SPACE WEATHER The International Journal of Research and Applications AGU

Shielding Space Explorers From Cosmic Rays

Expert opinions are split on the most promising strategies for protecting astronauts from the dangers of cancer-inducing radiation in space.

Eugene N. Parker

18 August 2005

Any space traveler far removed from the protective magnetic field that enshrouds Earth is subject to a continuing low dose of galactic cosmic radiation. The best available estimates predict that exposure to such radiation for as little as a year may be sufficient to increase the incidence of cancer a decade or two later. That is bad news for a potential Mars explorer, who would be vulnerable to the harsh realities of space for 2–4 years.

Most experts agree that a means of defending astronauts from cosmic radiation must be devised if interplanetary travel by humans is to become a reality. But how to accomplish this task is a matter of considerable difficulty—and controversy. Spacecraft walls have helped to protect astronauts orbiting Earth and making quick trips to the Moon, but for longer travel such conventional shielding cannot decrease the radiation below the desired level without making the spacecraft far too heavy.

As a consequence, NASA will be investing significant time and money in the coming years to develop new radiation shielding strategies. Scientists and engineers at NASA's Space Radiation Shielding Program at Marshall Space Flight Center in Huntsville, Ala., and at dozens of other institutions around the world have already made noteworthy progress. Particular attention has been paid to concepts that involve electrically charging the spacecraft or surrounding it with a strong magnetic field; both magnetic and electrostatic fields work to deflect or redirect the radiation.

Such efforts were the focus of a 2-day meeting NASA held at the University of Michigan in August 2004. The agency assembled 40-some top experts to ask their formal opinions on what technical approaches NASA should pursue. (Technical descriptions of the active radiation-shielding concepts presented at this workshop are available at http://aoss.engin.umich.edu/Radiation.)

The answers were not simple, however. Even the most promising radiation-shielding strategies engender an array of secondary problems. Magnetic fields cannot stop all radiation, for instance. Even more disconcerting is that the necessarily intense magnetic field itself might be harmful to the humans inside it. Generating an electrostatic field seems to require a potentially unrealistic power source, and the electrostatic field itself would create new problems by accelerating electrons toward the spacecraft. Some experts suggest these problems can be overcome with adequate investment, but others (including this author) are less optimistic. More practical and less costly solutions may emerge from the biomedical field. In any case, it is clear that critical discussions and investigations must continue.

The Danger

Devising effective strategies for shielding humans from the dangers of space travel requires first understanding the radiation danger itself. Galactic cosmic rays are actually particles—mostly protons, with a few heavier nuclei and some electrons—moving randomly through space at nearly the speed of light. As a consequence of their high speed and immense kinetic energy, cosmic ray particles can pass through the human body, leaving behind a wake of free electrons dislodged from the atoms and molecules, including DNA, encountered along the way.

The detailed, long-term consequences are still a subject of intense biomedical research, but it is generally known that cells with broken DNA may no longer be able to repair themselves or reproduce properly. Such malfunctions can cause the cellular mutations that lead not only to cancer but also to genetic defects in offspring and possibly even death.

On Earth's surface we are well protected by the massive atmosphere above us. This thick blanket of gas diminishes the cosmic rays so effectively that the radiation dose over a lifetime is of no consequence. The protective nature of the atmosphere suggests how one might shield astronauts far out in space: surround the astronauts with a great mass of material. But, alas, a careful design study conducted a couple of years ago at the

Marshall Space Flight Center came up with a necessary mass of about 400 t to shield a modest compartment to carry astronauts during interplanetary travel—quite impractical for flying into deep space. For comparison, the gross launch weight of a fully loaded space shuttle orbiter is well under 200 t.

Far out in space about one cosmic ray proton passes through each square centimeter every second. A week or a month of this bombardment would probably have no lasting biological consequences, but a voyage to Mars and back is a different story. One NASA estimate suggests that about one third of an astronaut’s DNA would be hit by ions for every year spent in deep space.

The question arises, then, of whether technology can reduce the incidence of cosmic rays to a tolerable level. After all, astronauts orbiting Earth near the equator rely on the sheltering effect of the main dipole (north-south component) of the planet’s magnetic field. The cosmic rays must cross that north-south field to reach the astronaut, and in doing so the numerous lower energy protons are turned harmlessly back into space.

