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# Deflection and enhancement of solar energy particle flux at the Moon by structures within the terrestrial magnetosphere

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[1] The Moon spends 25% of its orbit within the terrestrial magnetosphere. Particle tracking is used to investigate access points of 35 MeV and 760 MeV particles into the magnetosphere for both quiet and disturbed magnetospheric conditions. The results indicate that solar energetic particle (SEP) flux at the Moon can be reduced for storm conditions when the magnitude of the magnetic field in the sheath is enhanced, as particles in the 35 MeV range have limited access to the magnetosphere for storm conditions. Plasmoids are also effective at reducing SEP flux from the tailward direction. The results also indicate that the flux of SEPs from the dawnside of the magnetosphere can be focused into the current sheet, leading to a potential enhancement in SEP flux at the Moon. Particles traveling up the tail for both quiet and storm conditions tended to experience the greatest deflection away from the central tail.

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## 1. Introduction

[2] With the push to send humans to the Moon and beyond, radiation hazards are a significant concern with regard to the safety of astronauts. Once astronauts leave low Earth orbit, solar energetic particles (SEPs) and galactic cosmic rays (GCRs) constitute a substantial radiation hazard [e.g., *Robbins*, 1997]. While the Earth's atmosphere is the primary source of protection from GCRs at the surface, both the atmosphere and the terrestrial magnetic field protect those on the surface of the Earth from SEPs. GCRs can have energies in excess of $10^{18}$ eV (or 1 EeV), but the maximum flux is near 1 GeV/nucleon [e.g., *Gaisser*, 1990]. The flux at this energy varies by a factor of about 10 between solar minimum and solar maximum, with the minimum flux occurring at solar maximum [e.g. *Robbins*, 1997]. 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 [e.g., *Mewaldt et al.*, 2005].

[3] Because of both the lack of atmosphere and global magnetic field, shielding against these energetic particles is required for any type of long-term human outpost at the Moon. While a lunar base can be shielded from 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. SEPs would pose a particular hazard as they can occur without warning. Even in the case when they are preceded by a solar flare, warning times could be only on the order of a few minutes [*Mewaldt et al.*, 2005]. This would be insufficient for times when astronauts are far from the Earth or a lunar base. 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 important source of magnetic field for the Moon is the terrestrial magnetosphere. Missions transferring astronauts between the Earth and the Moon and extended missions on the surface of the Moon could be planned for times when the Moon is within the magnetosphere and radiation hazards may be minimized. However, first we must understand how, or if, SEP flux at the Moon is modified by a dynamic terrestrial magnetosphere.

[4] This paper builds on previous work that used total integrated magnetic field strength along a straight path to estimate the amount of deflection of energetic particles by the terrestrial magnetosphere [*Winglee and Harnett*, 2007]. The previous work neglected ion cyclotron motion. In the work presented in this paper, full 3-D particle tracking is used to investigate how SEP energy particles interact with structures, such as the plasma sheet or plasmoids, in the magnetotail. Particles with SEP energy ranges are launched from varying locations, and the resulting number of impacts is compared to when the Moon is in a region of uniform magnetic field, outside the magnetosphere. Magnetospheric configurations for both nominal and storm-like solar wind conditions are considered. These two cases represent the two extremes for the geometry of the terrestrial magnetic field in the magnetotail. While this does not lead to a quantitative measure of the SEP flux at the Moon for a given SEP event, it allows for a determination of how the SEPs incident on the magnetotail are modified by interactions with the magnetic fields in the plasma sheet and

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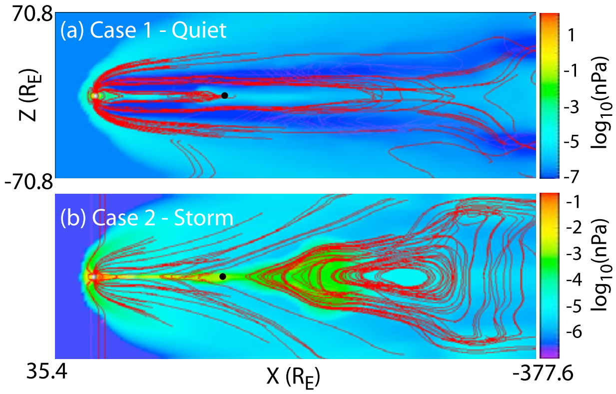


**Figure 1.** The hydrogen pressure along the noon-midnight meridian and the magnetic field lines within the Earth's magnetosphere. The black dot indicates the approximate distance downtail of the Moon when it is at both the dusk and dawn locations.

dynamics structures, such as a plasmoid that forms tailward of the Moon for the storm-like case.

