HOW TO GO TO MARS

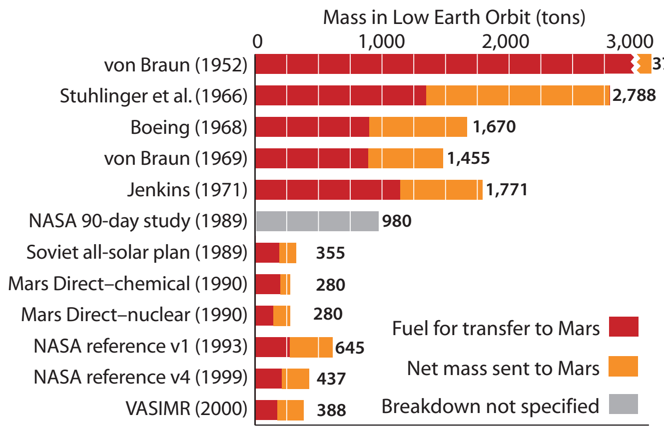
Staff writers George Musser and Mark Alpert make sense of the myriad ideas for a human mission

Going to Mars would be daunting. The planet never comes closer than 80 million kilometers to ours; a round-trip would take years. But scientists and engineers say they have solutions to the main technological challenges that a human mission would entail. The biggest obstacle is simply the enormous cost.

Cost estimates for a Mars mission boil down to one crucial number: the mass of the spacecraft. Lighter spacecraft need less fuel, which is the greatest single expense of a spaceflight. The history of Mars mission planning is largely an effort to minimize weight without unduly compromising safety or science. In 1952 rocket pioneer Wernher von Braun envisioned an armada of spaceships propelled by conventional chemical rockets and weighing 37,200 tons on departure. Just to haul such a fleet into Earth orbit would cost hundreds of billions of dollars. Since then, planners have wrung economies by using more efficient nuclear or electromagnetic rockets, scaling back the number of astronauts or the level of redundancy, and manufacturing fuel on Mars itself [*see chart at right*].

Today the barest-bone mission is the Mars Direct plan, with an estimated price tag of $20 billion in start-up costs, spread out over a decade, plus $2 billion per mission [see "The Mars Direct Plan," on page 52]. The National Aeronautics and Space Administration's own plan, the "design reference mission," has adopted many of the ideas of Mars Direct but costs roughly twice as much, in return for extra safety measures and a larger crew (six rather than four).

In its most recent version, NASA's plan [*see illustration on opposite page*] calls for three spacecraft: an unmanned cargo lander, which delivers an ascent vehicle and propellant plant to the Martian surface; an unoccupied habitat lander, which goes into Martian orbit; and a crew transfer vehicle (CTV), which, if the first two arrive successfully, sets out when Mars and Earth come back into alignment, 26 months after the



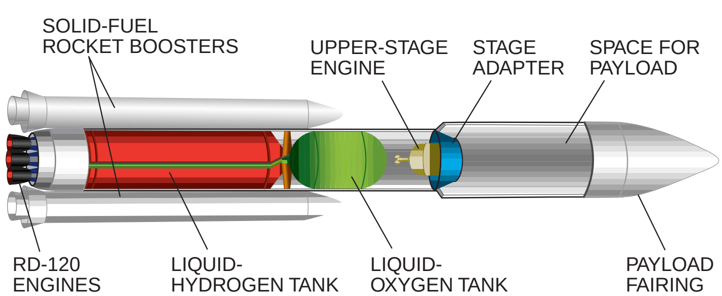
EDWARD BELL

WEIGHT of proposed Mars missions on departure from Earth orbit—a proxy for cost—has slowly come down. Each weight estimate includes both crew and cargo flights for one team of astronauts.

LAUNCH AND ASSEMBLY

In all the proposals for sending humans to Mars, the crucial first step is launching the spacecraft into a low Earth orbit (200 to 500 kilometers up). The basic problem is that any manned craft using present-day propulsion technologies will need a huge supply of propellant to get to Mars and hence will be extremely heavy: at least 130 metric tons and possibly twice that much. No launch vehicle now in use can lift that much mass into orbit. The space shuttle and heavy-lift rockets such as the Titan 4B have maximum payloads under 25 tons. Moreover, with launch costs currently as high as $20 million per ton, boosting a Mars spacecraft would be prohibitively expensive.

Aerospace companies are developing more cost-efficient rockets (such as the Delta 4) and reusable launch vehicles (such as VentureStar), but none could lift a 130-ton payload. The Apollo-era Saturn 5 could do the job, and so could the Energia booster developed by the former Soviet Union, but reviving production of either rocket would be impractical. So in all likelihood the Mars craft would have to be launched in stages and then assembled in orbit, preferably through docking maneuvers that could be controlled from the ground. (Assembling the craft at the International Space Station would be inefficient because the station's orbit has an inclination of 51.6 degrees; from the launch facilities at Cape



MAGNUM ROCKET is a relatively inexpensive option for launching the spacecraft that would carry the first astronauts to Mars. Using the same launchpads and solid-fuel boosters as the space shuttle, the Magnum could lift 80 tons into Earth orbit.

