Radiation mitigation at the Moon by the terrestrial magnetosphere

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[1] The Moon spends 25% of its orbit within the terrestrial magnetosphere. The magnetic field from the terrestrial magnetosphere can potentially provide radiation shielding from solar energetic particle events and lower energy galactic cosmic rays, which can be a significant hazard during extra-vehicle activities or during human exploration of the lunar surface. The level of shielding provided by the terrestrial magnetosphere is calculated in conjunction with 3D multi-fluid simulations of the terrestrial magnetospheres. It is shown that the level of shielding is dependent on IMF orientation and location of the lunar base. The natural terrain could be used to augment the terrestrial shielding for an equatorial lunar base. A polar lunar base would be exposed to twice as much radiation. But in both cases shielding of GeV particles is possible, with the upper range depending on the prevailing solar wind conditions.
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1. Introduction

[2] Solar energetic particle events (SEPs) and galactic cosmic rays (GCRs) constitute a substantial radiation hazard to astronauts beyond low Earth orbit. Long term exposure to these energetic particles can lead to a substantial increase in cancer rates [*Space Studies Board*, 1996; *Wilson et al.*, 1995, 1997]. GCRs have the harder spectrum with a maximum flux near 1 GeV/nucleon. The flux at this level varies by a factor of about 10 between solar minimum and solar maximum. SEPs have a softer spectrum, but their flux can vary by more than four orders of magnitude on a time scale of less than an hour for periods of several days and yield an energetic particle flux higher than GCRs.

[3] Shielding of these energetic particle by material walls is possible for lunar bases, though secondary production particularly by GCRs can lead to a radiation hazard as potentially harmful, if not more so, than the primaries [*Simonsen and Nealy*, 1991]. To avoid problems from secondaries, fairly thick walls will be needed. While a lunar base can be shielded from these energetic particles by the construction of thick walls for the structure, astronauts in transit or involved in surface exploration would not have the benefits of such shielding. They would be particularly prone to radiation hazards from SEPs, which can occur without warning. One potential method of radiation mitigation is in the form of magnetic fields. Since there are no material interactions, the production of harmful secondaries is not a problem. An extremely important source of magnetic field for the Moon is the terrestrial magnetosphere.

[4] During its 28 day orbit, the Moon traverses multiple magnetic field and plasma environments, from the undisturbed solar wind to deep inside the Earth's magnetosphere. The Moon spends approximately 25% of its orbit (or 7 days) inside the Earth's magnetosphere, and transits through three distinct regions - the lobe, the plasma sheet and the low latitude boundary layer [*Kallenrode*, 1998]. The lobe is the region where magnetic field from the Earth's poles connects to the interplanetary magnetic field (IMF) contained within the solar wind. It is a region of low plasma density ($\sim$0.1 cm^{-3}) and high magnetic field strength. The plasma sheet is the region in which dynamical processes occur that lead to intense auroral emissions and is characterized by higher plasma densities ($\sim$1 cm^{-3}) and lower magnetic field strengths. The low latitude boundary layer (LLBL) is a turbulent region in the equatorial plane where the plasma and magnetic field transitions from being of terrestrial origin to being of solar wind. The plasma densities are comparable to plasma sheet densities while the magnetic field magnitudes are comparable to that in the lobe.

[5] The plasma composition and ambient magnetic field strengths of all three regions is also highly variable, depending on the prevailing solar wind conditions and the direction of the IMF. The influence of the IMF on the characteristics of the magnetosphere have been well documented over the last two decades. Northward IMF leads to thickening of the plasma sheet, and a reduction in the length of the terrestrial tail, though there is some controversy over the exact length of the magnetotail during such periods. Southward IMF leads to the thinning of the plasma sheet, while IMF By can lead to rotation of the plasma sheet, which at the radial distance of the Moon, can be substantial. Depending on the IMF direction, the Moon could be magnetically connected to either the northern or southern hemispheres. These factors will cause the Moon to transit a variety of different regions during its orbit. In addition solar storms can drive dynamics in the magnetosphere which lead to rapid transitions, particularly between the lobe and the plasma sheet, on time scales of less than 30 minutes as the location of the plasma sheet moves relative to the Moon.