## 2. Model

[5] At the beginning of an SEP event, the particles are primarily incident along the direction of the interplanetary magnetic field (IMF). Afterward, SEPs flux occurs from all directions [e.g., *Reames et al.*, 1996]. Particles are launched in this study from four different locations around the magnetosphere: from the dayside, dawnside, and duskside of the terrestrial magnetosphere, or traveling up the terrestrial magnetotail. To set a baseline and determine how many SEPs would impact the Moon when they are unaltered by the the terrestrial magnetosphere, an additional case is included that recorded the number of impacts when the Moon was placed in the solar wind and the SEPs were incident from the sunward side.

[6] The magnetic and electric fields are determined from 3-D multifluid simulations. The details of the multifluid model can be found in the paper by *Winglee* [2004]. The fields are assumed to be static as the typical time scale over which the SEPs interact with the magnetosphere is on the order of 10–20 s for the high-energy particles tracked and 50 s for the low-energy particles. As detailed in section 3, the motion of the test particles is primarily due to gyromotion. Drift due to the electric field is present for a few cases, but it is not the dominate mechanism in those cases.

[7] Two sets of solar wind conditions are considered. Figure 1 shows the terrestrial magnetic field geometry for the two cases. The first is for a quiescent magnetosphere. Quiet solar wind conditions are assumed with an incident plasma speed and density equal to 300 km s$^{-1}$ and 6 cm$^{-3}$, respectively. The IMF is in the northward direction with a magnitude of 0.5 nT. The second case is a disturbed magnetosphere associated with storm-like solar wind conditions. The incident plasma speed and density are equal to 450 km s$^{-1}$ and 6 cm$^{-3}$, respectively. The IMF is in the southward with a magnitude of 5.0 nT. This is sufficient to generate the large plasmoid tailward of the Moon as shown in Figure 1b. This also highlights the advantage of using magnetic fields from a dynamic simulation; an empirical magnetic field model does not capture dynamics structures such as plasmoids or flux ropes.

[8] The path of the particles is determined by the Lorenz force law. The particle tracker uses a fourth-order Runge-Kutta to solve for particle velocity and position. The details of the particle tracker are explained by *Winglee* [2003]. Two surfaces, one representing the Earth and another representing the Moon, record particle impacts. The surface representing the Moon has a radius of 1741 km and is placed at a radial distance of 60 $R_E$ from the Earth. In the results listed in Tables 1 and 2, the Moon is located both dawnward and duskward of the midnight meridian at a position of $[x, y, z] = [-59, \pm 8.85, 2.0]$ $R_E$, where the $x$ axis points toward the Sun, $z$ points along the North Pole, and $y$ completes the coordinate system. Figures 1 and 2 show the locations at which the SEP flux was recorded for impacts with the Moon. The two circles in the tail in Figure 2 are when the Moon is duskward (bottom) and dawnward (top) of the midnight meridian. The position outside of the magnetosphere was used to determine the flux at the Moon when unaltered by the terrestrial magnetic field (i.e., the "solar wind" location). This location is sufficiently far enough upstream of the bow shock that the plasma is not influenced by the bow shock. The inner boundary at the Earth for calculating SEP impacts is set equal to 2.95 $R_E$.

[9] The SEPs are assumed to be hydrogen ions, initialized in a Maxwellian distribution. For the results presented in section 3, 700,000 particles where launched toward the Moon. The spatial distribution of the particles when they are launched is a box $[29.5 \times 5.9 \times 5.9]$ $R_E$. The exact

**Table 1.** Case 1: Counts Statistics for Quiet Conditions

| Case 1 | Hit Moon: Dawn | Hit Moon: Dusk | Hit Earth |
|---|---|---|---|
| 35 MeV | | | |
| Dawn | 331 | 295 | 0 |
| Tail | 0 | 14 | 6845 |
| Day | 15 | 1 | 0 |
| Dusk | 22 | 648 | 0 |
| Solar wind | 972 | | – |
| 760 MeV | | | |
| Dawn | 1303 | 0 | 0 |
| Tail | 113 | 17 | 35,307 |
| Day | 648 | 88 | 9823 |
| Dusk | 116 | 765 | 0 |
| Solar wind | 956 | | – |

