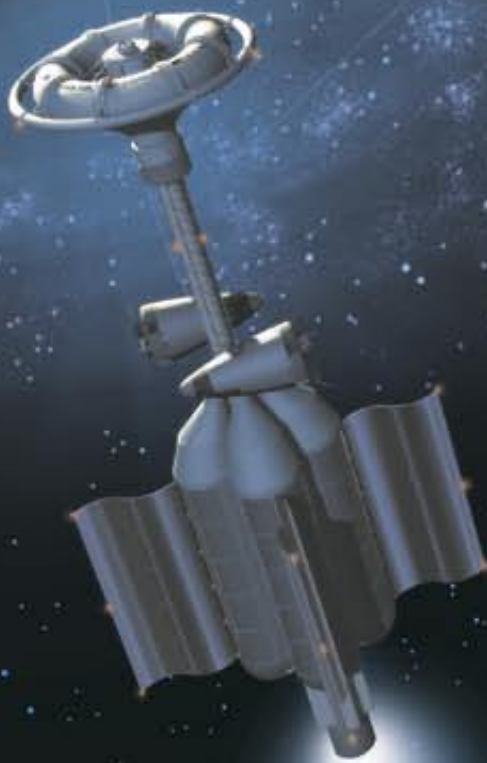


Shielding Space

In science fiction, the worst threats to space travelers are large ones: careening asteroids, ravenous creatures, imperial battle cruisers. In reality, though, the scariest menaces for humans in space are the tiniest: fast-moving elementary particles known as cosmic rays. On a long journey, they would give astronauts a dose of radiation serious enough to cause cancer. Unlike most of the other challenges of venturing into deep space, which engineers should be able to solve given enough time and money, cosmic rays pose irreducible risks, and dealing with them involves fundamental trade-offs. They could be the show-stopper for visiting Mars.



The perils of cosmic rays pose severe, perhaps insurmountable, hurdles to human spaceflight to Mars and beyond

Travelers

By Eugene N. Parker

ONE THIRD OF THE DNA in your body would be sliced by cosmic rays every year you spent in interplanetary space. Protecting astronauts against the onslaught will entail unavoidable trade-offs.

In the laboratory, cosmic rays first presented themselves as a minor annoyance. They were discovered when physicists noticed that electrically charged bodies do not stay that way; their charge slowly leaks away through the air. Something had to be ionizing the air, allowing it to conduct electricity. Many researchers blamed the ambient radioactivity of the soil and rocks underfoot. Austrian physicist Victor Hess settled the issue in 1912, when he went aloft in a balloon and showed that the higher he rose, the faster the charge leaked off his electroscope. So the cause of the ionized air was something mysterious coming in from space—thus the name “cosmic rays.”

By 1950 physicists had determined that the term is actually a misnomer. Cosmic rays are not rays but ions—mostly protons, with a few heavier nuclei mixed in—striking the top of the atmosphere at nearly the speed of light. Most come from beyond the solar system, but what catapults them to such a speed remains a question to this day. Experimenters, having once regarded cosmic rays as irksome, embraced them as an observational tool. Variations in cosmic-ray intensity were one of the ways my colleagues and I deduced the existence of the solar wind in the late 1950s.

Contrary to popular belief, it is not Earth’s magnetic field that shields people on the ground from the full brunt of these rays but rather the bulk of our atmosphere. Above every square centimeter of surface is a kilogram of air. It takes a vertical column of about 70 grams—about $\frac{1}{4}$ the distance through the atmosphere, achieved at an altitude of 20 to 25 kilometers (60,000 to 80,000 feet)—before the average incoming proton hits the nucleus of an atom in the air. The rest of the atmosphere serves to absorb the shrapnel of this initial collision. The impact

knocks a proton or neutron or two out of the nucleus and unleashes a shower of high-energy gamma rays and pi meson, or pion, particles. Each gamma ray propagates deeper into the atmosphere and ends up producing an electron and its antimatter counterpart, a positron. These two particles annihilate each other, yielding less energetic gamma rays, and so the cycle continues until the gammas become too weak to create particles.

Meanwhile the pions quickly decay into mu mesons, or muons, which penetrate to the ground. As they pass through our bodies, they produce ions and break chemical bonds but not enough to do us significant harm. The annual cosmic radiation dose of about 0.03 rem (depending on altitude) is equivalent to a couple of chest x-rays.