SARAH L. DONELSON

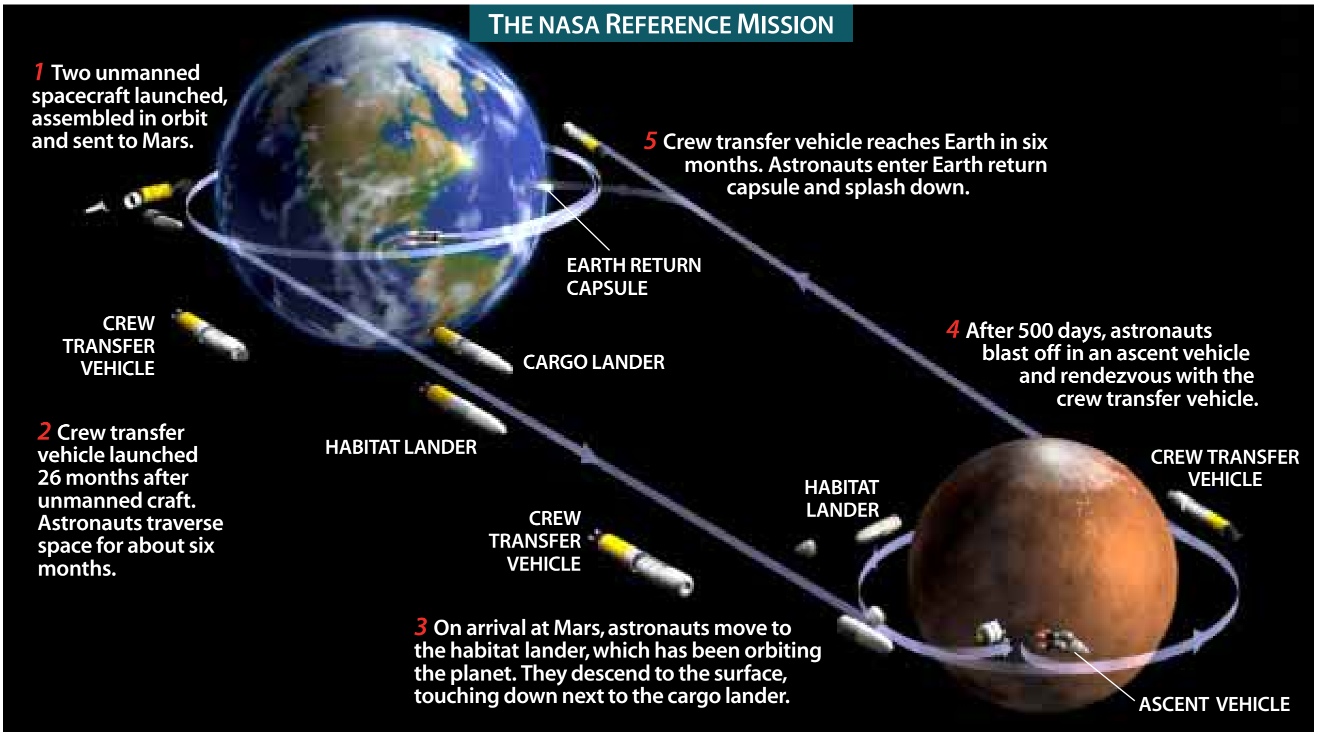
first launches. The CTV carries the astronauts to Mars and meets up with the habitat lander. The astronauts change ships, descend to the surface, stay for 500 days and return in the ascent vehicle. The CTV, which has been waiting in orbit, brings them home. Every 26 months, another trio of spacecraft sallies forth, eventually building up the infrastructure for a permanent settlement.

The estimated costs of these plans are cheaper than those of the International Space Station or the Apollo program. Still, NASA does not have a sterling reputation for adhering to cost estimates. For this reason, many Mars enthusiasts in organizations such as the Mars Society and the National Space Society have been casting about for new ways to run a space program.

The most fully developed plan is the work of ThinkMars, a group of students from the Massachusetts Institute of Technology and Harvard Business School. They propose setting up a for-profit corporation to manage the Mars project, contracting out the various tasks to private companies and NASA research centers. The U.S. and other governments would, in effect, buy seats or cargo space on the Mars ship at a reduced price. The difference would be made up by selling promotional opportunities and media rights and by licensing technological spin-offs.

Researchers have shown that a human mission is technically feasible. Now the enthusiasts need to win over the taxpayers, politicians and business leaders who would have to foot the bill.

We would like to thank the many scientists and engineers who have helped us map out the various technologies.

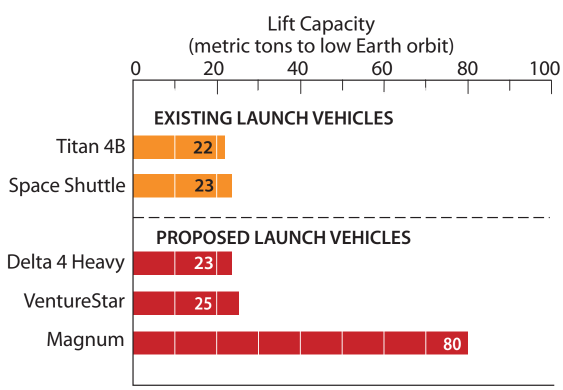


ALFRED T. KAMAJIAN

Canaveral, Fla., it is easiest to boost payloads into an orbit with a 28.5-degree inclination.) The space shuttle could transfer the crew to the Mars craft once it was completed.

To simplify the assembly, the number of launches and orbital rendezvous would have to be minimized. Engineers at the NASA Marshall Space Flight Center in Huntsville, Ala., have designed a rocket, called the Magnum, that could boost about 80 tons into orbit, enabling the deployment of a 130-ton Mars craft with only two liftoffs (for a comparison with other launch vehicles, see the chart below). The Magnum is designed to use the same launchpads and solid-fuel boosters as the space shuttle. The shuttle's boosters would be attached to a new two-stage rocket powered by three Russian-designed RD-120 engines. The Magnum could carry a 28-meter-long payload, and the skin of the rocket's upper stage could also serve as the Mars craft's heat shield.

Because the Magnum would use existing boosters and launch facilities, its costs would be relatively low: about $2 billion for development and $2 million per ton for each launch, which is a 10-fold improvement over the shuttle's costs. Furthermore, it may be possible to build an even more powerful launch vehicle from space shuttle components, as proposed by astronautical engineer Robert Zubrin. Called Ares, it would use a high-thrust upper-stage engine to put the manned spacecraft directly on a trajectory to Mars.



CURRENT LAUNCH VEHICLES cannot meet the needs of a human mission to Mars. Boosting a 130-ton Mars craft into Earth orbit would require six launches of the Titan 4B, space shuttle, Delta 4 Heavy or VentureStar—but only two of the Magnum.

SARAH L. DONELSON

PROPULSION SYSTEM

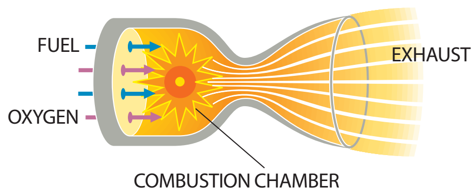
How can you propel a manned spacecraft from Earth orbit to Mars? Planners are considering several options, each with its own advantages and drawbacks. The basic trade-off is between the rocket's thrust and its fuel efficiency. High-thrust systems are the hares: they accelerate faster but generally consume more fuel. Low-thrust systems are the tortoises: they take longer to speed up but save on fuel. Both could be used in different phases of a single mission. High-thrust rockets can convey astronauts quickly, whereas low-thrust devices can handle slower shipments of freight or unoccupied vessels.

