a soft landing. But asteroids have such feeble gravity that landing on them is easy. Thus, a given rocket could land a larger payload on one of these NEAs than on the moon.

After landing on an asteroid, water could be extracted from the permafrost simply by warming it enough to evaporate or melt the water ice. A solar furnace—essentially a mirror the thickness of aluminum foil that would direct solar energy to the asteroid's surface—would do the job admirably. It could either be attached directly to the asteroid or be held in place close to the surface in the precise spot where the sun's gravity cancels that of the asteroid. An asteroid containing water-rich clays and hydrated salts would require heating to somewhat higher temperatures, again well within the capabilities of a solar furnace.

The crowning touch to this plan is that it would be far simpler to lift water off asteroids than it would be to lift water off the moon. A kilometer-size NEA has an escape velocity of about one meter per second, compared with 2,380 meters per second for the moon and 5,400 meters per second for Mars. Also, little propellant is needed to launch a spacecraft from an asteroid at a speed that would allow it to return to Earth. The spacecraft could then rendezvous with a space station in low orbit around Earth.



GEORGE RETSECK

SOLAR-THERMAL PROPULSION CRAFT focuses sunlight to heat water contained in a metallic thrust chamber; the resulting jet of steam powers the vehicle. Water is quite abundant in the inner solar system and could be mined for use as a rocket propellant.

A tanker returning from an NEA with a shipment of water could off-load its cargo at the station. There, as described earlier, electricity from solar panels could electrolyze some of the water into hydrogen and oxygen to fuel a small chemical rocket engine on the tanker sufficient to carry the empty tanker back out to another water-bearing asteroid. Each return trip could provide enough propellant for several dozen outbound flights. Over the lifetime of the craft, it could make multiple round-trips, returning 100 tons of propellants to the refueling depot for every ton of equipment launched from Earth. This bootstrapping scheme is said to have a "mass payback ratio" of 100. Of course, the tanker could be refurbished at the station between flights, lengthening the lifetime of the vehicle severalfold—and increasing the mass payback ratio to 500 or 1,000.

How would the tanker propel itself around the inner solar system? Would we have to put a complex electrolysis plant on an asteroid where there would be no one to tend to it? There are two techniques by which a rocket could use water itself as its propellant. In one scheme—nuclear-thermal propulsion—a nuclear reactor heats water to generate steam for the rocket engine. In a second method, called solar-thermal propulsion, sunlight is used to heat water inside a thrust chamber to produce superheated steam [*see illustration above*]. This concept of a solar-powered rocket was first described in the student notebook of American rocket pioneer Robert H. Goddard in 1908.

Such a transportation system, with the capacity for payloads dozens of times heavier than the propellant needed to power the vessel, could convey other commodities around the inner solar system. Metals extracted from stony asteroids, for example, could be retrieved for use in building large structures such as solar-power satellites in orbits around Earth.

All these benefits could accrue even if the high launch costs bemoaned at the outset of this article continue. But there are bright prospects for slashing launch costs by abandoning 1960s technology in favor of single-stage-to-orbit vehicles, hybrid or plug-nozzle engines or any of a variety of potentially reliable and cheap alternatives. A cost of $400 per kilogram appears achievable with fully reusable boosters and airline-style operations. Suppose we pay $400 per kilogram to launch equipment to a near-Earth asteroid, from which we have a mass payback ratio of 100. The costs of construction materials in Earth orbit would then amount to $4 per kilogram—comparable to the expense of building a home here on Earth. And when we can build a habitat in space for the cost of a house, then the space age will truly have begun. SA

John S. Lewis is professor of planetary sciences and co-director of the Space Engineering Research Center at the University of Arizona. He is the author of 150 research publications as well as undergraduate and graduate texts on planetary science. He has also written three popular science books: *Rain of Iron and Ice*, *Mining the Sky* (both from Addison-Wesley, 1996) and *Worlds without End* (Perseus, 1998).

Exploring Space on the Internet

Thanks to the World Wide Web, anyone with an Internet connection can explore space vicariously, browsing through dozens of Web sites for the latest news about space missions and projects. Some of the most informative and eye-catching sites are presented in the list below. For all Web addresses, add the prefix http:// —*The Editors*

SPACE AGENCIES

www.nasa.gov/
Home page of the National Aeronautics and Space Administration (NASA)

www.rka.ru/english/eindex.htm
Home page of the Russian Space Agency (RSA), in English

www.esa.int/
Home page of the European Space Agency (ESA), in English

www.nasda.go.jp/index_e.html
Home page of the National Space Development Agency of Japan (NASDA), in English

SPACE SHUTTLE AND STATIONS

www.ksc.nasa.gov/shuttle/missions/missions.html
Summaries of all space shuttle flights to date and plans for future missions

www.ksc.nasa.gov/shuttle/technology/sts-newsref/stsref-toc.html
A technical reference manual for the space shuttle

spaceflight.nasa.gov/index.html
News about the International Space Station, and real-time tracking of its orbit

liftoff.msfc.nasa.gov/
Information on space stations and satellites as well as a section for children

UNMANNED MISSIONS AND OBSERVATORIES

www.hq.nasa.gov/office/oss/missions/index.htm
A thorough list of NASA's space science missions—past, present and future

mpfwww.jpl.nasa.gov/
Mars missions managed by the Jet Propulsion Laboratory

www.jpl.nasa.gov/ice_fire//
Information on the "Ice and Fire Missions": Europa Orbiter, Pluto-Kuiper Express and Solar Probe

www.stsci.edu/
The latest discoveries made with the Hubble Space Telescope

nssdc.gsfc.nasa.gov/
Space research data from the National Space Science Data Center

SPACE ORGANIZATIONS

www.marssociety.org/
Information on the Mars Society's efforts to increase support for exploration of the Red Planet

www.nss.org/
Educational resources and more from the National Space Society, the oldest space advocacy group

www.space-frontier.org/
Home page of the Space Frontier Foundation, with links to companies in the space industry

www.prospace.org/
Home page of ProSpace, a lobbying group for space exploration

www-ssi.colorado.edu/
Resources for scientists and teachers from the Space Science Institute

www.asi.org/
Information on the Artemis Project, which is dedicated to establishing human communities on the moon

www.reston.com/nasa/watch.html
A non-NASA site about NASA activities, offering news about the agency's programs, budget and administrators

HISTORY OF SPACE EXPLORATION

www.ksc.nasa.gov/history/mercury/mercury.html
Historical information on the Mercury missions, the first U.S. manned flights into space

www.ksc.nasa.gov/history/gemini/gemini.html
Site for facts about the Gemini missions

www.ksc.nasa.gov/history/apollo/apollo.html
Descriptions of the Apollo missions and the first moon landings

www.ksc.nasa.gov/history/skylab/skylab.html
A history of Skylab, the first U.S. space station

ASTRONAUTS AND COSMONAUTS

www.jsc.nasa.gov/Bios/astrobio.html
Biographies of all active-duty U.S. astronauts and mission specialists from other countries who have flown on the space shuttle

www.jsc.nasa.gov/Bios/cosmo.html
Biographies of cosmonauts involved in U.S.-Russian joint projects

38.201.67.70/history/shuttle-mir/ops/crew/
Photographs and biographies of the crews who served on Mir, the Russian space station

GREAT PICTURES

photojournal.jpl.nasa.gov
At least 1,400 images of planets, moons, the sun and more

www.jpl.nasa.gov/pictures/archive.html
Illustrations of Mars Pathfinder, Galileo, Cassini and other spacecraft

nssdc.gsfc.nasa.gov/photo_gallery/
The National Space Science Data Center's archive of astronomy photographs

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