Outside the atmosphere, the cosmic-ray bombardment is intense. Approximately one proton or heavier nucleus would

pass through your fingernail every second, for a total of perhaps 5,000 ions zipping through the body every second, each one leaving a trail of broken

chemical bonds and triggering the same cascade that occurs in the atmosphere. The relatively few heavier nuclei among the cosmic rays do as much or more damage than the protons because their ability to break bonds is proportional to the square of their electric charge. An iron nucleus, for example, does 676 times more damage than a proton does. A week or a month of this radiation should not have serious consequences, but a couple of years on a jaunt to Mars is a different story. One estimate from NASA is that about one third of the DNA in an astronaut’s body would be cut by cosmic rays every year.

In addition to causing cancer, cosmic rays could lead to cataracts and brain damage.

Shields Up

THE ONLY QUANTITATIVE information available on the biological consequences of energetic radiation comes from the unfortunate individuals who have been exposed to short but intense bursts of gamma rays and fast particles during nuclear explosions and laboratory accidents. They have suffered cell damage and enhanced cancer rates. A Mars traveler would get similar doses, albeit spread out over time. No one knows whether the two situations are really equivalent, but the comparison is worrisome. Natural biological repair mechanisms may or may not be able to keep up with the damage.

The implications were recently studied by Wallace Friedberg of the Federal Aviation Administration’s Civil Aerospace Medical Institute in Oklahoma City and his colleagues. In a report published last August, they estimated that Mars astronauts would receive a dose of more than 80 rems a year. By comparison, the legal dose limit for nuclear power plant workers in the U.S. is five rems a year. One in 10 male astronauts would eventually die from cancer, and one in six women (because of their greater vulnerability to breast cancer). What is more, the heavy nuclei could cause cataracts and brain damage. (To be sure, these numbers are highly uncertain.)