Magnetic Shielding

Consider, then, the possibility of generating a magnetic field analogous to Earth’s to protect a spacecraft and its inhabitants. Because of the small dimensions of a spacecraft compared to a planet, a magnetic field around a spacecraft must be very intense, of the order of 20 T—400,000 times more intense than the static magnetic field of Earth.

Recent engineering studies indicate that adequately shielding a modest cabin for the astronauts can be achieved in this manner, but only if the system is constructed with superconducting wires to carry the electric current without loss. That scenario requires a system with a total weight of about 9 t—still too heavy to land on Mars and take off again—with most of that weight in the cryogenic system that maintains the cold, superconducting wires and in the rigid structure necessary to hold the current-carrying wires in place.

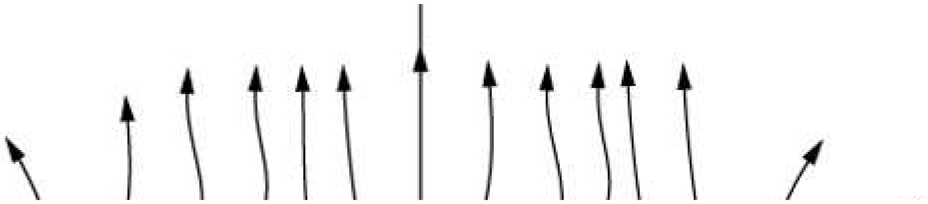
The nature of magnetic fields poses an additional complication. A certain number of particles will leak through even the most efficient magnetic shield. Once inside, the particles will be confined for a time for the same reason that they had difficulty getting in. Basic laws of physics tell us that without absorption, the magnetized space will eventually become filled with particles up to the same intensity as the cosmic rays in the surrounding space. That means a magnetically shielded spacecraft must also serve as a particle absorber to scavenge the accumulation of leakage. That is to say, even the best of ships must pump the bilges occasionally.

Some engineers think that advances in technology might eventually make it possible to generate a magnetic shield with a lighter system, and the spacecraft itself may well provide enough absorbing material to keep the leaking particles from accumulating in the shield field and exposing the astronauts. But even without these limiting factors, residing inside such a strong magnetic field may pose a serious health risk.

The biological consequences of long-term exposure to strong, static magnetic fields are inconclusive, but one reason for concern arises from a single data point that John Marshall mentioned to me many years ago. Marshall was referring to an informal experiment in which a magnetic field of 0.5 T—only about one fortieth of the required shielding field—caused electrolysis in the saliva (a lemony taste in the mouth) and scintillations in the retinas, indicating that any motion in such fields interferes with the normal chemistry of the human body.

Those findings alone suggest that any magnetic shielding system must cancel out most of the magnetic field over the living space of the astronauts. This field reversal could be accomplished by inducing two electrical currents around the living quarters to generate a magnetic field with the opposite polarity as the main shielding dipole (see Figure 1). The downside is that the spacecraft would be weighed down further by the additional steel it would take to hold those reverse currents in place.

To exactly what degree the shielding field must be weakened, however, is still unknown. Perhaps the human body can tolerate fields of 0.5 T or more. If so, the engineering challenges would be reduced□ in other words, the main shielding field would not have to be cancelled with great precision. More research is vital to determine what level of effort is truly necessary.