LEGEND FOR ILLUSTRATIONS
- PROPELLANT
- ELECTRIC CURRENT
- MAGNETIC FIELD
- OXYGEN

CHEMICAL

Nearly all spacecraft launched to date have relied on chemical rocket engines, which typically burn hydrogen and oxygen and use the expanding gases to provide thrust. It is a proven technology and produces more thrust than most other approaches, but less efficiently. Chemical rockets would require prodigious amounts of fuel to propel a manned spacecraft to Mars. One design calls for a 233-ton craft that would start the voyage with 166 tons of liquid hydrogen and oxygen. Its seven RL-10 engines (a venerable design used on many U.S. rockets) would be arranged in three propulsion stages. The first stage would boost the craft to a high elliptical orbit around Earth, the second would put the craft on a trajectory to Mars, and the third would propel the craft back to Earth at the end of the mission. Each stage would fire for a matter of minutes and then be discarded.

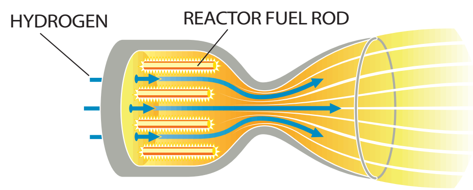
Thrust: 110,000 newtons
Exhaust speed: 4.5 kilometers per second
Sample burn time: 21 minutes
Sample fuel ratio: 55 percent



CHRISTOPH BLUMRICH

NUCLEAR THERMAL

The U.S. government built and ground-tested nuclear thermal rockets in the Rover/NERVA program of the 1960s. These engines provide thrust by streaming liquid hydrogen through a solid-core nuclear reactor; the hydrogen is heated to more than 2,500 degrees Celsius and escapes through the rocket nozzle at high speed. Nuclear propulsion delivers twice as much momentum per kilogram of fuel as the best chemical rockets, and the reactors can also be used to generate electricity for the spacecraft. A 170-ton manned vehicle containing three nuclear rockets and about 90 tons of liquid hydrogen could reach Mars in six or seven months. The big obstacle, however, is public opposition to putting a nuclear reactor in space—a problem for many other propulsion systems, too. NASA has not funded research into spaceborne reactors for nearly a decade.



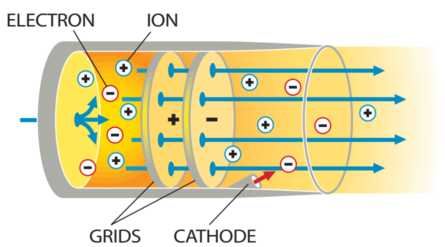
Thrust: 67,000 newtons
Exhaust speed: 9 kilometers per second
Sample burn time: 27 minutes
Sample fuel ratio: 32 percent

CHRISTOPH BLUMRICH

ION

First developed in the 1950s, ion propulsion is one of a number of technologies that use electrical fields rather than heat to eject the propellant. The gaseous fuel, such as cesium or xenon, flows into a chamber and is ionized by an electron gun similar to those in television screens and computer monitors. The voltage on a pair of metal grids extracts the positively charged ions so that they shoot through the grid and out into space. Meanwhile a cathode at the rear of the engine dumps electrons into the ion beam so that the spacecraft does not build up a negative charge. Just over a year ago the Deep Space 1 probe conducted the first interplanetary test of such a system. It consumed 2.5 kilowatts of solar power and produced a small but steady 0.1 newton of thrust. Unfortunately, the grids—which accelerate the particles but also get in their way—may not scale up to the megawatt levels needed for manned Mars missions. Also, a large ion drive might need to draw its power from nuclear reactors; solar panels capable of more than about 100 kilowatts would probably be unwieldy.

Thrust: 30 newtons
Exhaust speed: 30 kilometers per second
Sample burn time: 79 days
Sample fuel ratio: 22 percent

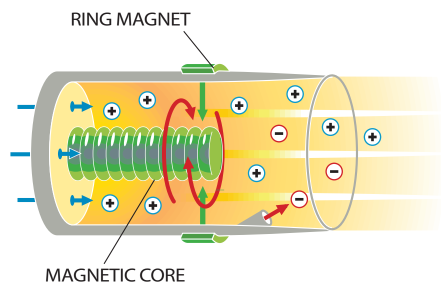


CHRISTOPH BLUMRICH; SOURCE: JAMES S. SOVEY *NASA Glenn Research Center*

HALL EFFECT

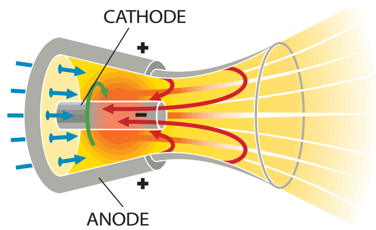
Like ion drives, Hall-effect thrusters use an electrical field to catapult positively charged particles (generally xenon). The difference is in how the thruster creates the field. A ring of magnets first generates a radial magnetic field, which causes electrons to circle around the ring. Their motion in turn creates an axial electrical field. The beauty of the system is that it requires no grids, which should make it easier to scale up than ion drives. The efficiency is lower but could be raised by adding a second thruster stage. Hall-effect thrusters have flown on Russian satellites since the early 1970s, and recently the technology has won converts in the U.S. The latest version, a joint U.S.-Russian project, consumes about 5 kilowatts and generates 0.2 newton of thrust.