The constant hailstorm of cosmic rays is not the only ra-

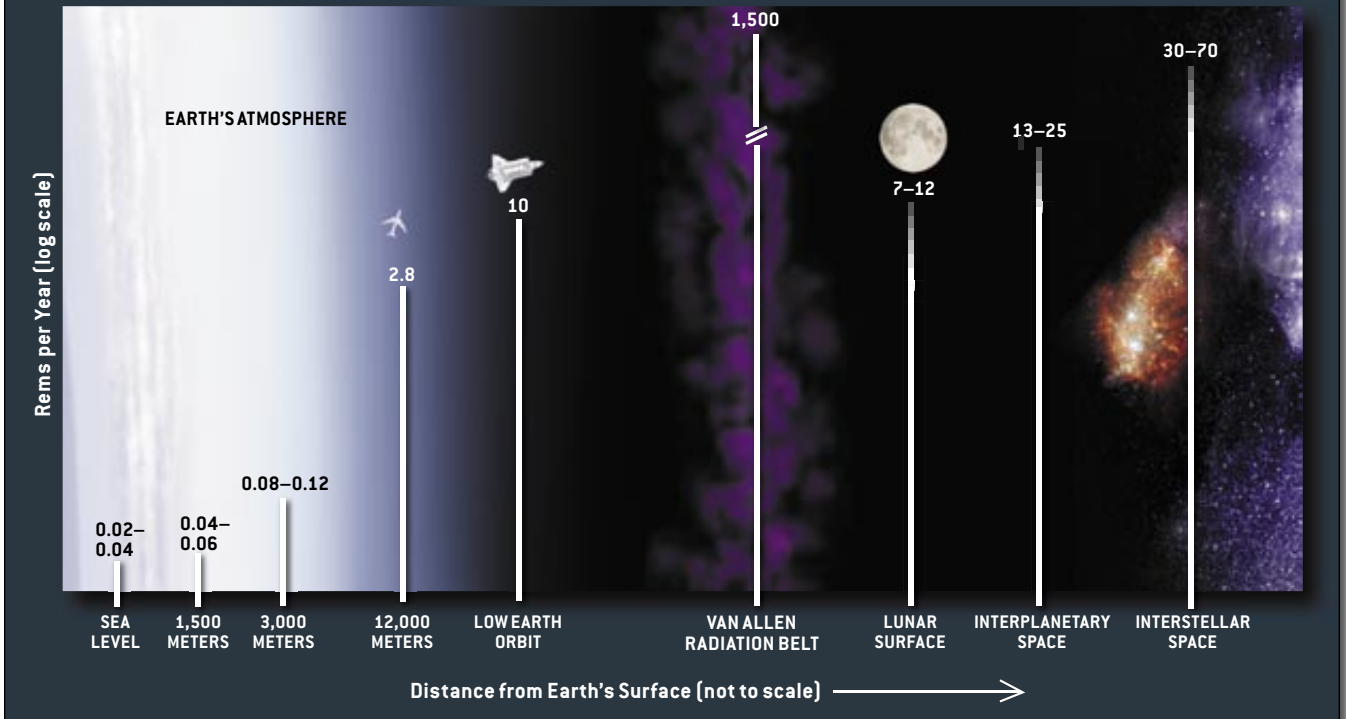
Overview/*Cosmic-Ray Hazard*

- The galaxy is pervaded with fast-moving particles that can rip apart DNA and other molecules. Here at the surface of Earth, we are well protected from this cosmic radiation by the air mass overhead. Astronauts in near-equatorial orbits are shielded by the planet’s magnetic field. But those who make long voyages away from Earth will suffer serious health consequences.
- A spherical shell of water or plastic could protect space travelers, but it would take a total mass of at least 400 tons—beyond the capacity of heavy-lift rockets. A superconducting magnet would repel cosmic particles and weigh an estimated nine tons, but that is still too much, and the magnetic field itself would pose health risks. No other proposed scheme is even vaguely realistic.
- Biomedical researchers need to determine more precisely how much long-term exposure to cosmic rays a person can tolerate and whether medicines could stimulate the body’s natural repair mechanisms.

WHAT ARE ASTRONAUTS GETTING THEMSELVES INTO?

It is not quite as bad as venturing inside a nuclear reactor, but traveling through space can still be hazardous to your health. This graph shows one estimate of the yearly radiation dose astronauts would receive from cosmic rays. A rem is a common unit of radiation exposure. Interplanetary

astronauts would absorb more radiation in a single year than radiation workers are supposed to receive in a lifetime, and a large number would develop cancer and other illnesses. Solar flares and Earth's Van Allen radiation belts can kill outright but are easier to avoid.



radiation threat, of course. The sun, too, can unleash tremendous bursts of protons and heavier nuclei traveling at nearly the speed of light. Such bursts occasionally deliver in excess of a couple of hundred rem over an hour or so—a lethal dose to an unshielded astronaut. The great flare of February 23, 1956, is a notorious example. Whatever measures are taken to ward off cosmic rays should also protect against these solar tempests. Even so, it might be wise to schedule a trip to Mars during the years of minimum solar magnetic activity.

In recognition of the radiation threats, NASA set up the Space Radiation Shielding Program at the Marshall Space Flight Center in Huntsville, Ala., in 2003. The first thought was to protect astronauts by surrounding them with matter, by analogy to Earth's atmosphere. A second proposal was to deflect the cosmic rays magnetically, much as Earth's magnetic field offers some protection for equatorial regions and for the International Space Station. A more recent idea has been to give the spacecraft a positive charge, which would repel the positively charged nuclei.

NASA set up a two-day meeting in August 2004 at the University of Michigan at Ann Arbor to assess where things stood. The conclusion was not hopeful. It was not obvious what the solution to the cosmic-ray problem might be. Nor was it obvious that there is a solution at all.

Force Field

TO MATCH THE PROTECTION offered by Earth's atmosphere takes the same one kilogram of shielding material per square centimeter, although astronauts could comfortably make do with 500 grams, which is equivalent to the air mass above an altitude of 5,500 meters. Any less would begin to be counterproductive, because the shielding material would fail to absorb the shrapnel.

If the material is water, it has to be five meters deep. So a spherical water tank encasing a small capsule would have a mass of about 500 tons. Larger, more comfortable living quar-

THE AUTHOR

EUGENE N. PARKER is the world's leading expert on interplanetary gas and magnetic fields. He is best known for hypothesizing and explaining the solar wind in 1958. Now the stuff of textbooks, the idea of a vigorous outflow of particles from the sun was initially so controversial that the *Astrophysical Journal* nearly rejected his paper. Parker also developed the modern theory of the solar magnetic field, including magnetic reconnection. An emeritus physics professor at the University of Chicago and a member of the National Academy of Sciences, Parker has received numerous prizes, including the U.S. National Medal of Science, the Henry Norris Russell Lectureship of the American Astronomical Society and the Kyoto Prize in Basic Sciences.

PLAN 1: MATERIAL SHIELD

A large mass around the astronauts absorbs incoming radiation and the secondary particles it produces. A spherical shell of water five meters thick provides the same protection that Earth's atmosphere offers at an altitude of 5,500 meters (18,000 feet).