**Table 2.** Case 2: Counts Statistics for Storm Conditions

| Case 2 | Hit Moon: Dawn | Hit Moon: Dusk | Hit Earth |
|---|---|---|---|
| 35 MeV | | | |
| Dawn | 1 | 1 | 783 |
| Tail | 1 | 10 | 8 |
| Day | 0 | 0 | 0 |
| Dusk | 0 | 0 | 0 |
| Solar wind | 972 | | – |
| 760 MeV | | | |
| Dawn | 1400 | 601 | 0 |
| Tail | 0 | 103 | 0 |
| Day | 9 | 26 | 9784 |
| Dusk | 7 | 4 | 15,413 |
| Solar wind | 962 | | – |

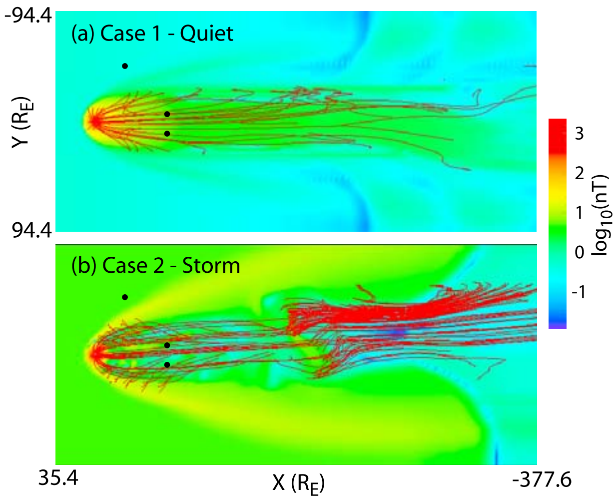


**Figure 2.** The magnitude of the magnetic field in the equatorial plane and the magnetic field lines within the Earth's magnetosphere. The black circles indicate the approximate positions in which the SEP flux was determined for the Moon. For the dawn location the coordinates of the Moon are $[x, y, z] = [-59.0, -8.85, 2.0]$ $R_E$. For the dusk position the Moon is located at $[x, y, z] = [-59.0, 8.85, 2.0]$ $R_E$.

location in which the particles were launched from varied for each case so as to maximize the number of impacts. Launching particles from a small region facilitates study of how the particles interact with structures within the magnetosphere. To get an estimate of total flux, a much larger number of particles are launched toward the Moon. For the results presented in section 4, 20 million particles were launched from each edge of the simulation grid, covering the entire extent of the grid for each edge. For both the quiet and storm cases, and all initial positions, the distribution has two different mean energies: 35.2 MeV or 759 MeV. The cases with a mean energy of 35.2 MeV will be referred to as the "low energy" cases and, the 759 MeV cases as the "high energy" cases. These two energies represent the approximate mean energy (35.2 MeV) and upper energy limit (759 MeV) for extreme SEP events like those that occurred during the Halloween 2003 storm or the January 20, 2005 event [*Mewaldt et al.*, 2005]. Additional cases were run with even higher energies in order to determine the maximum energy of SEPs that the plasmoid could deflect. In all of the cases the full width half maximum of the distribution is 30 eV. A primarily mono-energetic source was chosen so that if either acceleration or deceleration of the SEPs by magnetospheric structures occurred, its signature would be unambiguous. The particles were launched with velocities in a uniform direction in order to probe the nature of entry or deflection of the SEPs from a given direction. Relativistic effects are not included. For the 35 MeV particles, relativistic effects are negligible. For the 759 MeV particles, the larger effective mass translates to a larger gyroradius, when relativistic effects are included. Thus, these results will overpredict deflection of these particles by the magnetosphere.

## 3. Results

[10] Tables 1 and 2 show the number of particles that impact either the Moon or the Earth for each solar wind case and initial launch direction when 700,000 particles are launched at the magnetosphere. The number of particles that impact the surface of the Moon when the Moon is located within the magnetosphere is subdivided to include when the Moon was at either the dawn or dusk location in the tail. The final row lists the number of impacts at the Moon, when it was placed outside of the magnetosphere, in the solar wind. As an estimate of uncertainty, several of the cases were run with ten times the number of incident particles, launched from the same launch volume. For all the cases examined in this manner, the number of impacts increased by a factor of 10, approximately ±10%.

