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Paper Session II-B - Progress Toward Electrostatic Radiation Shielding of Interplanetary Spacecraft

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Progress Toward Electrostatic Radiation Shielding of Interplanetary Spacecraft

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Introduction

Particle radiation remains a significant obstacle to human exploration of space. Passive (materials-based) shielding technology has made significant progress but continues to be a costly in-flight option due to the required mass. Magnetic shielding has not come of age because it requires superconducting coils that are not only heavier than passive shields but contain single-point failure mechanisms and remain a technological challenge. Electrostatic shielding has been largely rejected because repulsion of the protons would attract a cloud of electrons, neutralizing the shield, whereas concentric shells of shielding to repel both electrons and protons would be heavy and would require large voltages over short radial distances, exceeding our current technology.

This paper provides a non-technical introduction to the radiation problem and a brief review of the various shielding strategies. Then it advocates an overlooked alternative: a multipole expansion of the electrostatic fields, which leverage the asymmetries inherent in the physics so that isotropic protection may be obtained without the limitations of concentric shells. This has the potential to dramatically reduce the mass of passive shielding while increasing the shielding effectiveness.

The Space Radiation Problem

Human exploration and development of the solar system is not possible without space radiation shielding to protect the crew and the spacecraft. The radiation damages biological tissues and may cause either acute (severe and immediate) effects or delayed (long-term and cumulative) effects. The acute effects from a severe solar radiation event may lead to death within a matter of weeks, whereas the delayed effects may increase the life-time cancer risk above an acceptable level. Long-duration missions on the Moon or to Mars without shielding is unacceptable for both reasons: the accumulated dose is unacceptably high even in the best of circumstances, and the risk is too high that a lethal radiation event may occur during the mission. Therefore, the president's agenda for exploration cannot proceed without radiation shielding.

The most damaging radiation consists of charged particles (electrons, protons, and heavier positively-charged ions) which are accelerated to nearly the speed of light in processes within our solar system (solar activity) or from without (supernovae). This leads to two categories of space radiation: radiation from Solar Particle Events (SPEs) and Galactic Cosmic Radiation (GCR). The SPEs are further categorized into two types of events: impulsive SPEs that are associated with solar flares, and gradual SPEs that are associated with coronal mass ejections (CMEs), during which the sun blows off a shell of plasma from some large region of its photosphere as illustrated in Fig. 1. Impulsive SPEs are known to be rich in electrons and to occur over a period of just hours. Gradual SPEs are known to be richer in protons and to occur through a period of several days.

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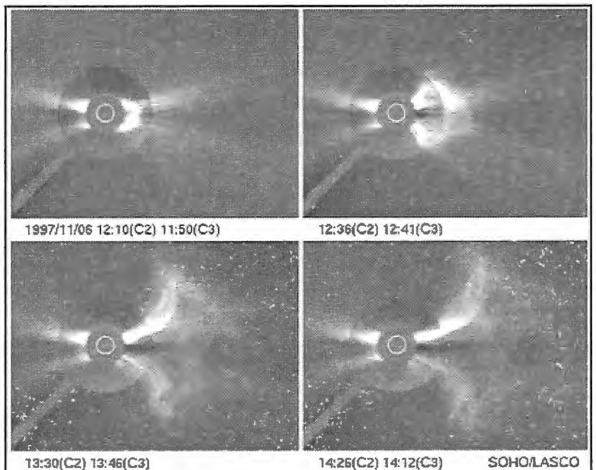

Figure 1. Progression of a Coronal Mass Ejection (CME). The small white circle is the location of the sun. The CME is on the right side of the sun. The white speckle in the bottom two frames are the penetration of CME-accelerated particles through the spacecraft instrument. Images taken by SOHO spacecraft. Courtesy of SOHO (ESA & NASA).

