SHIELDING ASTRONAUTS FROM COSMIC RAYS

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The astronaut far removed from the magnetically enshrouded mass of Earth is subject to a continuing low dose rate of galactic cosmic radiation. Exposure for a year or more may be sufficient to induce a high incidence of cancer a decade or two later. Effective shielding of an astronaut by surrounding mass involves too much total mass to be practical for launching into space. Magnetic shielding requires transverse field of about 10^7 Gauss cm (to deflect particles up to 2 Gev). A dipole field of 10^5 Gauss with a characteristic scale of 2m or more would be required. However, there is evidence that the induced emf's from human residence in fields of the order of only 10^3 Gauss may be seriously injurious. There is very little information available on this subject. The alternative concept of inflating a magnetic dipole field with plasma is ill founded, and, in any case would serve only to reduce the Gauss cm of transverse field. Electrostatic shielding, charging the spacecraft to $+2x10^9$ volts, would have to contend with the surrounding sea of thermal electrons, perhaps with a guard potential of -10^3 volts. The power requirements to operate such a system are enormous.

We suggest that there may perhaps be a solution to the problem in the biomedical field, stimulating the human body to effective repair of the ongoing radiation damage by the cosmic rays. Unfortunately there is very little information available on this prospect. It may be our only hope.

I Introduction

Round trip interplanetary travel by humans involves exposure to the galactic cosmic rays for periods of time comparable to the orbital periods of the planets in their vicinity. To shorten significantly the duration of the journey would require extremely fast travel beyond anything in the foreseeable future. So, for instance, a trip to Mars involves a time of the order of two years. The best available estimates of the accumulated cosmic radiation damage to the astronauts predict serious impairment of their health in the years following a successful return to Earth. This argues that a means for protecting astronauts from cosmic radiation must be devised if interplanetary travel is to become a reality. The principal problem is with galactic cosmic rays up to about 2 Gev/nucleon, which are both numerous and sufficiently energetic to create a modest shower of secondary particles (electrons, positrons, pi and mu mesons, and gamma rays, as well as secondary protons and neutrons). Beyond 2 Gev/nucleon the shower produced by each incoming cosmic ray proton or heavier nucleus grows more intense, but the number diminishes rapidly with increasing energy

The purpose of this presentation is to review the basic shielding possibilities and limitations in their generic forms for protecting the health of the astronauts. Fortunately many of the difficulties have already been noted and discussed in this Workshop, so I can mention them without elaboration.

The first thought is to surround the astronauts with sufficient mass. After all, that is what shields us here at the surface of Earth, where there is 1000gm/cm^2 of air interposed between ourselves and the cosmic rays.[1] A Workshop of experts was convened to study the problem, and they were forced to conclude that the required quantity of shielding matter is just too great to be tractable. Particles at Gev energies, and the secondary particles that they produce, are simply too penetrating to be blocked by the walls of a spacecraft. As someone summarized it, the astronauts would have to be surrounded by a million gallons of water, and that works out to 4000 tons. In simple terms, the thickness H of the walls of the spacecraft should provide something of the general order of magnitude of 10^3 gm/cm^2, so that an absorber with density D requires a wall thickness such that $HD \approx 10^3$ gm/cm^2 in general order of magnitude. For water this means $H = 10^3$ cm, and a sphere of water of this radius has a mass of about 4000 tons.

One can do better with absorbers such as ethylene, containing a larger fraction of protons, and one does not need the full 10^3 gm/cm^2, but evidently not enough better to make the material shielding concept tractable.

II Magnetic Shielding

The next consideration was with magnetic shielding. One may ask how much magnetic field is required to turn aside a proton with an energy of 2 Gev. Consider, then, the cyclotron radius R of a proton with mass M and kinetic energy ηMc^2 moving perpendicular to a magnetic field B. With $RB = Mc^2[\eta(\eta+2)]^{1/2}/e$ it follows that $RB = 0.3\times10^7[\eta(\eta+2)]^{1/2}$ cm. So a 2 Gev proton is deflected through 90° by 0.84×10^7 Gauss cm of magnetic field oriented transverse to the direction of motion of the magnetic field. That is a lot of magnetic field, and one thinks of a superconducting magnet. The technical difficulty with the cryogenics is not considered here (See the presentation by Ting and by others in this Workshop).