Thrust: 30 newtons
Exhaust speed: 15 kilometers per second
Sample burn time: 90 days
Sample fuel ratio: 38 percent



CHRISTOPH BLUMRICH; SOURCE: JAMES S. SOVEY *NASA Glenn Research Center*

MAGNETOPLASMADYNAMIC

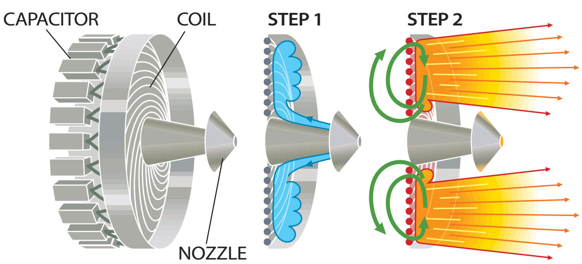


MPD rockets accelerate charged particles using magnetic rather than electrical fields. The device consists of a channel formed by an anode, with a rod-shaped cathode running down the middle. A voltage between the two electrodes ionizes the propellant, allowing a strong electric current to flow radially through the gas and down the cathode. The current in the cathode generates a circular magnetic field, which interacts with the current in the gas to accelerate particles in a direction perpendicular to both—that is, axially. The fuel can be argon, lithium or hydrogen, in increasing order of efficiency. After decades of intermittent interest, NASA resumed work on MPDs last year. Following up efforts at Princeton University and at institutions in Russia, Japan and Germany, the agency has built a 1-megawatt prototype in which the current comes in 2-millisecond pulses.

Thrust: 100 newtons
Exhaust speed: 20 to 100 kilometers per second
Sample burn time: 21 to 25 days
Sample fuel ratio: 6.7 to 31 percent

CHRISTOPH BLUMRICH; SOURCE: MICHAEL R. LAPOINTE *NASA Glenn Research Center*

PULSED INDUCTIVE THRUSTER

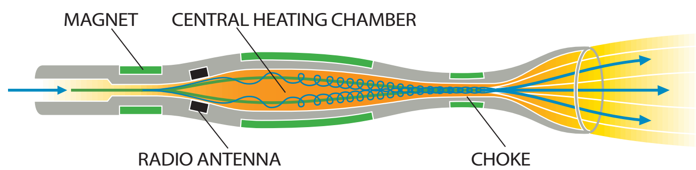


PIT is another technology that NASA is reexamining. The device relies on a rapid sequence of events that, like the MPD, sets up perpendicular electrical and magnetic fields. It begins when a nozzle releases a puff of gas (usually argon), which spreads out across the face of a flat coil of wire about 1 meter across. Then a bank of capacitors discharges a pulse of current, lasting about 10 microseconds, into the coil. The radial magnetic field generated by the pulse induces a circular electrical field in the gas, ionizing it and causing the particles to revolve in exactly the opposite direction as the original pulse of current. Because their motion is perpendicular to the magnetic field, they are pushed out into space. Unlike other electromagnetic drives, PIT requires no electrodes, which tend to wear out, and its power can be scaled up simply by increasing the pulse rate. In a 1-megawatt system the pulses would occur 200 times a second.

Thrust: 20 newtons
Exhaust speed: 50 kilometers per second
Sample burn time: 110 days
Sample fuel ratio: 14 percent

CHRISTOPH BLUMRICH; SOURCE: ROBERT VONDRA *TRW,* RALPH H. LOVBERG *University of California, San Diego* AND C. LEE DAILEY

VASIMR



The Variable Specific Impulse Magnetoplasma Rocket bridges the gap between high- and low-thrust systems. The propellant, generally hydrogen, is first ionized by radio waves and then guided into a central chamber threaded with magnetic fields. There the particles spiral around the magnetic-field lines with a certain natural frequency. By bombarding the particles with radio waves of the same frequency, the system heats them to 10 million degrees. A magnetic nozzle converts the spiraling motion into axial motion, producing thrust. By regulating the manner of heating and adjusting a magnetic choke, the pilot can control the exhaust rate. The mechanism is analogous to a car gearshift. Closing down the choke puts the rocket into high gear: it reduces the number of particles exiting (hence the thrust) but keeps their temperature high (hence the exhaust speed). Opening up corresponds to low gear: high thrust but low efficiency. A spacecraft would use low gear and an afterburner to climb out of Earth orbit and then shift up for the interplanetary cruise. NASA plans a test flight of a 10-kilowatt device in 2004; Mars missions would need 10 megawatts.

	Low gear	High gear
Thrust:	1,200 newtons	40 newtons
Exhaust speed:	10 km per second	300 km per second
Sample burn time:	2.1 days	53 days
Sample fuel ratio:	46 percent	2.4 percent

CHRISTOPH BLUMRICH; SOURCE: FRANKLIN CHANG-DIAZ
NASA Johnson Space Center

SOLAR SAILS

A staple of science fiction, solar sails take the trade-off between thrust and efficiency to an extreme. They are pushed along by the gentle pressure of sunlight—feeble but free. To deliver 25 tons from Earth to Mars within a year, a sail would have to be at least 4 square kilometers in size. Its material must be no denser than about 1 gram per square meter. Carbon fibers are now nearly that wispy. The next challenge will be deploying such a large but fragile structure. In 1993 the Russian Space Regatta Consortium unfurled the 300-square-meter Znamya space mirror, but in a second test last year it got tangled. NASA recently funded an analogous idea for a magnetic "sail" to catch the solar wind (charged particles streaming from the sun) rather than sunlight.

Thrust: 9 newtons per square kilometer (at Earth's distance from sun)
Exhaust speed: not applicable
Sample burn time: 58 days

ROCKETRY TERMS

Thrust: the force that a rocket engine of this type could provide on a Mars mission, measured in newtons (equal to about a quarter of a pound of force).

Exhaust speed: a measure of fuel efficiency.

Sample burn time: how long the rocket must fire to accelerate a 25-ton payload from low Earth orbit to escape velocity. The time is inversely related to the thrust.

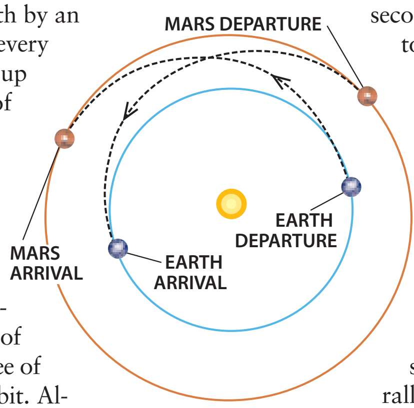
Sample fuel ratio: fraction of the total spacecraft mass taken up by propellant (in the above scenario). The amount of fuel is exponentially related to the exhaust speed.

WHICH ROUTE TO TAKE?