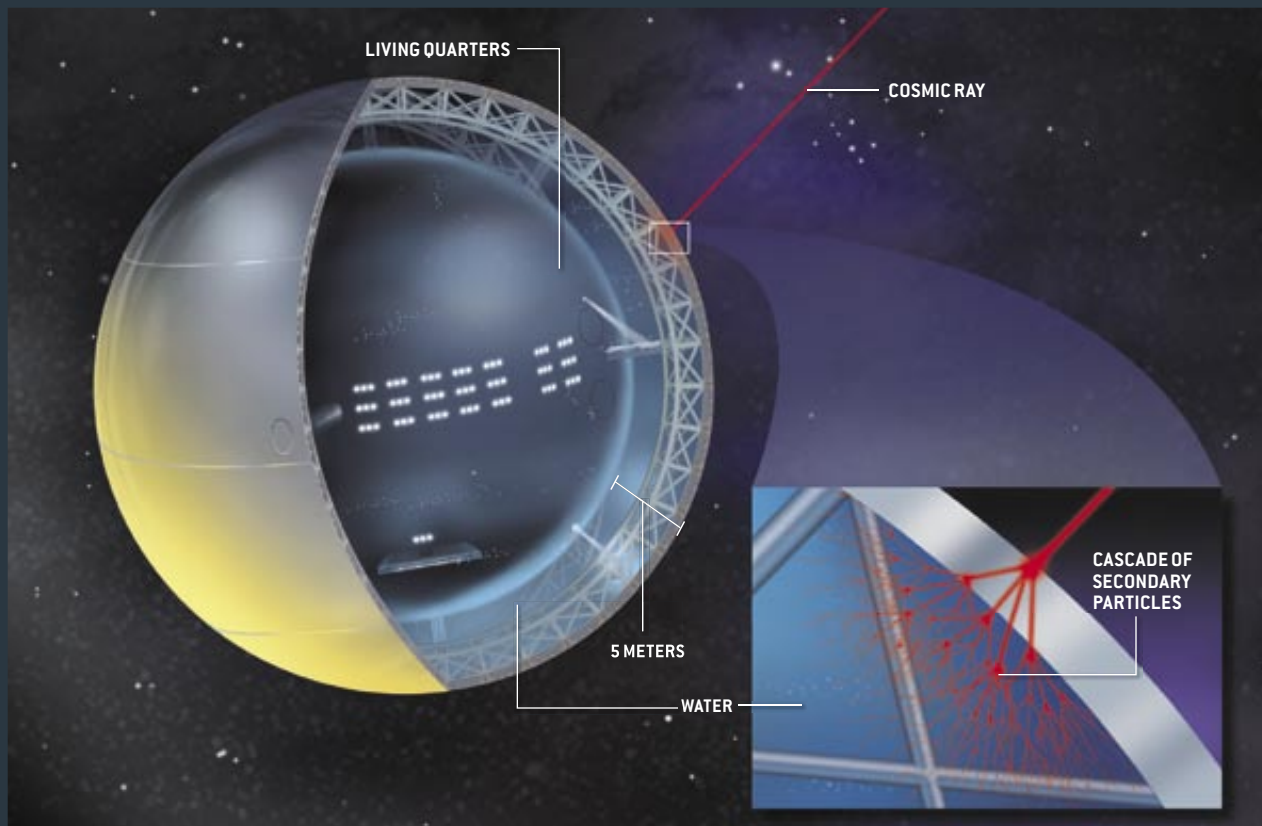
PROS:

Simple

Guaranteed to work

CONS:

Way too heavy



ters would require even more. By comparison, the space shuttle can carry a maximum payload of about 30 tons. Water is commonly proposed because astronauts would need it anyway and because it is rich in hydrogen. Heavier elements make less effective shields because the extra protons and neutrons in their nuclei fall in one another's shadows, limiting their ability to interact with an incoming cosmic ray. To increase the hydrogen content, engineers could use ethylene (C_2H_4), which has the further advantage that it can be polymerized to polyethylene, a solid, thereby avoiding the necessity for a tank to contain it. Even so, the required mass would be at least 400 tons—still not feasible. Pure hydrogen would be lighter but would require a heavy pressurized vessel.

Consider, then, the prospects for magnetic shielding. A charged particle moving across a magnetic field is deflected at right angles to its direction of motion. Depending on the arrangement of field lines, the particle can be sent in almost any direction or even forced to circle endlessly. On approaching the magnetic field of Earth at low latitudes, a charged particle is sent back out into space [see box on opposite page] if it is not too

energetic. A spacecraft could carry a magnet to do the same.