Suppose, then, that the astronaut is placed at the center of a circle of radius a of superconducting wire carrying a current I_a. The dipole magnetic moment M_a of the circle of wire is $M_a = \pi a^2 I_a / c$, and the field extends outward from the wire with a characteristic scale a. Outside the circle of wire the field is asymptotically of dipole form, and the magnetic field in the equatorial plane of the dipole (the plane of the circle of wire) is $B(r) \approx M_a / r^3$ for $r > a$. The number of Gauss cm, denoted by G, between $r = a$ and $r = \infty$ is given by

$$G = \int_a^\infty dr B(r) \approx \frac{M_a}{2a^2} = \frac{\pi I_a}{2c}$$

The magnetic field B_c at the center of the circle of wire is $B_c = 2M_a/a^3$, from which it follows that $B_c = 2G/a$. So, with $G = 0.84\text{x}10^7$ Gauss cm, a radius a = 2 meters yields $B_c = 1.7\text{x}10^5$ Gauss, while a = 10 meters gives $B_c = 3.4\text{x}10^4$Gauss. Note, then, that the astronaut residing within the circle of current would experience very strong magnetic fields.

The biological consequences of long term exposure to strong magnetic fields are not well studied, so far as I am aware. I have one qualitative data point, based on the fact that, putting

[1] Contrary to popular misconception, we are not significantly shielded by the geomagnetic dipole field. If the geomagnetic field were switched off, the ionizing radiation (mu mesons) at sea level would increase by about 10 percent at middle and low latitudes. The radiation would not increase at all at high geomagnetic latitudes, where the geomagnetic field provides no shielding anyway. The ten percent increase would put the intensity at about the same level as currently "enjoyed" in Denver, a mile above sea level.

one's head into the gap between the pole pieces of a large cyclotron magnet, where the field is of the order of 5×10^3 Gauss, introduces noticeable electrolytic effects. Rotating the head provides scintillations in the retina, and an acid taste soon develops in the saliva. Both of these effects suggest significant interference with the normal body chemistry. We need hard laboratory data on the biological damage to mammals residing in strong magnetic fields. The necessary experiments should not be difficult.