CONJUNCTION CLASS

For high-thrust rockets, the most fuel-efficient way to get to Mars is called a Hohmann transfer. It is an ellipse that just grazes the orbits of both Earth and Mars, thereby making the most use of the planets' own orbital motion. The spacecraft blasts off when Mars is ahead of Earth by an angle of about 45 degrees (which happens every 26 months). It glides outward and catches up with Mars on exactly the opposite side of the sun from Earth's original position. Such a planetary configuration is known to astronomers as a conjunction. To return, the astronauts wait until Mars is about 75 degrees ahead of Earth, launch onto an inward arc and let Earth catch up with them.

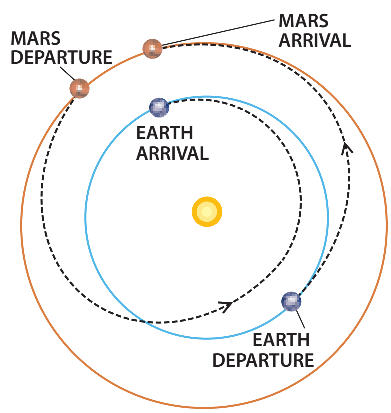
Each leg requires two bursts of acceleration. From Earth's surface, a velocity boost of about 11.5 kilometers per second breaks free of the planet's pull and enters the transfer orbit. Alternatively, starting from low Earth orbit, where the ship is already moving rapidly, the engines must impart about 3.5 kilometers per second. (From lunar orbit the impulse would be even smaller, which is one reason that the moon featured in earlier mission plans. But most current proposals skip it as an unnecessary and costly detour.) At Mars, retrorockets or aerobraking must slow the ship by about 2 kilometers per second to enter orbit or 5.5 kilometers per second to land. The return leg reverses the sequence.



The whole trip typically takes just over two and a half years: 260 days for each leg and 460 days on Mars. In practice, because the planetary orbits are elliptical and inclined, the optimal trajectory can be somewhat shorter or longer. Leading plans, such as Mars Direct and NASA's reference mission, favor conjunction-class missions but quicken the journey by burning modest amounts of extra fuel. Careful planning can also ensure that the ship will circle back to Earth naturally if the engines fail (a strategy similar to that used by *Apollo 13*).

OPPOSITION CLASS

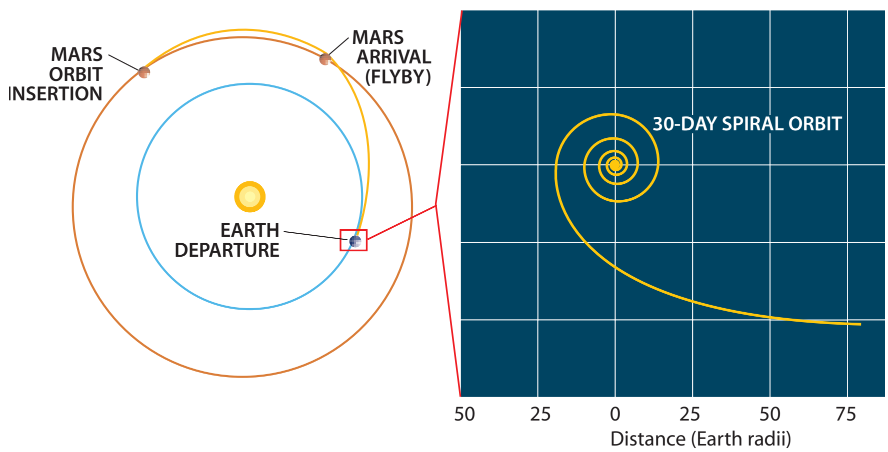
To keep the trip short, NASA planners traditionally considered opposition-class trajectories, so called because Earth makes its closest approach to Mars—a configuration known to astronomers as an opposition—at some point in the mission choreography. These trajectories involve an extra burst of acceleration, administered en route. A typical trip takes one and a half years: 220 days getting there, 30 days on Mars and 290 days coming back. The return swoops toward the sun, perhaps swinging by Venus, and approaches Earth from behind. The sequence can be flipped so that the outbound leg is the longer one. Although such trajectories have fallen into disfavor—it seems a long trip for such a short stay—they could be adapted for ultrapowerful nuclear rockets or "cycler" schemes in which the ship shuttles back and forth between the planets without stopping.



LOW THRUST

Low-thrust rockets such as ion drive save fuel but are too weak to pull free of Earth's gravity in one go. They must slowly expand their orbits, spiraling outward like a car switchbacking up a mountain. Reaching escape velocity could take up to a year, which is a long time to expose the crew to the Van Allen radiation belts that surround Earth. One idea is to use low-thrust rockets only for hauling freight. Another is to move a vacant ship to the point of escape, ferry astronauts up on a "space taxi" akin to the shuttle and then fire another rocket for the final push to Mars. The second rocket could either be high or low thrust. In one analysis of the latter possibility, a pulsed inductive thruster fires for 40 days, coasts for 85 days and fires for another 20 days or so on arrival at the Red Planet.

A VASIMR engine opens up other options. Staying in low gear (moderate thrust but low efficiency), it can spiral out of Earth orbit in 30 days. Spare propellant shields the astronauts from radiation. The interplanetary cruise takes another 85 days. For the first half, the rocket upshifts; at the midpoint it begins to brake by downshifting. On arrival at Mars, part of the ship detaches and lands while the rest—including the module for the return flight—flies past the planet, continues braking and enters orbit 131 days later.