[6] This paper quantifies the radiation mitigation at the Moon associated with the terrestrial magnetosphere for nominal solar wind conditions. It focuses on the difference in shielding when the Moon is in the plasma sheet verses when it is in the low latitude boundary layer. These two environment typify the regions with the weakest magnetic field that the Moon will traverse within the magnetosphere,

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and thus represent worst case scenarios for nominal solar wind conditions.

2. Model

[7] For both GCRs and SEPs (particularly after the latter's initial rise) an isotropic source exterior to the magnetosphere can be assumed. The ability of these particles to propagate into the magnetosphere will be determined by whether the gyro-radius of the particle is larger than the scale length of the magnetic field providing the shielding. If the gyro-radius is large, the particle will have an almost linear trajectory and propagate through the system. If the gyro-radius is smaller, the particle will undergo a fraction of a gyro-radius and be turned away. Thus, a criterion for the ability of an external particle to reach the Moon when it is in the terrestrial magnetosphere is that the gyro-radius is on the order of, or smaller, than the scale size of the magnetosphere.

$$\frac{v}{\frac{qB}{m}} \leq L \tag{1}$$

This is equivalent to:

$$\frac{vm}{q} = \frac{m_o}{q}\frac{v}{\sqrt{1-\frac{v^2}{c^2}}} = \frac{m_o}{q}\mathrm{u}_\perp^{\mathrm{deflect}} \leq \int \mathrm{B}_\perp \mathrm{dr} \tag{2}$$

where $\mathrm{u}_\perp^{\mathrm{deflect}}$ is the relativistic momentum per unit rest mass (i.e. velocity $\times$ gamma) of the particle, q and m_o are the particle's charge and rest mass, respectively, and $\mathrm{B}_\perp$ is the magnetic field sensed by the particle along its path (or gyro-motion) $\int dr$. To simplify the calculation we approximate the path length by a straight line linked to the Moon. This approximation is accurate for the most energetic particles reaching the Moon. Lower energy particles will deviate from a straight line. The above approximation though gives an estimate of if these particles will be deflected away from a straight line trajectory to the Moon. It therefore indicates if a reduction in the flux of these particles at the Moon occurs when assuming an isotropic external source. The ratio of $\frac{v^2}{c^2}$ for a 1 GeV proton is approximately 0.75. If it is assumed to be one, then the ratio on the left hand side of equation 2 becomes $\frac{cm_o}{q}$, which is equal to 6 Tm. This implies that to deflect a 1 GeV/nucleon particle, the integral of the magnetic field must be on the order of a few Tm. While the magnetic field of the terrestrial magnetosphere is weak ($\sim$10's of nT), it extends 100's of Earth radii, so GeV shielding is possible, at least in certain directions.

[8] For these calculations, we consider the resulting magnetosphere for two IMF configurations and otherwise nominal, quiet solar wind conditions (incident plasma speed and density equal to 450 kms^{-1} and 6 cm^{-3}). The magnetospheric configuration is determined by running a 3D multi-fluid model of the terrestrial magnetosphere assuming these solar wind conditions until steady-state is achieved. The details of the multi-fluid model are given by *Winglee* [2004]. The first case assumes zero IMF. This represents the worse case scenario as only magnetic flux from the Earth is present to act as shielding. The second case is for northward IMF with a magnitude of 5 nT. This represents the best case scenario as the solar wind adds magnetic flux to the system. Southward IMF is an intermediate between these two cases, as magnetic field is eroded from the dayside and convected into the tail. As such, southward IMF removes magnetic flux from the magnetopause but adds magnetic flux to the tail. The overall magnetic field in the tail is stronger for southward IMF than for zero IMF but weaker than for northward IMF.

[9] Figure 1 shows the magnetic field magnitude within the magnetosphere for the two cases as determined from the 3D global multi-fluid model [*Winglee*, 2004]. The Moon is within the magnetosphere out to angles of about ±30°. Note that, particularly in the northward IMF case, the magnetic field strength can be larger at the Moon's orbital distance when the Moon is at the edges of the magnetosphere ($\sim$ ±30°) than when it is along the Sun-Earth line (0°). For the zero IMF case, the tail current sheet is sufficiently strong that there is a discernible minimum in the magnetic field strength at the equator that incorporates the plasma sheet and LLBL.