The reason for the longer duration of gradual SPEs is that the shell of plasma blown off during a CME has embedded within it a shockwave that accelerates charged particles to high velocity. This structure propagates outwardly through the solar system, eventually overtaking and passing by the location of the Earth. The high-energy particle radiation is generated continuously by this shockwave throughout its existence. The resulting flux of high-energy particles appears to be nearly isotropic, especially after the wavefront overtakes and passes the location of the observer. By comparison, impulsive SPEs occur on or very near the photosphere and run their course in a matter of hours with the solar flare. The resulting flux of high-energy particles is non-isotropic, being generated in a very narrow region of the photosphere. However, their path through the solar system spirals about the lines of the Interplanetary Magnetic Field (IMF) so they still impinge upon an observer through some solid angle.

Neither the impulsive nor gradual SPEs should be confused with the normal solar wind, which consists of far less energetic particles at a much higher flux.

The flux of GCR radiation is on average perhaps two or three orders of magnitude less than the flux of an SPE, but the GCR particles are an order of magnitude more energetic. GCR consists of a spectrum of particles including electrons, positrons, and positively charged nuclei ranging for the most part from hydrogen (Z=1) to iron (Z=56, where Z is the number of protons plus neutrons). Hydrogen is the most prevalent but iron is by far the most biologically damaging, being alone responsible for most of the accumulated dose. Heavier species are not common because iron is the heaviest element synthesized in the fusion of stars. Biological damage may be described as a function of the Linear Energy Transfer (LET) into the tissue along the linear trajectory of the particle. The mechanism for LET differs with the type of particle. Protons transfer energy primarily by Coulomb (electrostatic) interaction, the series of collisions with valence shell electrons in the tissue. The LET of the higher-Z particles is dominated by their propensity to shatter into a shower of smaller particles, and thus the LET is much higher for high-Z particles and increases with energy. These high-Z, high-energy particles ("HZE particles") are the primary cause of concern for GCR.

Whereas SPEs are occasional, discrete events whose occurrence is still largely unpredictable, GCR is very predictable and ever-present, varying by a factor of two to ten over the course of the 11 year solar cycle. GCR flux is approximately isotropic because the particles originate in the shock waves around supernovae distributed through the galaxy, and the resulting particle trajectories are steered through a wide range of angles by the galactic magnetic field. The penetration of GCR into the solar system's heliosphere is described well by a diffusion equation, and the diffusion is hampered by increased solar activity. Hence, the GCR flux near the earth is less at solar maximum and greater at solar minimum.

Two related radiation problems must be noted. First, stopping a charged particle results in electromagnetic radiation. If the deceleration is sufficiently large, the result will be x-ray emission,

Figure 2. Aurora seen from the Space Shuttle. Image Credit: STS-39 Crew, NASA

known as bremsstrahlung radiation. The dose of bremsstrahlung radiation may be a health hazard or even lethal to the crew if it is sufficiently high. Second, the use of passive radiation shields (materials such as foams) results in secondary particle radiation, particles that have been ejected from the shield itself by the impact of SPE or GCR particles. The total dose received by the crew may include a significant contribution from the secondary radiation, so any solution to the total radiation problem must take that into account.

Finally, the effect of a planet must be considered. Life on the surface of Earth is provided excellent protection by the global magnetic field and the dense atmosphere. Particles are deflected around the planet by the magnetic field. Those that have sufficient energy to penetrate it will for the most part give up their energy in collisions through the upper regions of the atmosphere. The vast portion of the resulting secondary radiation does not reach the surface due to the atmosphere's thickness. However, traveling above the surface in an aircraft significantly increases the dose and especially so during an impulsive SPE. The equivalent of 100 chest x-rays or more could be received by a person flying in a commercial airliner from Los Angeles to Orlando during one of the largest observed SPEs. The dose is higher not only by flying at higher altitudes but also by flying at higher latitudes, since the magnetic field lines originate nearer the poles and guide trapped radiation down into the atmosphere at those latitudes. (This is the cause of the spectacular auroras, as high particle flux transfers energy into the upper atmosphere as illustrated in Fig. 2.) At low Earth orbit the flux is higher still, and no benefit is gained from the earth's magnetic field at the Moon.