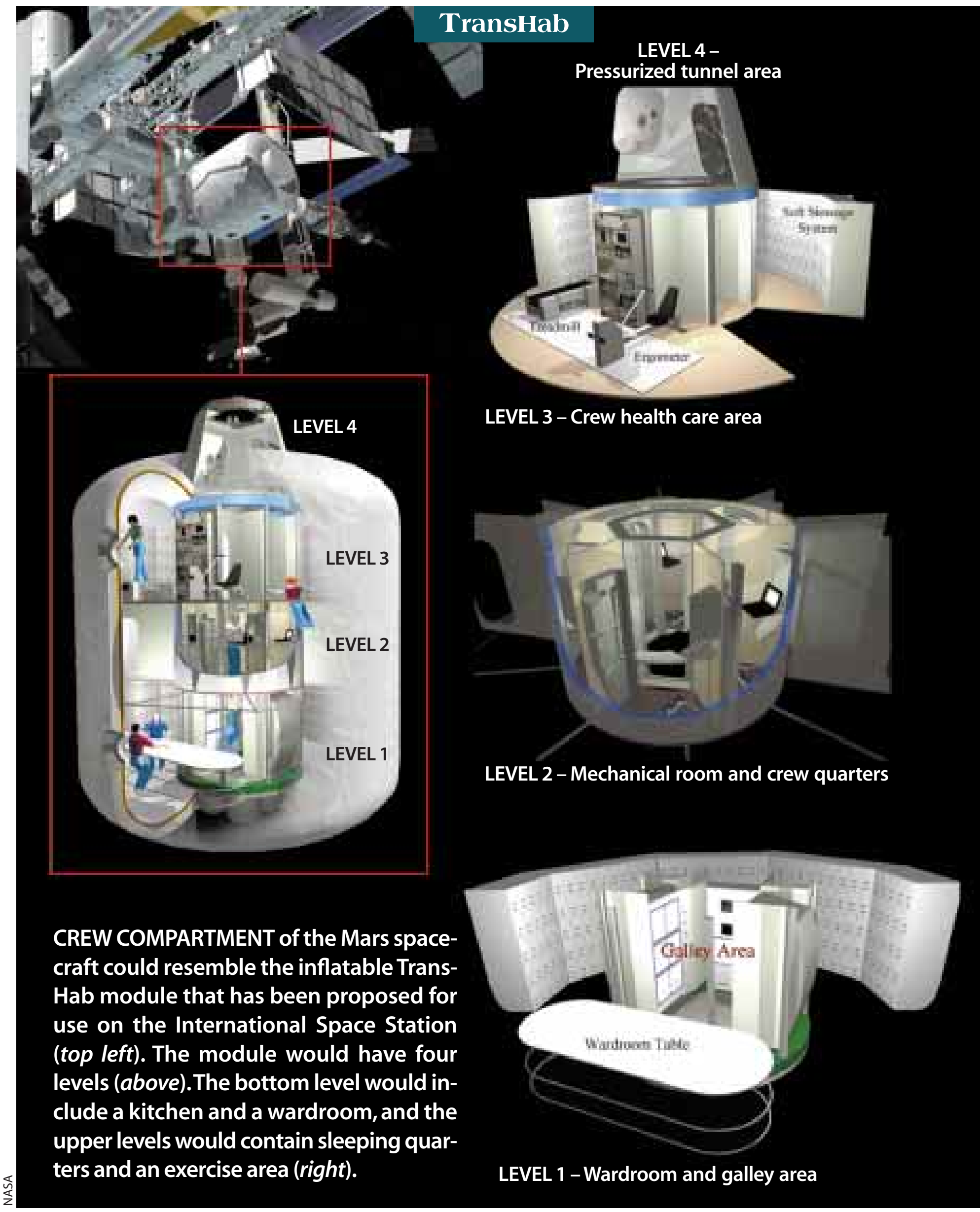
ILLUSTRATIONS BY EDWARD BELL

During the journey to Mars, nothing will be more essential to the crew's safety than the spacecraft's life-support systems. Researchers at the NASA Johnson Space Center in Houston have already begun an effort to improve the efficiency and reliability of current systems. Volunteer crews have spent up to three months in a closed chamber designed to test new technologies for recycling air and water. In addition to physical and chemical methods, the experiments included demonstrations of biological regeneration—for example, processing the crew's solid wastes into fertilizer for growing wheat, which provided the volunteers with oxygen and fresh bread.

Scientists are also studying how to minimize the health effects from prolonged exposure to zero gravity. Astronauts who have spent several months in Earth orbit have lost significant amounts of bone mass, among other health problems [see "Weightlessness and the Human Body," by Ronald J. White; SCIENTIFIC AMERICAN, September 1998]. One way to stave off atrophy would be to slowly rotate the Mars spacecraft during its interplanetary cruise. In several plans, a tether or truss connects the crew capsule to a counterweight, such as a used rocket stage. One rotation per minute around a 340-meter-long spin arm would simulate the 0.38-*g* force on the Red Planet's surface. Doubling the rate shortens the required spin arm by a factor of four but worsens the Coriolis force, which would sway the astronauts as they moved inside the spacecraft. Mission planners, however, are not enthusiastic about spinning the spacecraft during its flight, because it would complicate maneuvering and communications procedures. Medical researchers are also considering alternatives such as exercise regimens, dietary supplements and centrifuge chairs.

Another concern is radiation. The crew would be exposed to two types: cosmic rays, the high-energy ions that stream constantly through our galaxy, and solar flares, the intense streams of protons that are periodically ejected from the sun. Cosmic rays are more energetic than solar flare protons and thus more difficult to block. An astronaut in space would absorb a dose of 75 rems per year; on board a spacecraft, behind an aluminum wall six centimeters thick, the dose would be 20 percent lower. (Extra shielding does little good. Even astronauts on the Martian surface will receive this dose.) Radiation experts believe, however, that this annual dose would increase the probability of an astronaut dying from cancer within 30 years by only a few percentage points. Antioxidant pills might counteract some of this risk.

Solar flare radiation is more dangerous because it comes in unpredictable bursts, which could deliver 4,000 rems to the skin and 200 rems to internal organs in a single deadly dose. At least one such storm occurs near the peak of the 11-year-long solar cycle, and smaller yet potent storms erupt every couple of years. Astronauts in low Earth orbit are protected by the planet's magnetic field, which traps and deflects the incoming protons, but travelers en route to the moon and Mars forgo this safety. Fortunately, the particles can be easily blocked. The best shields are made of hydrogen-rich materials such as polyethylene or water; heavier atoms are not as effective, because the proton collisions can dislodge the atoms' neutrons, triggering a dangerous cascade of radiation. A 10-centimeter layer of water reduces the dose to 20 rems. Mission planners have proposed creating a solar-flare storm shelter on the Mars craft simply by storing the crew's water in bladders surrounding their sleeping area. Satellites observing the sun could warn the astronauts of an impending flare.