[11] Figures 3–6 show snapshot images of the SEPs traveling through the magnetosphere and impacting the

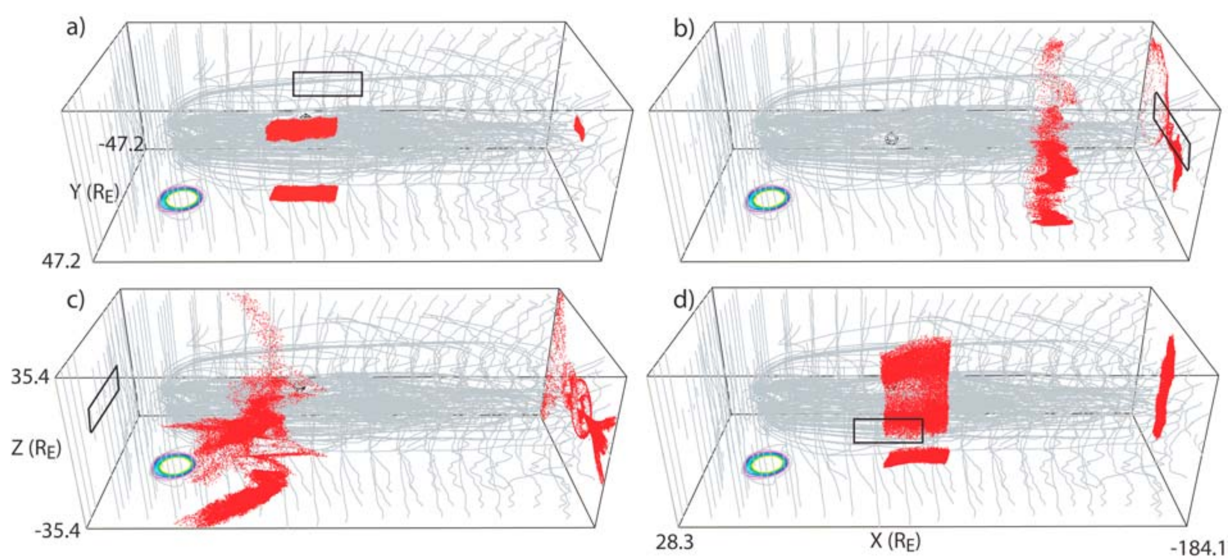


**Figure 3.** Low-energy (35.2 MeV) SEPs launched from (a) the dawnside, (b) uptail, (c) the sunward side, and (d) the duskside for the quiet magnetosphere (case 1). In Figures 3a, 3c, and 3d the Moon is at the dawn location, while in Figure 3b it is at the dusk location.