Above low Earth orbit are the Van Allen belts. These consist of particle that are trapped by the Earth's magnetic field. Their energy and flux levels are hazardous to a crewmember passing through the belts. However, astronauts will not spend much time in those regions. The inner Van Allen belt is increasingly dense above LEO, maximum around 3000 km altitude, and tapers off by about 5500 km altitude. It is fairly stable and varies with the 11 year solar cycle. The outer Van Allen belt is more variable, depending upon the quantity of radiation recently trapped from solar storm activity and other factors, and roughly extends over 9,000 to 30,000 km above the earth. Other planets may or may not have global magnetic fields and radiation belts. Jupiter's intense radiation belts are a significant problem for human or robotic exploration (see Fig. 3).

Mars does not have a global magnetic field and the atmosphere is thin, so protection is limited on the surface. However, planets without radiation belts provide at least one hemisphere of protection from radiation, and the planet's regolith may be used to construct an inexpensive shield in situ.

To summarize the radiation environment, then, the order of decreasing flux and increasing energy is (1) solar wind, (2) outer Van Allen belt protons, (3) SPE and inner Van Allen belt protons, and (4) GCR particles [1]. (This order of flux should be interpreted as instantaneous during an SPE, not averaged over many events.) The normal solar wind is not a radiation problem despite the high flux because the energy is sufficiently low that normal spacecraft structures are able to stop the particles without generating secondary or bremsstrahlung radiation. Van Allen belt radiation is a consideration and passing through the belt should be considered in the calculation of total mission dose. The occurrence of an SPE outside of the Earth's protection presents the possibility of acute radiation effects, even lethality, due to the extremely high flux. It also contributes to the cumulative mission dose which is a concern for delayed radiation effects such as the occurrence of cancer. The occurrence of SPEs is random and thus far

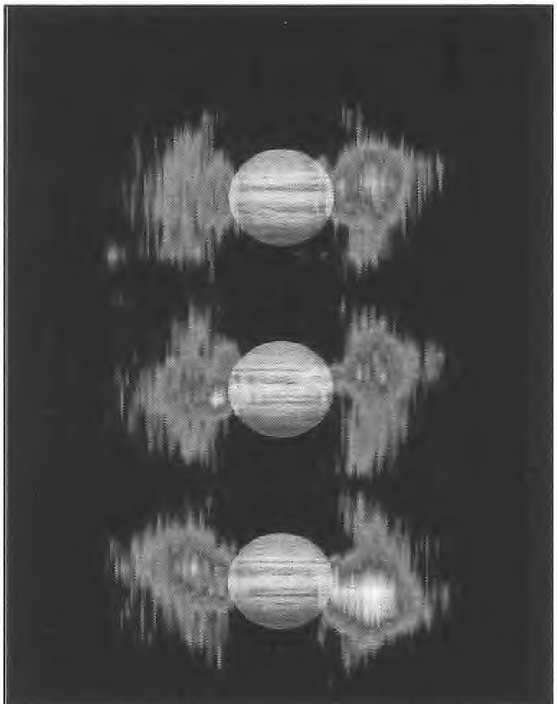

Figure 3. Inner radiation belt of Jupiter measured by the Cassini spacecraft, in three orientations. Courtesy JPL.

unpredictable, and it would have been disastrous if a large one had occurred during the Apollo lunar missions. This risk is not acceptable for future missions, especially considering the extended durations. Gradual SPEs are more or less isotropic, and so isotropic protection is required. GCR is fairly constant but low-flux, so the concern is not acute effects but rather cumulative dose leading to delayed effects. The GCR is basically isotropic so isotropic protection is required.