CREW COMPARTMENT of the Mars spacecraft could resemble the inflatable TransHab module that has been proposed for use on the International Space Station (*top left*). The module would have four levels (*above*). The bottom level would include a kitchen and a wardroom, and the upper levels would contain sleeping quarters and an exercise area (*right*).

DESCENT AND ASCENT

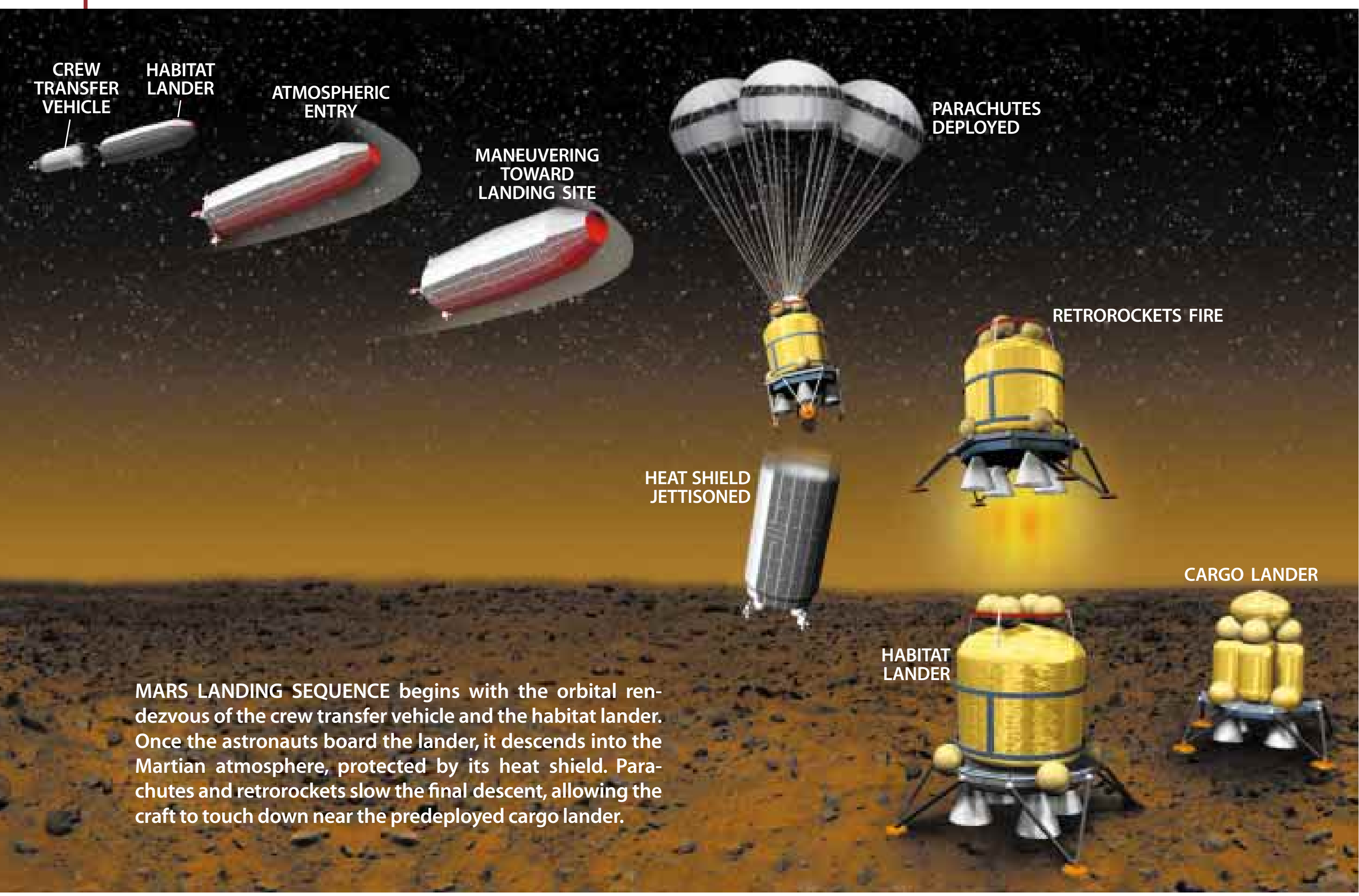
Landing a manned spacecraft on Mars will be significantly more difficult than landing the Apollo lunar modules on the moon. Mars, unlike the moon, has an atmosphere, and its gravity is twice as strong as the moon's. Furthermore, the Mars lander would be much more massive than the lunar modules because it would carry the habitat in which the astronauts would live during their 500 days on the surface.

Only three robotic vehicles have successfully landed on the Red Planet: Vikings 1 and 2 in 1976 and Mars Pathfinder in 1997. All three employed heat shields, parachutes and retrorockets to slow their descent. (Pathfinder also used air bags to cushion its landing.) A manned lander would follow the same basic sequence, but its geometry would be different [*see illustration below*]. The robotic craft sat on saucer-shaped heat shields and plunged uncontrolled through the Martian atmosphere, like a child skidding down a ski slope on a garbage-can lid. A manned craft, though, would need precise guidance during the descent, because it would have to land very close to the unmanned cargo vehicle that would have been sent to Mars earlier.

NASA's current plans call for a bullet-shaped lander wrapped in an outer shell that serves as the heat shield. According to the plan, the lander is sent to Mars unmanned, in advance of the crew. It goes into orbit by aerobraking against the Red Planet's atmosphere. The lander remains in orbit until the astronauts arrive in the crew transfer vehicle. After the astronauts board the lander, it descends much like the space shuttle, with its nose tilted upward. By rolling the spacecraft to the left or right, the pilot can steer it toward the landing site. Parachutes slow its descent, and then the retrorockets fire, enabling the pilot to set the craft down at exactly the right spot.

At the end of 500 days the astronauts board an ascent vehicle that blasts off the surface to an orbital rendezvous with the crew transfer vehicle, which then brings the astronauts back to Earth. On the first human mission to Mars, a fully fueled ascent vehicle would be connected to the habitat lander; on subsequent missions, however, the ascent vehicles would be predeployed and would use rocket fuel manufactured on the Red Planet. A propellant production unit about the size of a large automobile could combine liquid hydrogen brought from Earth with carbon dioxide from the Martian atmosphere. A series of chemical reactions would yield liquid-methane and liquid-oxygen propellant, as well as extra water and breathable air for the crew. The production techniques will be tested on the Mars Surveyor robotic landers currently scheduled to be launched in 2001 and 2003. The plans for Surveyor 2003 include the test-firing of a small rocket engine using methane and oxygen made on Mars.