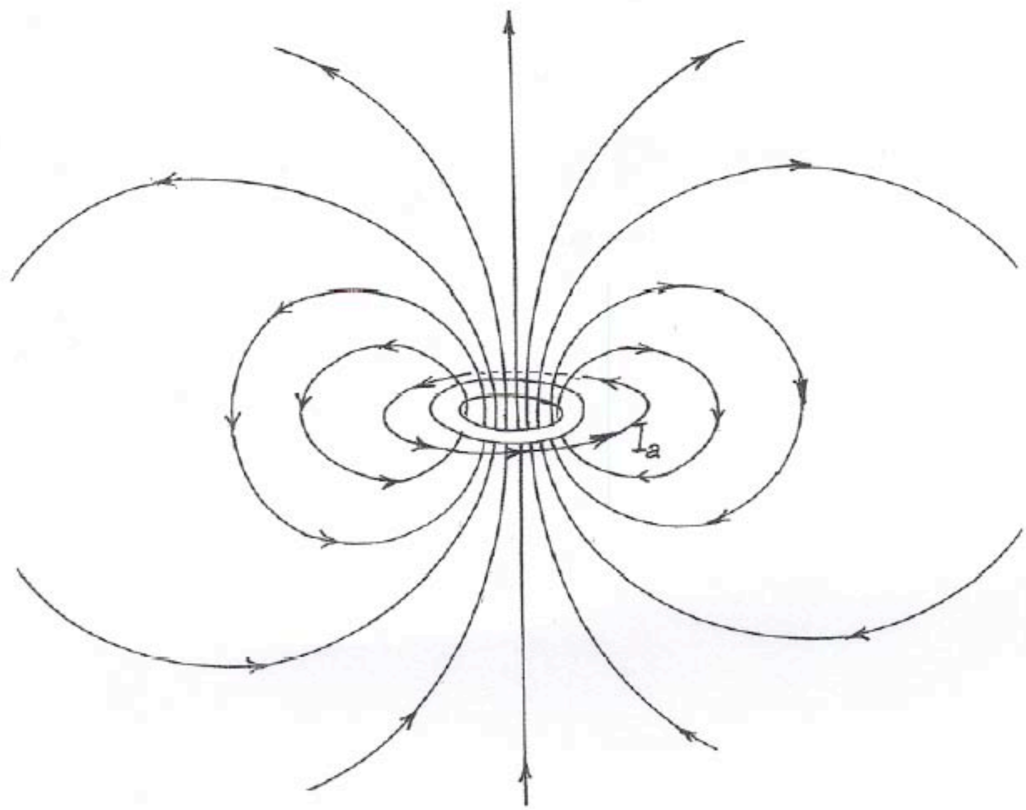

Figure 1 A sketch of the torus with minimum cosmic ray intensity in the magnetic field of a ring current.

Based on the single qualitative data point from the cyclotron magnet, it appears that the astronauts must be shielded from their magnetic shield. A weak field region must be created in the midst of the field of the circle of current carrying wire. How weak the field must be remains to be determined from biomedical laboratory data. The simplest scheme would be to introduce a coplanar smaller circle of wire, of radius b ($<a$) and current I_b at the center of the larger circle of wire. With the field $B_b = 2\pi I_b / bc$ at the center of the smaller circle put equal to $-B_a$, i.e. I_b flows the opposite way around from I_a, it follows that $I_b = I_a b/a$. There is then a relatively field-free region at the center of the two coplanar coaxial current loops. The net dipole moment of the system is reduce by the factor $1 - (b/a)^3$, so that I_a must be increased by the same factor to maintain the external dipole field. However, the astronauts would remain healthy, so long as they remain sufficiently close to the neutral point of the field.

Now it must be appreciated that cosmic ray particles are free to come in along the field from the poles of the dipole magnetic shielding system. Liouville's theorem tells us that their intensity is undiminished. It is necessary, therefore, that the astronauts be place off axis, so that there are no lines connecting that volume to infinity. We may imagine the astronauts to be confined to a torus that is coaxial and coplanar with the two circular currents, sketched in Fig. 1. Shielding the astronauts from the magnetic field at the torus would then require two circular electric currents, and the whole scheme requires a larger I_a , of course.

Finally, it should be recognized that a magnetically shielded spacecraft must serve as a particle absorber to stop the few energetic particles that succeed in leaking through the magnetic shield. For without absorption, Liouville's theorem and the ergodic nature of magnetic field lines without ideal mathematical form and perfect symmetry, tell us that the magnetized space would eventually become completely filled with particles to the same intensity as the cosmic rays in the surrounding space. A modest amount of absorbing material would prevent this from accumulating, and I suspect the spacecraft itself would suffice.

III Inflated Magnetic Fields

It has been proposed that a dipole magnetic field can be greatly inflated and puffed out to large distances by inflating it with plasma. The purposes vary, but the general idea seems to be to stretch the field lines out through larger volumes of space. The proposal does not recognize that efforts have been underway in the laboratory for the last fifty years to confine plasma within a magnetic field. That work has clearly established the numerous violently unstable degrees of freedom of the plasma and field system, so only a slight inflation of the field can be achieved before the plasma escapes. So far as one can tell, a strong inflation, perhaps doubling the scale of the magnetic field, would require an outward flow of plasma with pressure equal to the magnetic pressure and traveling at a speed of the general order of the Alfven velocity. In order of magnitude, the energy input to maintain the inflation – if indeed the inflation can be maintained - would be equivalent to replacing the magnetic energy every Alfven transit time.