One big problem, though, is the immense kinetic energy of an individual cosmic-ray proton. Adequate protection for the astronauts means repulsing the very numerous cosmic-ray protons with two billion electron volts (the standard unit of energy used in particle physics). To stop them within the space of a few meters, a shield would have to have a magnetic field of 20 teslas, or about 600,000 times the strength of Earth's field at the equator. So strong a field requires an electromagnet constructed with superconducting wires, akin to those used in particle accelerators. Samuel C. C. Ting of the Massachusetts Institute of Technology headed up a design group that devised such a system with a mass of only nine tons—a big advance over material shielding but still discouragingly heavy to think of carrying all the way to the Martian surface and back.

The magnetic scheme has a number of fine points that should be appreciated. Magnetic fields provide no significant shielding near the magnetic poles, where incoming particles come in parallel to, rather than across, the field. That is why Earth's field provides little protection except for people living

PLAN 2: MAGNETIC SHIELD

An electromagnet pushes incoming particles back into space. To deflect the bulk of cosmic rays, which have energies of up to two gigaelectron-volts, requires a magnetic field 600,000 times as strong as Earth's equatorial field.

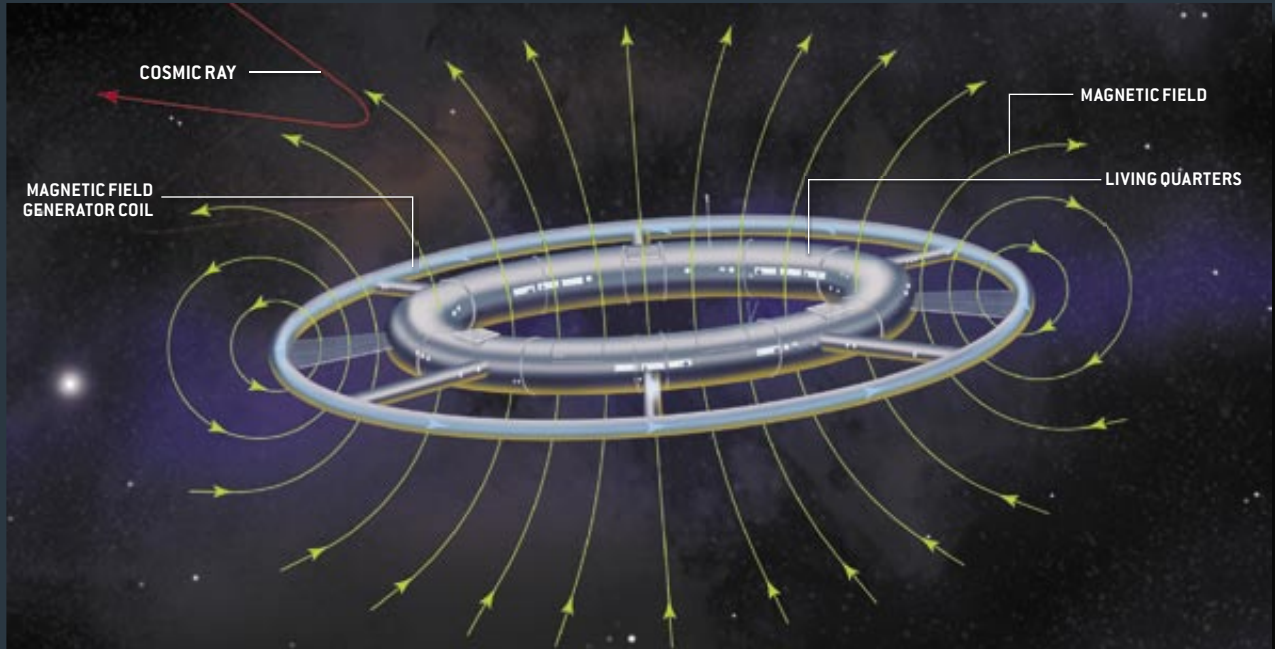
PROS:

Much lighter than material shield

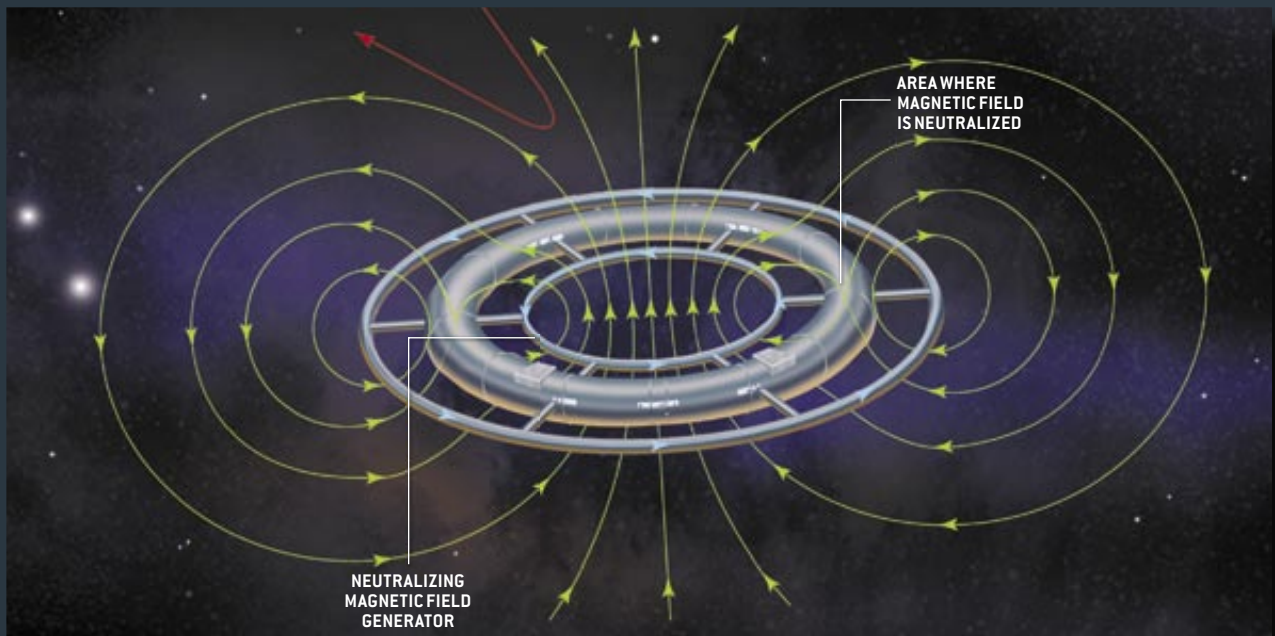
CONS:

Offers no protection along axis

Strong magnetic field may itself be dangerous



To suppress the field inside the living quarters, the spacecraft designers could add a second, inner electromagnet ring. But the cancellation is only partial and greatly increases the complexity of the system.



in equatorial regions. To keep astronauts in the equivalent of an equatorial region, the living quarters of the spacecraft would have to be doughnut-shaped. The astronauts would have to endure a magnetic field of 20 teslas, and no one knows what the biological effects would be. The late John Marshall, a University of Chicago experimental physicist, remarked to me many years ago that when he stuck his head in a 0.5-tesla field in the gap of an old particle-accelerator magnet, any motion of his head produced tiny flashes of light in his eyes and an acid taste in his mouth, presumably caused by electrolysis in his saliva.

Given that a strong field can affect body chemistry in this way, researchers need to conduct some laboratory experiments to verify the safety of a 20-tesla shield. If it proves haz-

ardous, engineers may have to cancel out the field within the living quarters using an opposing electromagnet. A secondary magnet clearly makes the system more complicated and more massive.

Some researchers have proposed using a field that extends over a distance much larger than a few meters. The field could be pushed out using a plasma, much as the ionized gas of the solar wind carries the solar magnetic field out to great distances from the sun. Advocates claim that such an “inflated” field would not need to be as intense; 1 tesla, or even less, might suffice. Unfortunately, this scheme disregards the fact that plasmas are notoriously unstable. The laboratory effort over the past 50 years to trap plasma in a magnetic field, for the purpose of producing energy from nu-

My colleague stuck his head into a 0.5-tesla magnetic field. Any motion of his head produced tiny flashes of light in his eyes and an acid taste in his mouth.