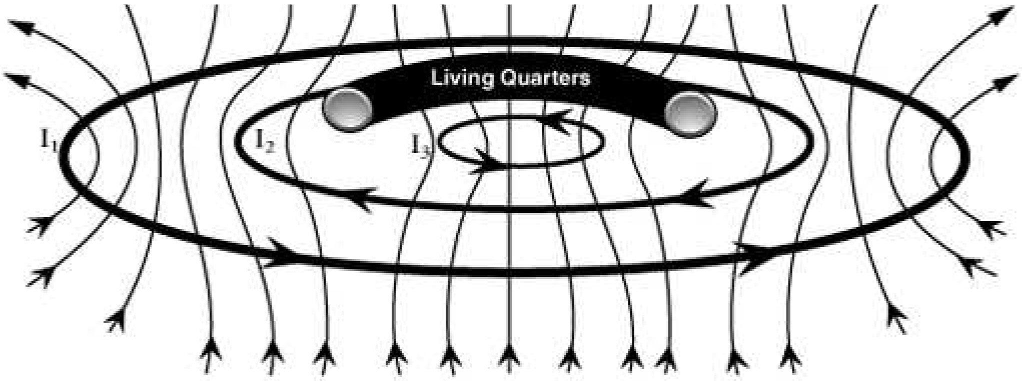


Figure 1. Living inside a magnetic field strong enough to stop cosmic radiation may pose a potential health risk to astronauts. First, living quarters would need to encircle the shielding magnet's main dipole axis like a donut, because cosmic particles would enter the spacecraft freely along this axis. Then, to cancel the strong field over the living quarters, circular electrical currents (I) could be introduced around the living space to produce a second, localized magnetic field with polarity opposite that of the shielding field, thereby bringing the total magnetic field close to zero.

Inflated Magnetic Fields

Some radiation-shielding investigators have proposed that a dipole magnetic field can be greatly puffed out to large distances by inflating it internally with plasma. They claim that stretching the field lines out through larger volumes of space enhances the magnetic shielding provided by a magnetic field of a given strength. But the power required to produce a strong inflation, perhaps doubling the scale of the magnetic field, appears quite high in contrast to the zero input required to maintain the superconducting magnet system with its field of 20 T. And, unfortunately, this proposal does not recognize that laboratory experiments over the last 50 years show that only a slight inflation of the field can be achieved before the plasma escapes.

Proponents of field inflation have run extensive computer simulations of successful inflations in space. Although interesting, these simulations are not conclusive in the face of the laboratory experience to the contrary. There is no reason to think that the absence of laboratory walls can make much difference, as some field inflation advocates have argued. In the laboratory, the plasma finds its way to the walls only after it has escaped the clutches of the inner magnetic field. The escape issue must be addressed experimentally, if at all, on the large scale appropriate for a spacecraft. A terrestrial laboratory experiment is neither large scale nor without walls. An experiment in space might mitigate these difficulties, but would be yet another expensive space mission that NASA would have to budget for.

The fatal point is that this inflation strategy fails to recognize that inflating the magnetic field, if it could be accomplished, would serve only to reduce the ability of the field to deflect incoming cosmic ray particles. As a shielding magnetic field is inflated outward from the spacecraft, the magnetic barrier intended to deflect incoming cosmic ray particles grows thinner—in essence, reducing the effectiveness of the shield (see Figure 2). At the same time, the outward inflation of the dipole field opens up the cone of free particle access over each of the spacecraft's magnetic poles.

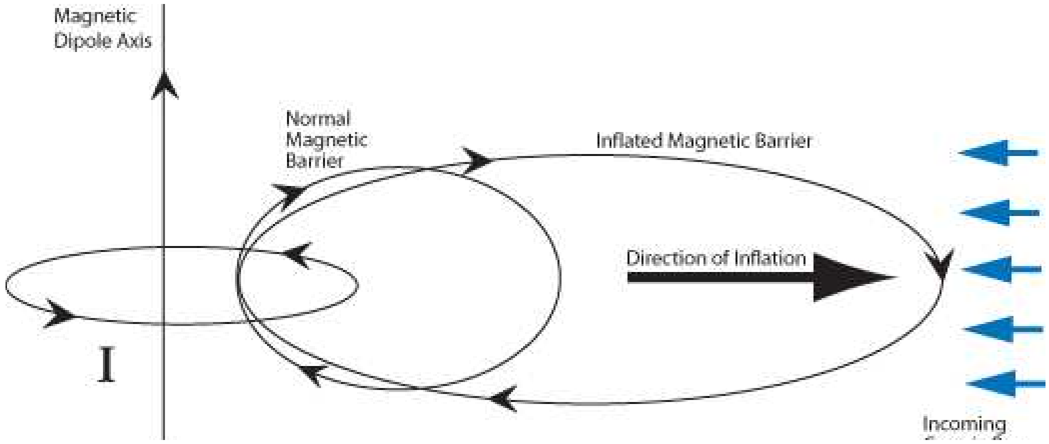


Figure 2. As a shielding magnetic field is inflated outward from the spacecraft, the magnetic barrier intended to deflect incoming cosmic ray particles grows thinner, reducing the effectiveness of the shield. Inflating the dipole field to larger radii pushes that essential shielding component outward so that the transverse magnetic flux is spread more thinly around a larger circle, and hence offers a thinner barrier to be crossed by an incoming particle.