The claim is made by the proponents of field inflation that a large-scale magnetic field in a space without walls could be greatly extended by inflation with plasma. Their extensive compute simulations are interesting but certainly not conclusive, and the issue must be addressed experimentally. But, of course, the terrestrial laboratory experiment is neither large scale nor without walls. An experiment in space might get around these difficulties, but would be quite expensive. Further, the proposal to apply an inflated field to the shielding of astronauts fails to recognize that inflating the magnetic field serves only to reduce its ability to deflect incoming cosmic ray particles. The essential deflection is produced by the field component that is transverse to the path of the incoming particle, and that is principally the component parallel to the axis of the dipole, with a maximum in the equatorial plane of the dipole. Inflating the dipole field to larger radii pushes that essential component outward so that its flux is spread around a larger circle, and, hence offers fewer Gauss cm to be crossed by an incoming particle, sketched in Fig. 2. At the same time the outward extension of the dipole field opens up the cone of free particle access over each pole. In the extreme case of inflating a field all the way to infinity, the field lines are all radial and the field provides zero shielding. An isotropic particle velocity distribution at infinity maps in along the field lines to the origin with undiminished intensity.

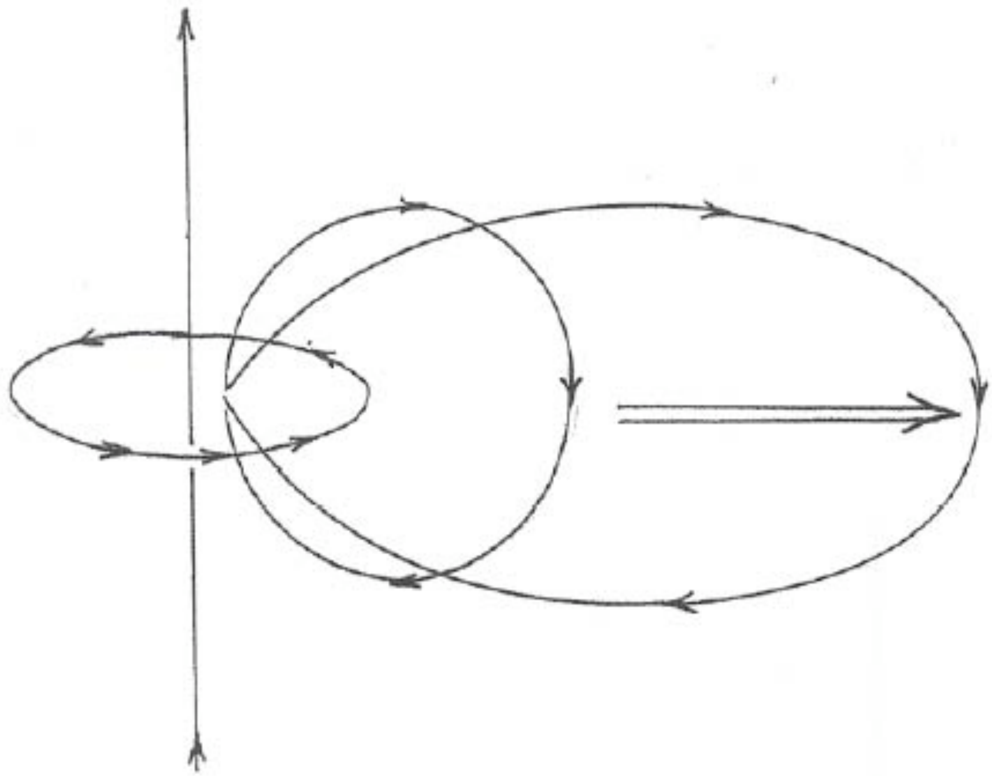

Figure 2 A schematic drawing of the outward displacement of the shielding field component, thinning the magnetic barrier of available Gauss cm.