Review of Shielding Strategies

The "shielding" strategy in the Apollo program was to roll the dice and keep the mission short. No disastrous SPEs occurred and the cumulative exposure to GCR was reducible by keeping the mission shorter. Obviously that strategy will not work for future missions. However, faster propulsion is always a valid way to reduce mission time and GCR dose.

The most promising shielding idea so far has been the use of passive (materials-based) shields to surround the astronauts. This is similar to the protection afforded by the Earth's atmosphere. The difference is that it cannot be as thick as the atmosphere, and so secondary radiation gets through the shields. The challenge is to reduce their mass. With the existing materials, passive shields requires a significant increase in the liftoff and propulsion costs. The mass can be minimized by using the usual spacecraft structures and consumables (such as drinking water) to surround the astronauts as part of the shielding. However, sufficient protection from the largest SPEs still requires a significant increase in mass. This can be minimized by using a "storm shelter" approach [1], so that the heaviest shielding protects only a small region of the spacecraft, to which the crew retreats in the event of an SPE. The lighter shielding will sufficiently reduce the GCR in the remainder of the spacecraft to control the mission-cumulative dose.

Another concept that has been studied is the use of a magnetic field to mimic the protection of the Earth's global magnetic field [2,3]. The problem with this concept is that the field strength must be so high that superconducting coils would be needed to create it. But the coil would suffer tremendous stress under its own fields, and so it must be mechanically reinforced, increasing its mass. It has been argued that the mass of the coil would be put to better use if it were converted to foam and spread on the outside of the spacecraft as a passive shield [4].

A third concept is electrostatic shielding to repel the positively charged particles [5,6]. Electrons are easily stopped by the spacecraft hull and the positive particles (protons and HZE particles) are the ones that are both penetrating and biologically damaging. Therefore, a positive field will repel the most harmful particles. However, it has been pointed out that this creates a secondary problem. A positive field sufficient to repel 100 MeV protons will also attract nearby electrons, imparting 100 MeV to them by the time they strike the hull of the spacecraft. Being non-penetrating, they will be easily stopped by the hull, causing them to emit bremsstrahlung radiation. This might not seem to be a problem at first, because SPE electrons at 100 MeV and greater are already striking the hull and emitting bremsstrahlung radiation, and their dose is so low that it is not a concern. However, there is a vast difference in the flux of low-energy electrons in the solar wind compared to the SPE electrons, a difference of many orders of magnitude. Accelerating these low energy electrons to 100 MeV would create a bremsstrahlung dose that would be lethal. If that were not bad enough, this influx of electrons would neutralize the shield and eliminate the protection against positively-charged particles.

To fix this, it was assumed that an electrostatic shield must consist of concentric shells of alternating charge. (As we show below, this assumption was incorrect.) The overall spacecraft would then be maintained at a slightly negative charge in order to drive away the large quantity of low-energy electrons. The electric field between the concentric shells would be directed outwardly to drive away positively-charged particles. As discussed in Ref. 4, maintaining 3.02 GV between the concentric shells would be enough to drive away iron particles up to 1.4 GeV, which is in the band of GCR energies. However, this creates a secondary problem. In order to get 3.02 GV between concentric shells, the electric field will be 3.02 GV divided by the spacing between them. If this exceeds approximately 20 MV/m [7] then the shells will undergo vacuum breakdown, meaning that the electrons will be stripped away from the surface of one conductor and accelerated through the vacuum toward the other, thus discharging the shield. Keeping below this vacuum breakdown limit requires a spacing of 151 meters between shells. A conductive shell at over 150 meters radius would obviously be quite heavy for an exploration spacecraft. It was this consideration that killed the concept of electrostatic shielding.

A fourth concept is the "Plasma Radiation Shield" [8]. This is an attempt to combine the best of electrostatic and magnetic shielding. The idea is that a positive electrostatic field will repel the protons and an electrically negative plasma will be captured and maintained around the spacecraft by a magnetic field. Thus, the 151 meter outer shell has been replaced by a plasma of nearly zero mass. The effectiveness of plasma radiation shielding against the higher-energy GCR particles has not been investigated [1]. Perhaps the chief concern with this method, though, is that it is complicated and remains largely theoretical.