PLAN 3: ELECTROSTATIC SHIELD

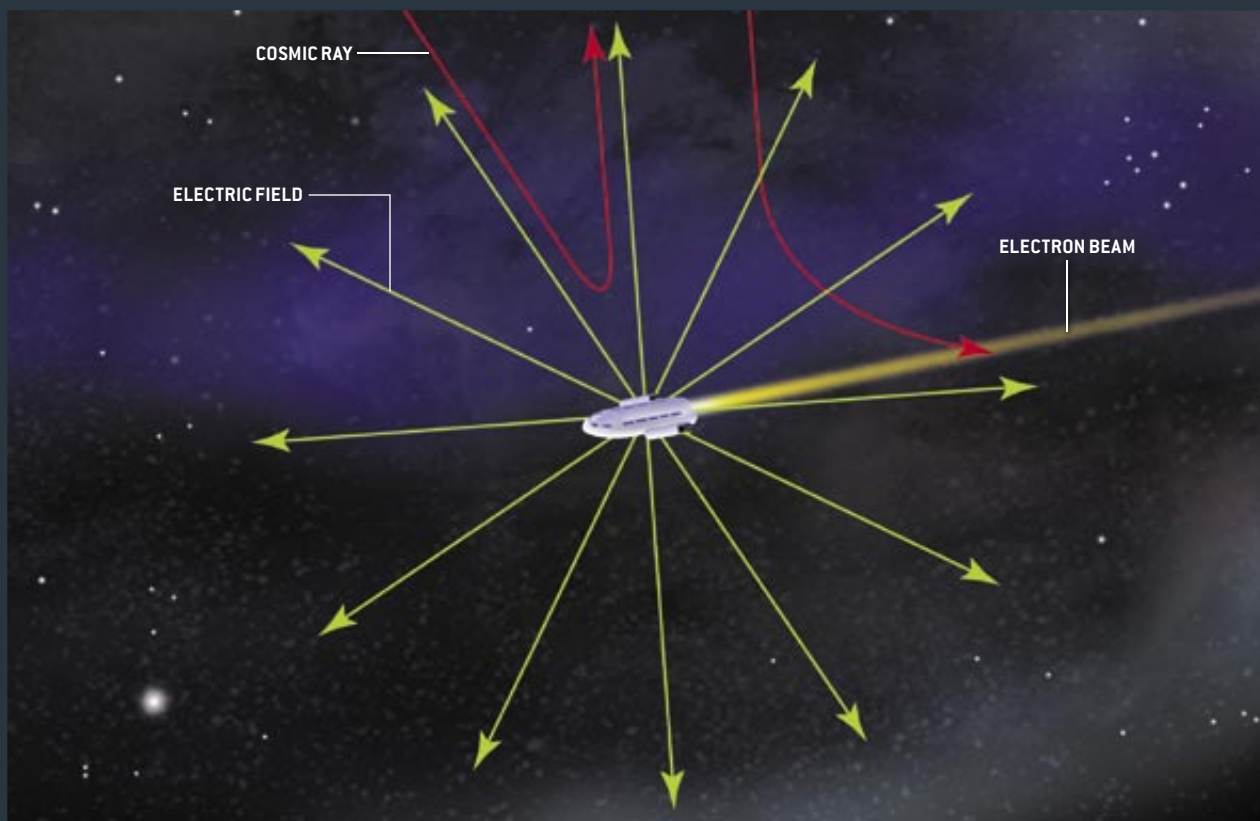
Firing a beam of electrons into space causes a positive charge to build up on the spacecraft. This charge repels cosmic rays. To deflect particles with energies of up to two giga-electron-volts, the ship would have to be charged to two billion volts.

PROS:

- No gaps in coverage
- No hazardous magnetic field

CONS:

- Creates nasty influx of negatively charged particles
- Requires gargantuan electric current



KENT SNODGRASS

clear fusion, has shown the remarkable ability of a plasma to wiggle free of any attempt to control it. Even if the plasma could be harnessed to inflate a magnetic field, it would serve only to weaken, rather than enhance, the shield. The field lines would be pushed out radially and spread around a larger circumference, so that an incoming proton would have to cross fewer field lines. The shield strength would fall, just as it does in the midlatitudes and polar regions of Earth.