IV Electrostatic Shielding

It has been noted that charging the spacecraft to $2x10^9$ volts would keep out cosmic ray protons up to 2 Gev. Needless to say, that alone would pull in an enormous flux of electrons from the electron rich environment (typically $5/cm^3$), accelerating them to 2 Gev at the spacecraft and providing a radiation level far in excess of the cosmic ray intensity at 2 Gev. So 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, intended to keep out the electrons, attracts the ambient thermal ions, thereby setting up a plasma sheath around the region. 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 $2x10^9$ volt electrostatic field. The engineering of such a composite electrostatic system would be a complex undertaking, involving the ejection of both positively and negatively charged particles from different regions (See the contribution by Youngquist in this Workshop).

V Biomedical Solutions

It is my impression that the biomedical field may be a fruitful place to look for a solution to the difficulty posed by the accumulated radiation dosage of voyaging astronauts. The fact is that the human body is able to carry out some limited repair of radiation damage. Exactly how much is not known because of the difficulty obtaining data on the long term effects of low dose rates. The best that can be done at present is to interpolate linearly from zero damage at zero dosage to readily observable damage caused by relatively heavy dosage, as sketched in Figure 3. The question is how much radiation can be handled by the normal repair, i.e. how much radiation can be tolerated before it begins to outrun the limited repair ability? Then interpolate linearly from the last point of zero damage, shown in Fig. 3, and reassess the accumulated damage of long exposure to the galactic cosmic rays. How serious is the problem really?

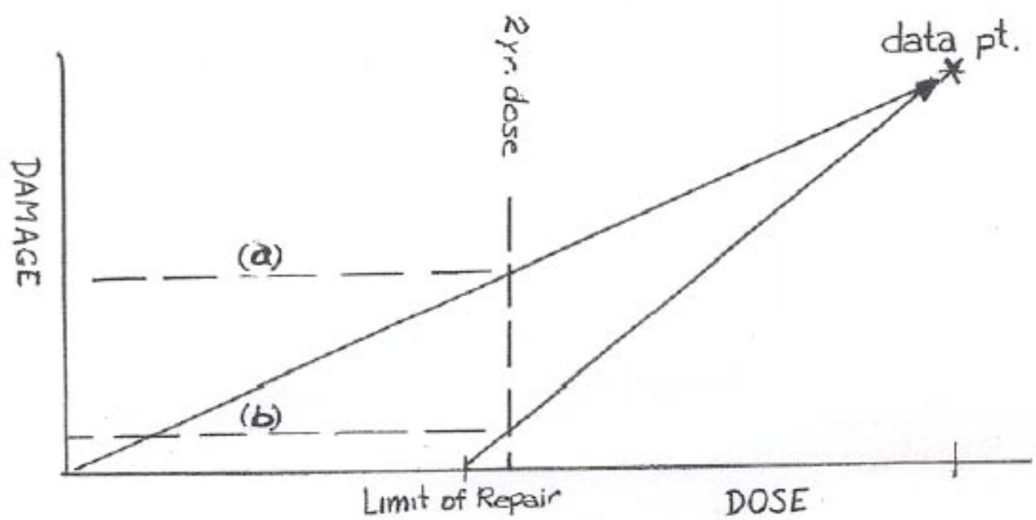

Figure 3 A schematic plot of radiation damage versus radiation dose, based on a linear interpolation from the origin to a single point for a large dose and on a linear interpolation from the point of maximum biological repair of radiation damage.

If a problem still remains, is there something that can be done to stimulate the human body to more effective repair of radiation damage, so that a couple of years of cosmic ray exposure produces no great long term health problems? I do not know the answers to these questions, nor is it obvious to me how one can acquire data on long exposure to low radiation dose rates. However, in view of the foregoing dubious possibilities for shielding astronauts from galactic cosmic rays, I think it is important to look seriously for biomedical solutions. There are others here at this Workshop that can bring us up to date on the present state of knowledge and future possibilities