A new, fifth concept is the "M2P2" or the Mini-Magnetospheric Plasma Propulsion system [9]. As its name implies, this was originally proposed as a propulsion system and only as a side-benefit has it been considered as a method of shielding. The idea is to create a plasma with an embedded magnetic field structure, which can be inflated to many kilometers in diameter. This creates a much larger magnetic field structure than the brute-force use of superconducting coils, and without the excessive mass. This is a new concept which needs further study, but it seems to us that two problems exist. First, the magnetic bubble has two poles located at the ends of the spacecraft, and therefore particles that follow the field lines will be directed in at both ends (as with the Earth's auroras). While this does allow the passive (materials) shields to be concentrated at the two ends, reducing spacecraft mass by eliminating the need for isotropic protection, it also raises the question how focused the pole-seeking particles will be. If they are not sufficiently focused, then the passive mass may need to cover significant regions of the two ends of the spacecraft, essentially putting the need for isotropy back into the passive shielding. Second, it has been learned recently that magnetic structures in the solar wind frequently break the Earth's magnetic field lines and attach themselves to their ends. This creates a direct thoroughfare of radiation into a "hotspot" region of the aurora. The M2P2 would seemingly be subject to the same problem, and if solar wind magnetic lines attach to the M2P2's bubble then large quantities of radiation would be channeled directly in. Even worse, the bubble might completely break and be swept away during the passage of a CME's magnetic structure, leaving the spacecraft with no shielding at all just at the time it is needed the most. These problems have not been demonstrated, but we raise them here only as concerns that should be investigated.

A sixth concept is a multipole expansion of electrostatic fields [10] to be presented below. In summary of the other five shielding strategies, the active (electrostatic and magnetic) systems can completely repel the entire flux of particles below some cutoff energy level. However, the problem is generating fields strong enough to repel the highest energy particles in the GCR. Passive shielding, on the other hand, , can provide a reduction of flux even for the most energetic GCR particles, but it does not provide a complete cutoff and so the fraction of the flux that gets through may still be too high if the incident flux is extremely large, as in the case of a large SPE. It is possible the best solution will be a combination of active and passive shielding. The passive shields may be needed to adequately reduce mission dose of the GCR, while the active system may be needed to entirely eliminate the flux of the less energetic but higher-fluence SPE particles during the course of a solar event. The concept in the next section may fill that purpose. However, it is also possible that this new concept may be adequate by itself without passive shielding.

Multipole Expansion in Electrostatic Shielding

It is well-known that arbitrary electrostatic fields may be decomposed mathematically into an infinite superposition of components, a decomposition known as a "multipole expansion." The lowest-order term in this expansion is the monopole component, followed by the dipole, the quadrupole, and so on. The monopole component decreases in strength inversely proportional to the distance, r^{-1}, whereas the sequence of higher order components decay like r^{-3}, r^{-5}, r^{-7} and so on. At a particular distance, one of the terms will dominate the field. It should be possible to assign different shielding functions to each term in a multipole expansion of the fields. For example, a very strong quadrupole term may dominate the physics closest to the spacecraft, while a weaker but farther-reaching monopole term dominates the physics further away. Thus, it is possible to have "shells" of protection surrounding the spacecraft without using any concentric structures to deploy them. Thus, electrostatic shielding is possible without the mass of the 151 meter sphere and without the complications of magnetic plasma containment.