Electrostatic Shielding

The third leading active shielding strategy currently under development relies on the idea that the most dangerous of the cosmic ray protons can be warded off by charging the spacecraft to a positive electrostatic potential of the order of 2 x 109 V. This shielding principle is simple: The positively charged spacecraft would repel the positively charged cosmic ray protons.

The outstanding difficulty stems from the fact that galactic cosmic rays are not alone in space. Negatively charged particles stream constantly outward from the Sun in the solar wind; on average there are something of the order of five free electrons per cubic centimeter in space. (That number can jump by a factor of a thousand or more, albeit briefly, in the wake of the most intense solar flares.) That means that the positively charged spacecraft would attract the vastly greater number of free electrons. The violent inward acceleration of electrons would cause them to arrive at the spacecraft with energies of 2 x 109 eV, and each electron would be approximately as damaging to the health of the astronauts as the occasional single cosmic ray proton.

Under any circumstances, the electrostatic shield would have to be surrounded by a negative guard potential of at least a few hundred volts to keep out the ambient electrons. Unfortunately, this negative potential attracts the ambient thermal ions of some five per cubic centimeter. The electric current carried inward by the ions would appear to be large as a consequence of the large area of the outer surface of the region controlled by the central 2 x 109 V electrostatic field. Crude estimates of the inward current of electrons attracted by the electric potential of the spacecraft suggest currents of 1000 A or more. So far as I know, no serious thought has been given so far to this electron problem and the associated power problem, or how to charge the spacecraft to 2 x 109 V in the first place.

Biomedical Solutions

In view of the dubious and difficult technological possibilities for shielding astronauts from galactic cosmic rays, other scientists and I have pointed to the importance of looking seriously for other solutions, particularly in the biomedical field. Some promise lies in ongoing research on the myriad effects of long-term radiation exposure.

NASA set up the National Space Radiation Laboratory at Brookhaven National Laboratory in 2003 to study these effects. Biologists and medical experts there are conducting a variety of radiation experiments to determine the molecular pathways of cell damage, for example, with the hope of finding certain chemicals that can reduce or prevent the damage. Other investigators are assessing the ways in which radiation damages DNA and which types of damage are most difficult for cells to repair. It may turn out that certain people are genetically less prone to long-term problems and might run a lesser risk to their health from radiation damage.

It is also important to answer an even more fundamental question: How much radiation can most humans actually tolerate? Unfortunately, the only estimates of the consequences of the low-level, long-term radiation exposure—the same estimates that suggest a year in space might cause cancer later in life—stem from the assumption that biological damage is simply proportional to the total accumulated radiation dose, whether that dose was administered slowly over an extended period of time (as one would experience in space) or in a short, intense burst (as people have experienced in the wake of nuclear explosions).

Medical evidence suggests that the human body is able to carry out some limited repair of radiation damage, so that radiation administered slowly over a long period may not be as serious as the same dosage delivered in one short burst. Is it possible, then, that the biological damage done by cosmic rays over a period of a couple of years may not be as severe as the present estimate indicates? No one knows for sure.

The future of manned exploration of space may depend as much or more on the answers to these questions as on any amount of investment in active shielding technologies. It just might be that a voyage to Mars and back is feasible without being able to reduce the cosmic ray exposure. But if not, and if current active shielding strategies do not pan out, then voyages in excess of a few months are out of the question—unless undertaken by people who are willing to sacrifice their long-term health for the excitement of the journey.

Eugene Parker is professor emeritus at the University of Chicago.

Citation: Parker, E. (2005), Shielding Space Explorers From Cosmic Rays, Space Weather, 3, S08004, doi:10.1029/2005SW000176.

RELATED ARTICLES
Active Radiation Shielding in Space? (2 October 2004)