DON FOLEY



MARS LANDING SEQUENCE begins with the orbital rendezvous of the crew transfer vehicle and the habitat lander. Once the astronauts board the lander, it descends into the Martian atmosphere, protected by its heat shield. Parachutes and retrorockets slow the final descent, allowing the craft to touch down near the predeployed cargo lander.

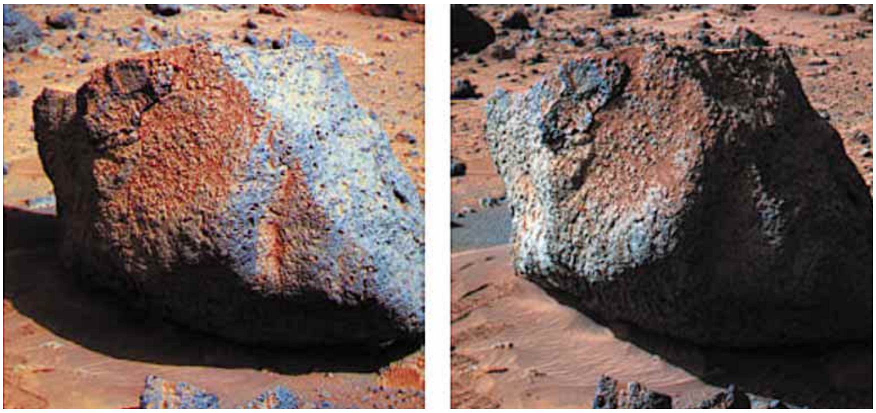
WHAT WILL IT BE LIKE?

As soon as astronauts disembark, they will know they are in an alien world; the weaker gravity will be obvious in the very act of walking. Taking a step is like swinging a pendulum, which occurs at a tempo related to the strength of gravity. Consequently, people will tend to walk about 60 percent as fast as on Earth and burn half as many calories doing so. A speed that would be a casual stroll here is best handled as a run on Mars.

In the thin atmosphere—the equivalent of Earth's at an altitude of about 35 kilometers—temperature and pressure fluctuate widely and quickly, but weather patterns are generally uniform from place to place. Although the wind can gust to 100 kilometers per hour, the force it exerts is low. Astronauts may see fog, frost and wispy blue clouds in the early morning. The sky changes in color depending on when and where one looks. At noon and toward the horizon, dust scattering makes it red. The rising and setting sun is blue; elsewhere the sky is butterscotch. The lighting plays tricks on the eye. Because of the varying proportion of direct sunlight and indirect sky glow, the coloring of rocks looks different depending on the time of day [*see illustration above*].

Mars is boringly flat. The famous Twin Peaks at the Mars Pathfinder site are just 50 meters high yet clearly visible a kilometer away. Even Olympus Mons, the largest mountain in the solar system, generally has a grade of only a few percent. The topography gets more interesting on the rim of Valles Marineris, which is thought to resemble the Canyonlands in Utah.

Because of the flatness, astronauts will be able to see that Mars is smaller than Earth: the distance to the horizon is proportional to the square root of a planet's radius. Two people 170 centimeters tall (about 5 feet 8 inches) could see each other up to seven kilometers away. On Earth you seldom notice the theoretical horizon (in this case, 2.5 kilometers farther) because topography intrudes. The horizon is also the limit of direct radio communications on Mars, which lacks an ionosphere. Astronauts will need relay satellites.



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YOGI, a rock much photographed by the Mars Pathfinder lander in 1997, looks different in the morning (*left*) than in the afternoon (*right*) because of the vagaries of Martian light.

DUST

Tiny particles may be the biggest problem for humans on Mars. Because the Red Planet utterly lacks liquid water, which mops up fine particulates on Earth, it is covered in dust with an average grain size of about two microns—comparable to cigarette smoke. The dust will gum up space suits, scratch helmet visors, cause electrical shorts, sandblast instruments and clog motors. On the moon, which is similarly dusty, suits lasted only two days before they began to leak. In addition, Viking lander analyses suggest that particles are coated with corrosive chemicals such as hydrogen peroxide. Although their concentrations are low, these toxins could slowly wear away rubber seals. NASA plans more detailed studies on upcoming landers.

If even a small fraction of the dust particles are quartz, as Mars Pathfinder results hint, they could pose a major health threat if inhaled: silicosis, an incurable lung condition that kills several hundred miners and construction workers in the U.S. every year. To keep their habitat dust-free, astronauts will need to clean off thoroughly before entering. That will not be easy. Being magnetized and electrically charged, the dust sticks to everything, and water will be in short supply. Astronauts might scrub with dry-ice snow condensed out of the atmosphere. They could also wear two-layer space suits, the outer layer of which would be left in a special airlock outside the main habitat.

Another issue is electric power. On Mars Pathfinder, the output of the solar panels fell 1 percent every three days as powder accumulated on them. A dust storm would darken the skies and halve power generation. For these reasons, a mission might need a 100-kilowatt nuclear reactor.

PLANETARY PROTECTION

Microbes will inevitably accompany astronauts to Mars, complicating the search for native life. Conversely, any Martian bugs will be able to hitch a ride back to Earth. The organisms probably would not cause disease in humans or other species—most scientists think they would simply be too different from terrestrial life-forms—but the risk of a global disaster is not zero. Although NASA is developing a bioisolation system for robotic sample-return missions, there is no equivalent way to decontaminate an astronaut. The quarantine procedures during the Apollo program were cumbersome, controversial—and leaky. And quarantines lead to horrible dilemmas. If the astronauts get sick, are they to be prevented from returning to Earth on the off-chance they have picked up an alien plague? It would be better not to have to make that decision. A 1992 National Research Council report concluded that the existence of extant or dormant life on Mars should be resolved before astronauts are sent. At the very least, astronauts will need to know in advance which parts of the planet are safe to explore and what precautions they should take elsewhere to avoid direct contact with any possible forms of Martian life. SA