For example, the quadrupole term may be assigned the task of repelling positively-charged particles, including those at very high energy (protons and HZE particles). The monopole term may be assigned the task of repelling electrons. This arrangement may leverage the two natural asymmetries that exists in the physics mentioned above: (1) the flux of the lower energy particles is much higher than the flux of the higher energy particles, and (2) electrons are more easily stopped by the spacecraft's hull than are protons and heavier nuclei. Thus, while the monopole term may not be strong enough to repel the highest-energy electrons that are part of an SPE or a component of the GCR, there are not enough of these to create a significant bremsstrahlung problem when they strike (and are stopped by) the hull of the spacecraft. The great quantity of lower-energy electrons need only to be brushed away from the central, quadrupole-dominated region, in order to keep them from being accelerated by the electrostatic field into the spacecraft (which would create a bremsstrahlung problem). On the other hand, the high energy positively-charged particles and the much higher quantity of lower-energy positively-charged particles (which are part of the solar wind) will both be repelled by the large quadrupole term dominating the region immediately around the spacecraft. Thus, it is possible for one multipole expansion to solve all parts of the shielding problem. An example of an electric field obtained with a linear quadrupole shield geometry is shown in Fig. 4.

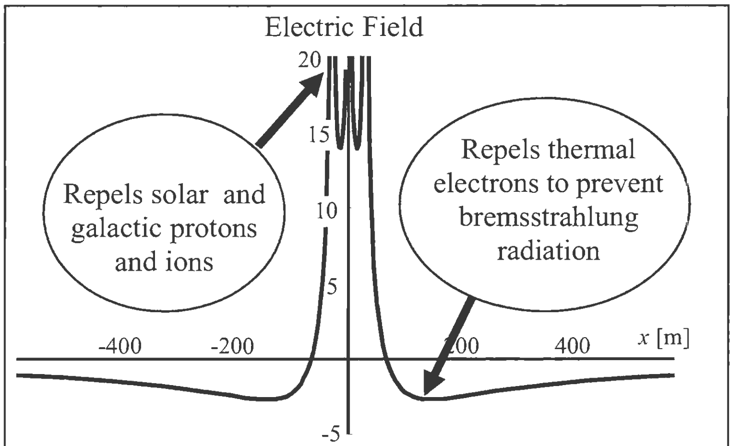

Figure 4. Typical electric field resulting from a linear quadrupole arrangement.

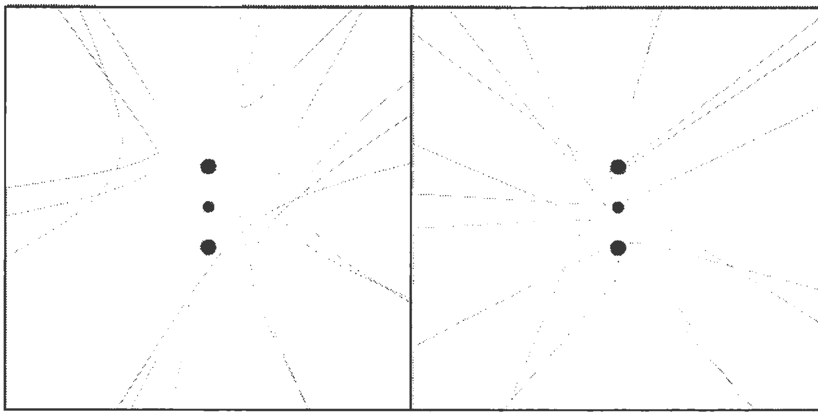

Figure 5. View of 3D particle trajectories. The outer circles are the balloons. The central circle is the spacecraft .

(Left) Electrons are repelled over a wide region.

(Right) Protons are repelled from the central region (the spacecraft). No particles reach the spacecraft.

This arrangement can be deployed very easily by lightweight structures in space. The charge that creates the electric field may be driven onto the surface of lightweight balloons, which self-inflate under the Coulomb force when the voltage is applied. That voltage may be created by simple electrostatic generators such as a Van de Graaf machine. The current output from such a device is very low, but likewise the influx of solar and galactic particles onto the balloons is also very low and so it is feasible for the generators to sustain the voltage. Tethers and only lightweight, flexible rods may be sufficient to deploy the balloons around the spacecraft. Thus, the entire system is low mass and depends only upon well-known technology. Some improvement is needed in the electrostatic generators to provide the level of voltage that is needed to protect against the largest solar flare protons and against the most significant flux of HZE particles, but this improvement seems achievable, as described below.

