Evaluation of Magnetic Shielding of Interplanetary Spacecraft from Cosmic Radiation

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Abstract

The continuous exposure to cosmic radiation is a possible constraint on long duration (multi year) manned interplanetary missions. The magnetic shielding concept is often considered as a possible method to reduce the radiation dose from the cosmic radiation. We have evaluated possible magnetic field configurations to determine what is required to reduce, by one-half, the cosmic ray flux impacting a spacecraft. This evaluation has been accomplished by tracing cosmic ray trajectories through different magnetic field configurations. We find that the magnetic field gradient is the primary factor that controls the magnetic shielding effectiveness. A pseudo dipole configuration ($1/r^3$) magnetic field gradient requires unreasonably large magnetic fields. A ($1/r^2$) magnetic field gradient is capable of much better magnetic shielding. A (1/r) magnetic field gradient would be best for magnetic shielding. We have evaluated possible mini-magnetosphere configurations to determine the magnetic shielding that might be attainable. The mini-magnetosphere configurations evaluated are consistent with a ($1/r^2$) magnetic field gradient.

1. Introduction — the Cosmic Ray Spectrum

A representation of the solar minimum cosmic ray integral spectrum [1] is illustrated in Figure 1. Inspection of this figure shows that half of the proton flux exists at energies $\leq\sim$ 1.5 GeV, (rigidities $\leq\sim$ 2.2 GV). For alpha particles and heavier nuclei, half of the flux exists at energies $\leq$ 0.9 GeV/nucleon, ($\sim$rigidities $\leq\sim$ 3.1 GV). So about one-half of the 4π steradian solid angle of a unit sphere must have a magnetic cutoff rigidity of $\sim$ 2 GV in order to reduce the cosmic ray exposure by one-half.

2. Magnetic Shielding by Pseudo-Dipole Magnetic Fields

We have written software to determine what H_0 magnitude a pseudo-dipole magnetic field must have to reduce the cosmic ray flux by one-half for a scale size of 160 meters. For a dipole magnetic field with a $1/R^3$ gradient, 160 m scale size, a H_0 of $\sim 30,000$ Gauss is required.

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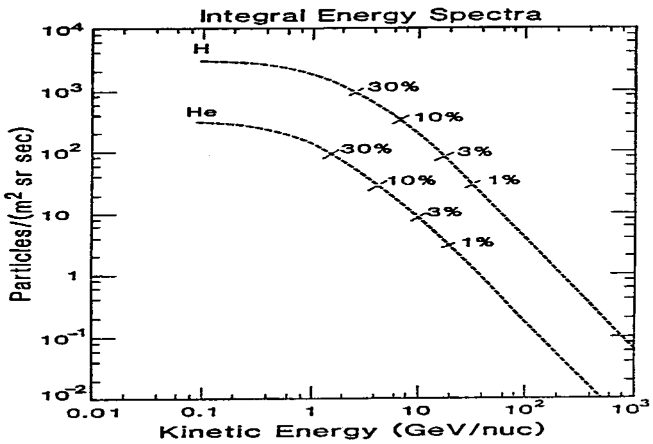

Fig. 1. The solar minimum cosmic ray spectrum for proton and alpha nuclei.

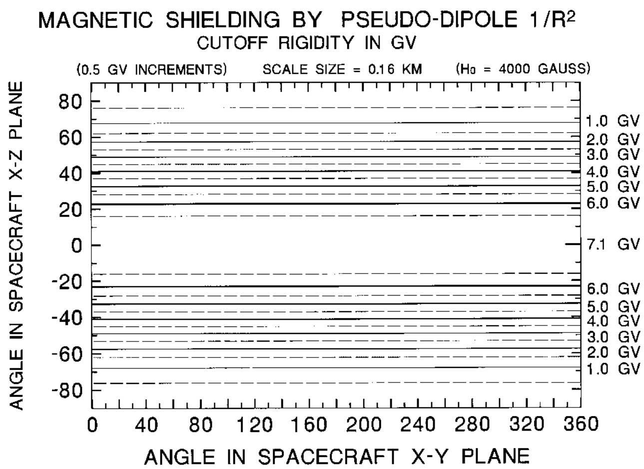

Fig. 2. Magnetic cutoff rigidity contours resulting from a pseudo-dipole magnetic field, H_0 of 4000 gauss, gradient of $1/R^2$, and scale size of 160 m.

For a pseudo-dipole magnetic field with a $1/R^2$ gradient, 160 m scale size, with the following characteristics:

$$B_r = (2H_0 \cos\theta)/R^2; \qquad B_\theta = (H_0 \sin\varphi)/R^2; \qquad B_\varphi = 0;$$

we found that a H_0 magnitude of ~4000 Gauss was required to reduce the cosmic ray proton flux by one-half, i.e. the magnetic cutoff rigidity over ~ 1/2 the solid angle of an unit sphere is greater than 2 GV. This result is shown in Figure 2.