3. Results

[10] Figures 2 and 3 show plots of the integral of the magnetic field (equation 2) as a function of zenith and azimuth angle when the Moon is in the plasma sheet and LLBL respectively. The integrals are performed at one degree increments in both zenith and azimuthal angles. The integral of the magnetic field is calculated for four different lunar base locations: at the Earth-facing equator, at an Earth-facing mid-latitude region, at the north pole, and at the far side equator. The lunar base is located at position (0°, 0°) in each panel, with integrated magnetic field shown for look directions between ±90°. Red indicates exposure to a 1 GeV/nucleon galactic cosmic ray while blue indicates shielded regions.

[11] The case with zero IMF has the least amount of shielding but can provide shielding from particles traveling along a trajectory originating back towards the Earth (Figures 2a, 2b, 2c, 3a, 3b, and 3c). This represents the longest path length through which a particle would traverse through the magnetosphere to arrive at the lunar base, while simultaneously passing through the region of strongest magnetic field centered around the Earth. This is the Earth's effective shadow. For the equatorial base, shielding of overhead GCRs can be achieved both when the Moon is in the plasma sheet and in the LLBL (Figures 2a and 3a). Augmentation by natural features, such as the limb of a crater, would lead to excellent shielding in all directions, even for this worse case scenario.

[12] The farside base is the most exposed for zero IMF, with little shielding along any look direction (Figures 2d and 3d). Even though a particle may traverse a path through the magnetosphere in excess of 100 R_E long, the magnetic field along the path is parallel to the velocity vector of an incident particle. Thus this base would have little shielded from particles along any look direction.

[13] The lack of IMF also means that look directions along the Earth's equatorial plane but outside of the Earth's shadow are particularly exposed to GCRs for all lunar bases, both in the plasma sheet and the in the LLBL (Figures 2a–d and 3a–d). The magnetic field in the LLBL

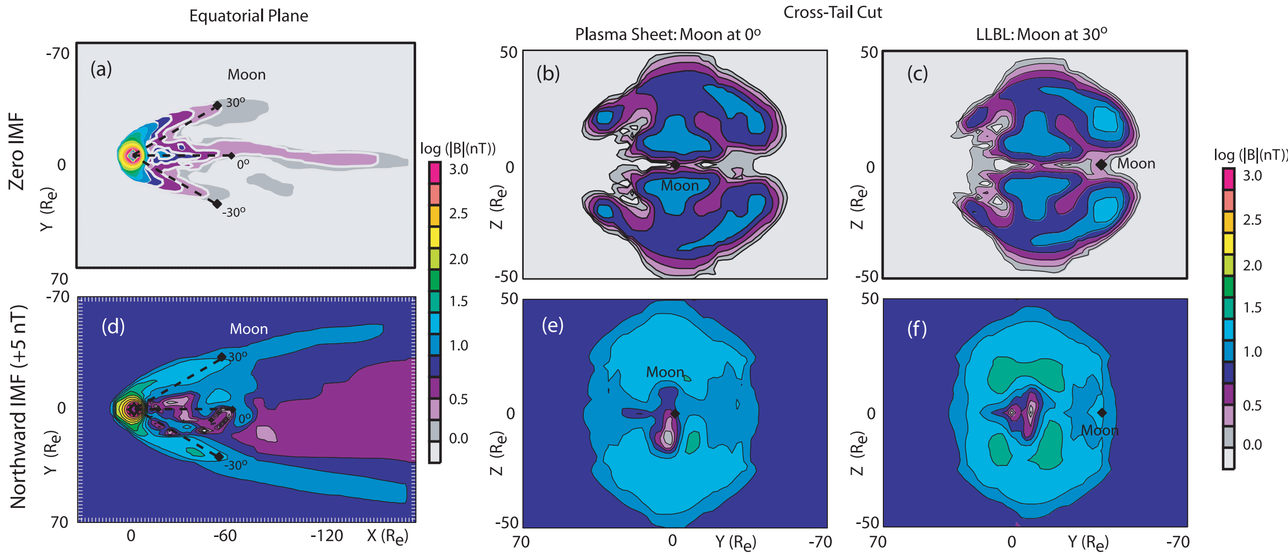

Figure 1. (a, d) The magnetic field strength within the Earth's magnetosphere along the equatorial plane and (b, c, e, f) across the tail at the Moon's orbital distance for two different IMF cases. The cross tail cuts are at the position of the Moon. For Case 1, where the Moon is in the plasmasheet, this is equal to a distance of 60 R_E downtail. For Case 2, where the Moon is in the LLBL, this corresponds to a distance of 52 R_E downtail. The radiation shielding is calculated in detail when the Moon is in the plasma sheet (Figures 1b and 1e) and the LLBL (Figures 1c and 1f).

is primarily of IMF origin, as can be seen by comparing the relative magnetic field strengths in the region for the two different cases (Figure 1). Thus this indicates an example of why the zero IMF case represents the worse case scenario. Even though southward IMF makes the dayside of the terrestrial magnetosphere physically smaller, magnetic flux is added to the tail, particularly in this equatorial region outside of the plasma sheet, thus shielding in still possible.