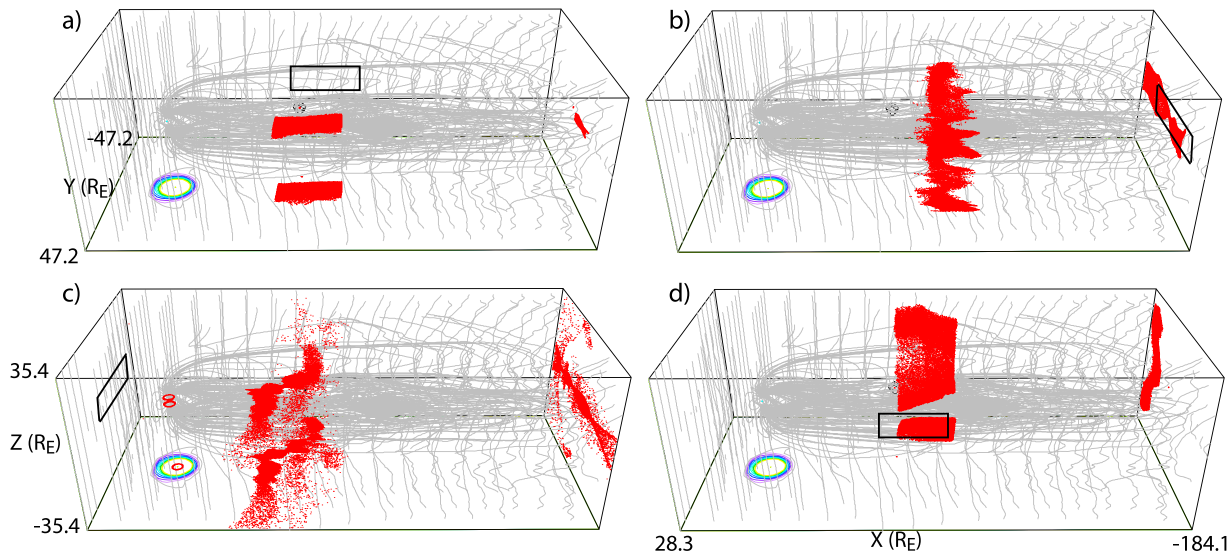


**Figure 4.** The same format as Figure 3 except for high-energy SEPs in case 1.

Moon and/or the Earth. The gray lines are magnetic field and the color contours in the lower plane are the plasma pressure. The SEPs are shown as red spots at their location within the magnetosphere, as well as in projection on the bottom and back planes. The black square indicates the projection of the approximate launch location of the SEPs. A black wire cage surrounds the region in which impacts are recorded at the Moon. It is larger than the actual surface that recorded impacts in order to emphasize the location.

### 3.1. Case 1: Quiet Conditions

[12] The flux of 35 MeV SEPs originating from the dawnside magnetopause follow a large radius cyclotron motion and transit across the magnetotail, impact the Moon and then exit on the duskside of the magnetopause $\sim$10 $R_E$ closer to the Earth along the Earth-Sun line than when they entered the magnetosphere (Figure 3a). For particles traveling from dawn to dusk, the gyromotion leads to a focusing effect. Particles both above and below the current sheet move toward the current sheet. As the gyroradius of the particles is large compared to the width of the tail, the gyromotion for particles above the current sheet is downward, and the the gyromotion for particles below the current sheet is upward. As the particles move towards the current sheet, the magnetic field becomes weaker and the gyroradius larger. Thus, the particles do not "overshoot" and cross the current sheet and instead are focused into the current sheet. This affect is most pronounced for the low-energy SEPs. Even though the particles are being focused into the current sheet, the number of impacts is smaller than the case when the Moon is in the solar wind as the Moon is situated $\sim$2 $R_E$ above the current sheet. When the Moon is moved to being within the current sheet, the number of impacts increases to 1931, more than double the number of hits when the Moon is in the solar wind. This focusing affect also means that if the Moon is above the current sheet, the number of impacts will decrease further the particles travel across the magnetotail. Thus, the number of impacts is reduced when the Moon is moved to the dusk location, above the current sheet (Table 1), or when the Moon is moved to above the plasma sheet, at $z \sim 7R_E$.

[13] The number of high-energy impacts from the dawnside, when the Moon is above the current sheet, is still larger than when the Moon is outside the magnetosphere, but the particles are only moderately focused into the current sheet. The particles have a larger gyroradius, thus fewer of the particles are below the location of the Moon, relative to the low energy case, by the time they encounter the Moon

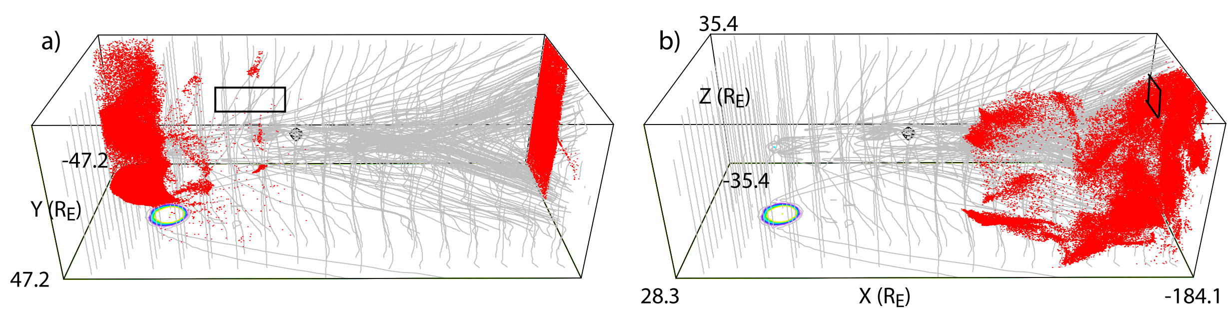


**Figure 5.** The same format as Figure 3 except for case 2. Also, the cases when the SEPs are launched from the sunward side and duskside of the magnetosphere are not shown as no particles enter the magnetosphere. Only the inner edge of the projection of the initiation region is shown in Figure 5b.