Simulations of such a shielding strategy have been performed at the Kennedy Space Center. A model was written in Fortran to simulate the trajectories of high-energy charged particles in the presence of a set of charged balloons. For now, the radiation of energy away from the deflected particles has been neglected, but this will be included in the next generation of the model. Also, the distribution of charges on the balloons has for the present been assumed uniform, which we found to be a valid simplification as long as the spacing between balloons is more than three times their diameter. A future version of the model will include the method of image charges and other numerical techniques to more accurately predict the fields that result from the actual (non-uniform) charge distributions. Typical particle trajectories are shown in Fig. 5. Such simulations were performed for large numbers of particles at various energies and with several shield configurations.

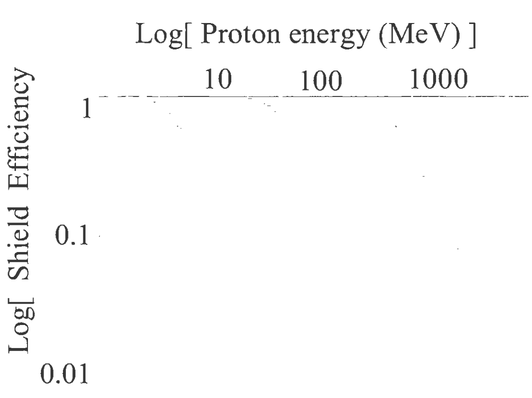

Figure 6. Shield efficiency versus proton energy. Solid line—nominal shield voltages. Dashed line—1/10th voltages. Dotted line—10 times voltages.

Shielding efficiency is defined as the percent reduction in the number of particles that strike the protected region, as a function of particle energy. This has been calculated for a sample shield geometry using several different voltages on the spheres, and the results are shown in Fig. 6. Our research indicates that asymmetric electrostatic shielding is feasible, not only to protect against SPE radiation but also to significantly reduce the GCR dose, if the electrostatic voltages are a factor of 40 greater than what is currently available using Van de Graaf generators on the Earth. This seems achievable for two reasons. First, in space there is no risk of atmospheric ionization and so greater electric fields can be sustained. Therefore, it is possible to simply connect multiple generators in series to increase the voltages (equivalent to increasing the belt length in a Van de Graaf machine). This is sufficient by itself to solve the problem. Second, until now there has been no motivation to improve electrostatics generators in a way that will support typical applications in the space environment (where there is no atmosphere, no ever-present ground plane, and more spatial freedom due to a lack of gravity) and so the technology is still relatively immature and rapid advances can be expected.

Even if the most energetic GCR particles cannot be stopped by multipole electrostatics, used in conjunction with passive shielding it will provide a dramatic improvement over passive shielding, alone. Passive shields cannot provide sufficient reduction of flux for the most powerful SPEs without the addition of excessive mass. Electrostatics with very little mass will deflect the entire flux up to a particular energy level. It will also reduce the energy of those GCR particles that get through, thereby reducing secondary radiation. Thus, electrostatic protection against SPEs coupled with passive shielding protection against the highest energy GCR may, in that case, provide the optimal solution.

Conclusion

Multipole electrostatic shielding is a promising concept that deserves further attention. A proper multipole expansion of the field leverages the asymmetries in the physics and thereby repels both electrons and protons without generating excessive bremsstrahlung radiation. It does not require heavy structures or concentric shells of charge to deploy the fields, and the vacuum breakdown limit can be easily avoided. This concept may provide a lightweight, inexpensive solution to the radiation problem that may be implemented on spacecraft immediately, thus enabling human exploration and development of the solar system.

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