[14] Northward IMF provides significantly more shielding not only in all look directions, but at all lunar base locations, even the far side equatorial base (Figures 2h and 3h). The effective shadow region increases beyond the 30° radius region present in the zero IMF case due to both the increase in magnetic field magnitude in the LLBL by approximately an order of magnitude near the equatorial plane (Figure 1a vs. Figure 1d) and the increase in the magnetic field strength in the lobe regions off of the equatorial plane by about a factor of 5 (Figures 1b and 1c vs. Figures 1e and 1f). Thus a lunar base at the Earth-facing equator (Figures 2e and 3e), would be protected from 1GeV/nucleon particles from nearly all look directions in both the plasma sheet and the LLBL. The bases at other locations are all at least partially shielded.

[15] The presence of an IMF and the subsequent increase in LLBL field strength means that the bases are actually protected from particles traveling along the Earth's equatorial plane, unlike the zero IMF case, where the highest exposure is due to particles traveling along the equatorial

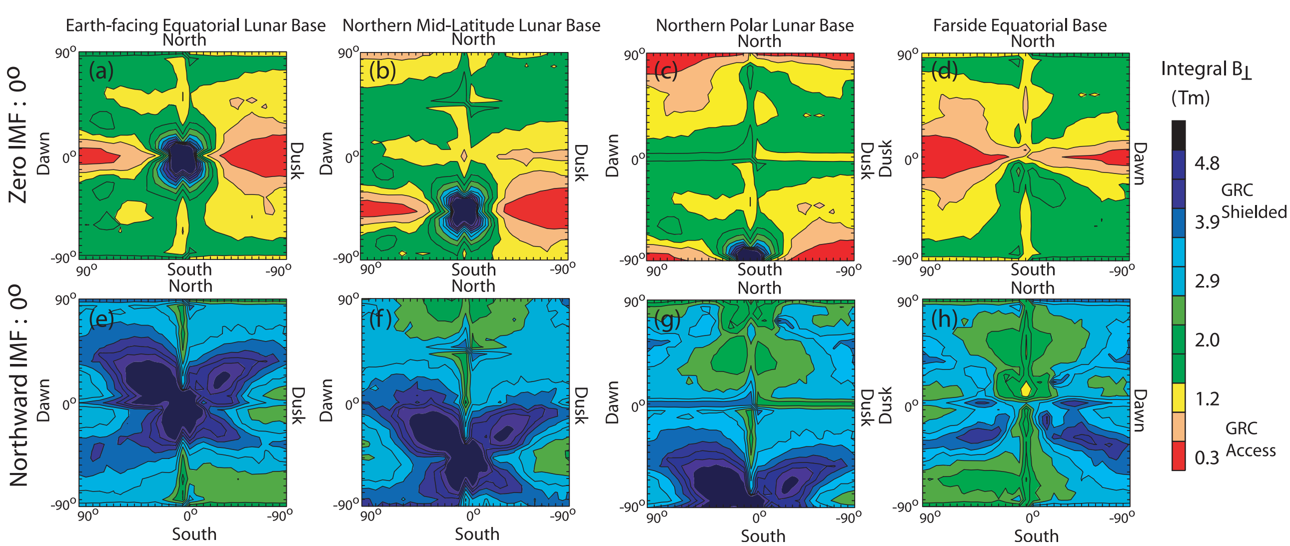

Figure 2. Case 1: The shielding at the lunar surface when the Moon is in the plasma sheet, as indicated in Figures 1b and 1e.