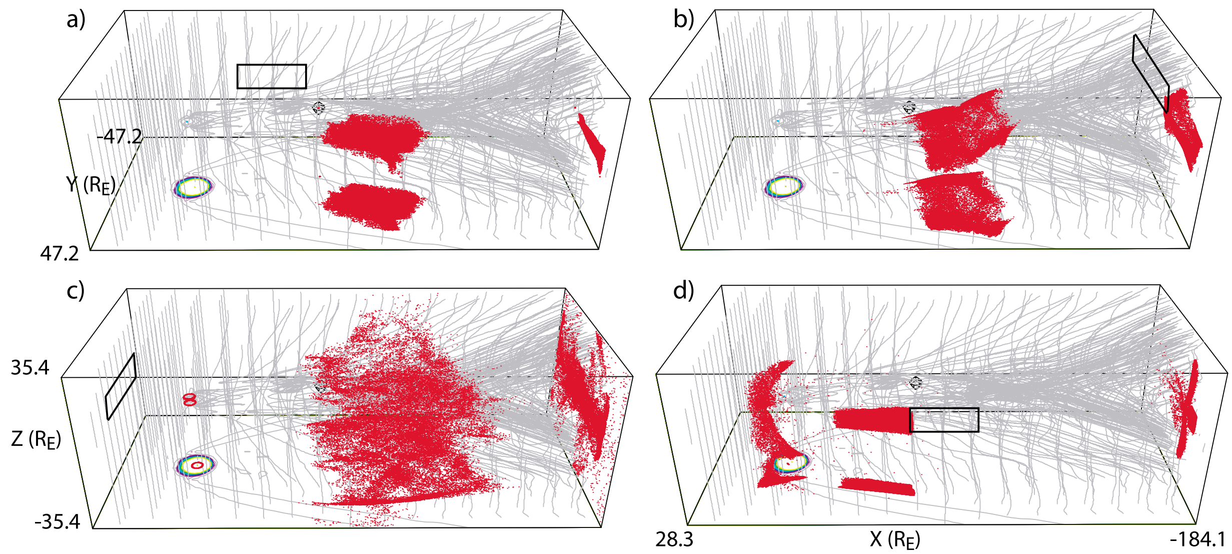


**Figure 6.** The same format as Figure 3 except for high-energy SEPs for case 2.

(Figure 4a). Moving the Moon into the current sheet still increases the number of impacts, though (to 2258).

[14] When the Moon is on the dawnside of the magnetosphere, the flux of both low- and high-energy particles entering from the duskside that impact the Moon is reduced relative to the impacts from SEPs entering from the dawnside. As the particles travel from dusk to dawn across the tail, the gyromotion of the particles about the tail magnetic field is away from the current sheet. As they move above or below the current sheet, the magnetic field becomes stronger, leading to a smaller gyroradius, causing the particles to move further away from the current sheet. This leads to a large-scale deflection of the particles away from the equatorial plane and away from the lunar orbital plane (Figure 3d). The higher-energy particles are also deflected above and below the plasma sheet, but they are deflected less than the low-energy particles as their gyroradius remains large relative to the size of the magnetosphere (Figure 4d). Thus more will remain within the plasma sheet by the time they encounter the Moon in the dawn position, resulting in an increase in the number of impacts, relative to the low energy case. As the particles move across the tail and out of the plasma sheet, the number of impacts at the Moon will decrease as the SEPs travel across the tail (and are deflected to higher latitudes). When the Moon is moved to the duskside of the midnight meridian, the number of both low-energy and high-energy impacts increases relative to when the Moon is in the dawn location, as the SEPs have not been significantly deflected out of the plasma sheet by the time they encounter the Moon. As the particles are deflected away from the plasma sheet as they cross the tail, moving the Moon to a location above the plasma sheet on the dawnside nearly doubles the number of high energy impacts. No impacts occur when the Moon is above the plasma sheet on the duskside.