For a pseudo-dipole magnetic field with a 1/R gradient, 160 m scale size, with the following characteristics:

$$B_r = (2H_0 \cos\theta)/R; \qquad B_\theta = (H_0 sin\varphi)/R; \qquad B_\varphi = 0;$$

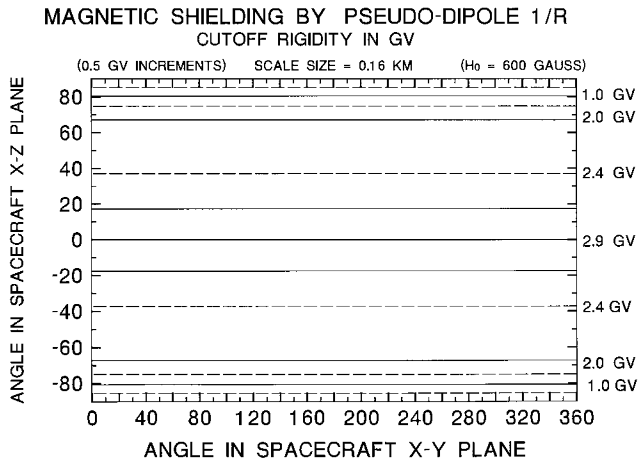

Fig. 3. Magnetic cutoff rigidity contours resulting from a pseudo-dipole magnetic field, H_0 of 600 gauss, gradient of 1/R, and scale size of 160 m.

we found that a H_0 magnitude of ∼600 Gauss was required to reduce the cosmic ray proton flux by one-half, i.e. the magnetic cutoff rigidity over ∼ 1/2 the solid angle of a unit sphere is greater than 2 GV. This result is shown in Figure 3.

3. Magnetic Shielding by a Mini-Magnetosphere — M2P2

The work of Winglee [2] advances the concept that plasma filled magnetic fields surrounding a spacecraft will have a characteristic scale gradient that is different from the standard R^{-3} expected from a magnetic field in air or in vacuum. A useful analogy is the sun's magnetic field into the heliosphere, which has a characteristic scale gradient of R^{-2}. In simulations of the magnetic field generated by a laboratory prototype, Winglee [2] computed that in the M2P2 configuration, the field gradient in the direction of the solar wind stagnation point may have a characteristic scale gradient of R^{-1}.

We have been evaluating the magnetic shielding provided by magnetic fields contained in this type of mini-magnetosphere (designated as M2P2). Dr. Winglee has provided MHD simulations of the vector magnetic fields expected as generated by various M2P2 configurations. We have evaluated the magnetic shielding by the trajectory-tracing process. The magnetic fields in these mini-magnetospheres can be characterized as being turbulent. The magnetic field vectors do not behave in a smooth continuous manner; in fact they are rather lumpy (especially in the pulsed mode configuration). The trajectories calculated in these magnetic field topologies are very complex in comparison with those calculated in a pseudo-dipole magnetic field. Our interpretation of the results is that the particles are actually scattered as they cross boundaries in the MHD simulations of the M2P2 magnetic field. This scattering becomes much more

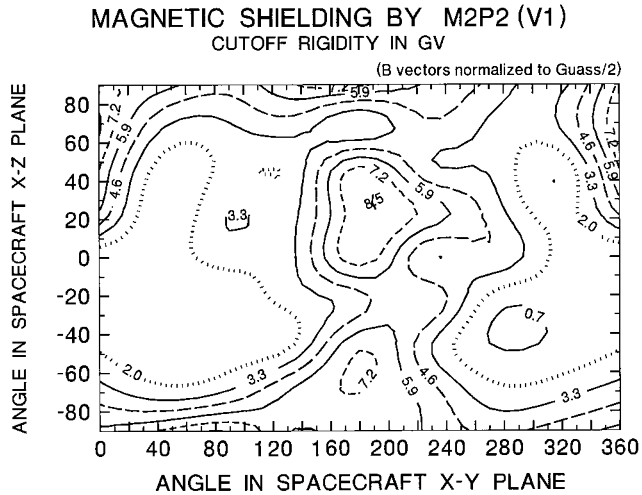

Fig. 4. The "vertical" cutoff rigidity surrounding an interplanetary spacecraft encompassed in a M2P2 magnetic field.

serious at low rigidities. An example of the magnetic shielding achieved by one possible configuration is displayed in Figure 4.

4. Summary

The magnetic cutoff results from trajectory tracing in mini magnetosphere magnetic fields are consistent with a $1/R^2$ field gradient, and may be even slightly better. While the field gradients in the mini magnetosphere near the stagnation points may approach a scale of 1/R, these fields do not appear to have a major contribution to the total magnetic shield. In our simulations, the cutoffs from a plasma-filled mini-magnetosphere do not approach the shielding provided by a uniform 1/R magnetic field gradient.

5. Acknowledgements

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6. References

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2. Winglee, R.M., Slough, J., Ziemba, T., Goodson, A., 2000, J. Geophys. Res., 105, No. A9, 21,067.