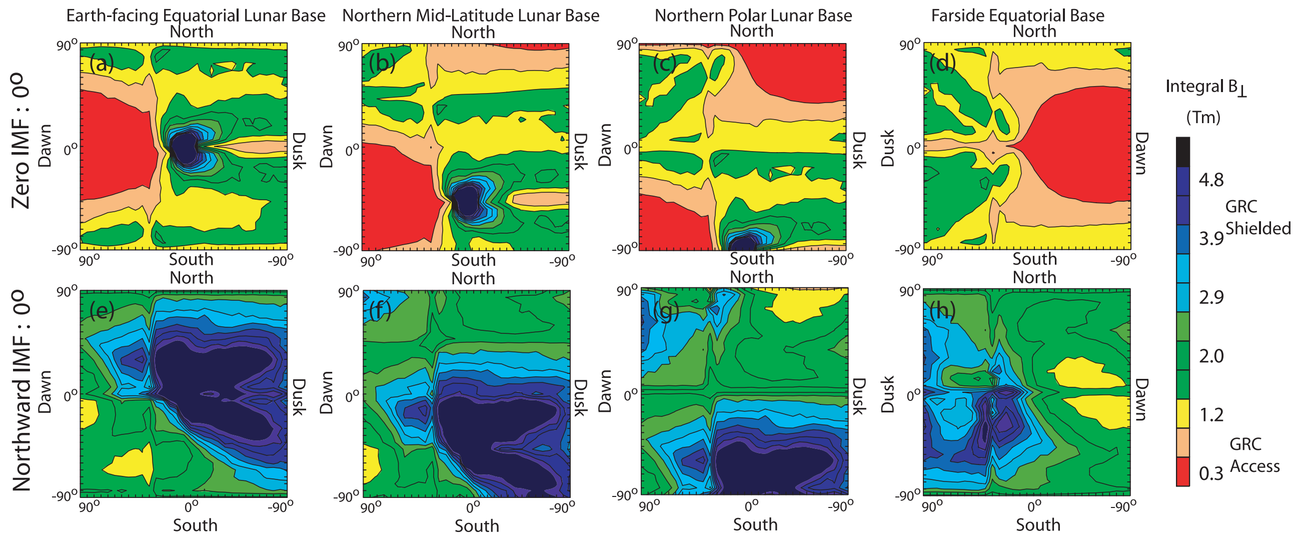

Figure 3. Case 2: The shielding at the lunar surface when the Moon is in the LLBL, as indicated in Figures 1c and 1f.

plane. The subsequent increase in the lobe magnetic field magnitude and the large scale size of the lobe regions means that all lunar bases are as equally protected from particles traveling through the lobes as they are from particles incident from the Earth's shadow.

4. Conclusions

[16] Initial calculations indicate that the quiet magnetosphere may offer some level of protections for astronauts from solar energetic particles and galactic cosmic rays, particularly for a lunar base at the Earth-facing equator. The level of the shielding and the area over which shielding occurs increases with the magnitude of the magnetic field within the solar wind. The IMF adds magnetic flux to the magnetosphere, particularly increasing the shielding from particles traveling along the Earth's equatorial plane. In the worse case scenario when the IMF is approximately zero, energetic particles moving along the current sheet can reach the Moon directly. An equatorial lunar facing the Earth would see these particles coming in from close to the dawn/dusk horizons, but the flux of GeV/nucleon particle would be reduced over most of the sky, thereby providing of shielding of SEPs, and partial GCR shielding. In the best case scenario when there is northward IMF, reduction in the flux of particles up to 5 GeV/nucleon across the entire sky is possible. In this case the terrestrial magnetosphere would provide effectively shielding for both SEPs and GCRs.

[17] The present model does not take into account effects of scattering of energetic particles from the inner magnetosphere, which may act as an interior source of energetic particles. And these results say nothing about the potential for radiation mitigation during solar storms. Storm events can lead to substantial modification in the terrestrial magnetic field, with changes occurring on time scales of minutes to hours. During these times, not only is the magnetic field within the magnetosphere undergoing large changes, heavy ions also within the magnetosphere can be accelerated up to MeV energies, thus leading to another interior source of energetic particles, albeit with a softer spectrum.

[18] The next step in this work will be to establish the plasma environment around the Moon during more disturbed times and determine if the magnetosphere can actually produce more hazards in the vicinity of the Moon, and how those hazards change with solar wind/cycle variation. Besides determining shielding for quiet conditions, the work establishes a baseline which simulations for more disturbed times can be compared to.

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