No Charge

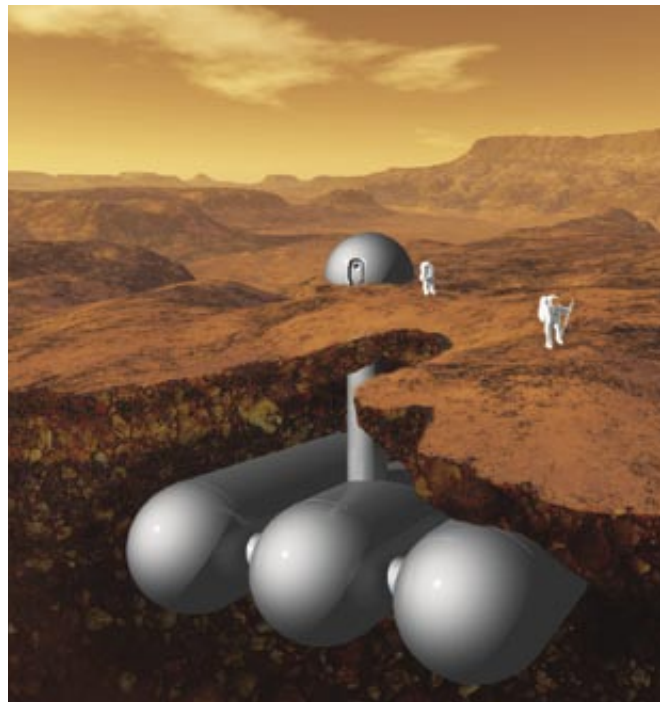
STRIKING OUT in another direction, other researchers have proposed to charge the spacecraft electrically. If the outer walls had a voltage of two billion volts relative to the surrounding space, they would repel all the cosmic-ray protons with energies up to two billion electron volts. A similar scheme has been proposed for a moon base.

The proposers seemed to be unaware that space is not empty. In the vicinity of Earth, the solar wind fills space with about five ions and five electrons per cubic centimeter. These electrons, being negatively charged, would be powerfully attracted by a positively charged spacecraft. Because the electric field would extend out to where its potential energy fell below the thermal energy of the electrons—a distance of tens of thousands of kilometers outward from the spacecraft—it would pull in electrons from an immense volume. They would hit the walls with an energy of two billion electron volts and behave just like cosmic rays, each having as much energy as the protons the system repels. Therefore, the natural cosmic-ray flux would be replaced with a vastly more intense artificial one. The electrons would produce gamma rays on impact with the spacecraft, and the intensity of that bombardment would be staggering, dwarfing the original problem.

That is not all. Simple estimates of the power requirements to maintain the charge of the spacecraft are mind-boggling. One ampere of current at two billion volts amounts to 2,000 megawatts—the output of a good-size electric power plant. Rough estimates suggest the current would exceed 10 million amperes. The proposers have not spelled out how they hope to charge the spacecraft to two billion volts in the first place. Curiously, like the idea of inflating magnetic fields, the notion of charging the spacecraft to shield the astronauts has received substantial attention and funding without a clear explanation of how it might work.

Others have proposed more prosaic options. Larger rockets or advanced propulsion technologies could speed the journey and lessen astronauts' exposure time. But the optimum travel time to Mars is more or less a fixed fraction of the orbital period of the planets, and to trim it by much would take a good deal more fuel (and hence money). On Mars itself, the problem does not go away. The atmosphere is scrawny, a mere 10 grams per square centimeter. Burying the base under hundreds of tons of soil would provide protection but require heavy machinery.

At the present time, then, the proposals for protecting astronauts from cosmic rays give little encouragement. But on



MARS'S PITIFUL ATMOSPHERE is scant protection against cosmic rays. Astronauts will have to bury their base under tons of dirt and limit their exposure outside. The prospect for permanent settlement hinges on whether biomedical researchers can develop antiradiation medicine.

the bright side, researchers are only beginning to explore the biomedical side of the problem. Natural healing processes in the cell may be able to handle radiation doses that accumulate over an extended period, and some people's bodies may be better at it than others'. If so, the present estimates of the cancer incidence, all based on short, intense bursts of radiation, may overestimate the danger.

In 2003 NASA set up the National Space Radiation Laboratory at Brookhaven National Laboratory to determine the molecular pathways of cell damage, with the hope of finding drugs to reduce or repair it. The lab is investigating precisely how radiation batters DNA and what types of injury do not readily heal. So far the only known chemicals that improve the resistance of laboratory rats to radiation damage are themselves toxic.

It would be too bad if the romance of human space travel ended ignominiously with cosmic rays making it infeasible. Capable people might be willing to go to the moon or Mars just for the adventure, come what may. Even so, the radiation hazard would take the luster off the idea of human space travel, let alone full-scale colonization. SA

MORE TO EXPLORE

Shielding Space Explorers from Cosmic Rays. Eugene Parker in *Space Weather*, Vol. 3, No. 8, Article no. S08004; August 18, 2005. Presentations from the 2004 NASA workshop on radiation shields are available at aoss.engin.umich.edu/Radiation
NASA's own Web site on space radiation is at www.radiationshielding.nasa.gov