[15] The Moon is partially protected from impacts by the lower-energy SEPs traveling up the tail (Figure 3b). As the particles travel up the tail, they also drift across the tail from dawn to dusk. The particles that remain in the postmidnight sector are deflected to higher latitudes as they travel up the tail, while the particles in the premidnight sector are deflected into the plasma sheet (see the projection into the back plane in Figure 3b). Here $B_y$ is the dominate component of the magnetic field not aligned with primary direction of the velocity vector (**x**). Above the current sheet $B_y$ is positive in the premidnight sector and negative in the postmidnight sector. The $B_y$ is in the opposite directions below the current sheet. This means the gyromotion of particles in the postmidnight sector is away from the current sheet, and toward the current sheet in the premidnight sector. The particles that cross from the postmidnight sector into the premidnight sector will be focused backed into the plasma sheet. Particles in the premidnight sector scatter off in the inner magnetosphere, then travel back downtail, primarily in the dusk sector of the plasma sheet. The particles in the postmidnight sector that are deflected to higher latitudes can impact the Earth as is evident by the ~1% precipitation rate (Table 1). The particles are deflected to the duskside by the crosstail electric field as they travel both up the tail and then back down after they encounter the Earth. As a result, the protection at the Moon from SEPs incident from the tail is also a function of the location of the Moon. When the Moon is at the dawn location, no particles impact the Moon as they are deflected to higher latitudes before they can impact the Moon. When the Moon is moved to the duskside, nine particles impact the nightside of the Moon as the SEPs travel up the tail (and are focused in the plasma sheet) and five impact the dayside after they interact with the inner magnetosphere and then reflect back downtail.

[16] The Moon is not protected from higher-energy SEPs traveling up the tail as these particles are not significantly deflected to the outer edge of the plasma sheet as they travel earthward due to the larger gyroradius (Figure 4b). The result is an increase in impacts at the Moon as compared to the low-energy SEPs traveling up the tail. The high-energy particles can either scatter off the inner magnetosphere and then travel back downtail on the duskside or are lost to the solar wind when they travel across the dayside magnetopause. A significant portion of the particles that scatter off the inner magnetosphere are scattered to high latitudes, out

of the plasma sheet, before they travel back downtail. Thus, the number of impacts decreases (two on the nightside and 15 on the dayside) when the Moon is moved to the duskside.

[17] Low-energy SEPs originating from the dayside are deflected around the flanks of the plasmasphere and then downtail (Figure 3c). As they travel downtail, a portion of the the SEPs impact the Moon. The particles that impact the Moon first convect around the dawnside of the plasmasphere and then travel both crosstail and downtail simultaneously. By the time the particles reach the orbital distance of the Moon, they are spread out across the entire tail so particles can also impact the Moon when it is in the dusk sector. The number of impacts at the Moon when it is in the dusk position is low as many of the particles in the vicinity of the Moon for this baseline dusk location have been scattered to high latitudes. At other locations on the duskside, the number of impacts will be higher. Moving the Moon closer to the duskside sheath increases the number of impacts to 11. High-energy particles originating from the dayside can precipitate into the polar caps at the Earth. The particles that do not precipitate then travel downtail, after having drifted around the Earth, also primarily on the dawnside, where they can then impact the Moon. The high-energy SEPs also drift across the tail as they travel down the tail. The particles are also not scattered to high latitudes to the same extent as the low energy case, thus leading to an increase in the number of impacts at both the dawn and dusk locations. Moving the Moon above the plasma sheet substantially reduces the number of impacts.

### 3.2. Case 2: Storm Conditions

[18] The storm conditions used for this work act to enhance the total protection of the Moon from SEPs. Both the formation of a plasmoid and the stronger magnetic fields in the magnetosphere increase the amount of deflection and scattering that SEPs undergo. The core magnetic field within the plasmoid is $\sim$10 nT, while the magnetic field magnitude is 1 nT, or less, tailward of the plasmoid (Figure 2b). Earthward of the plasmoid, the magnetic field is 10–15 nT within an $R_E$ above and below the current sheet at lunar radii in the tail. The magnetic field magnitude of the sheath in the equatorial plane is also 10–15 nT. For comparison, the magnetic field strength for quiet conditions at the same locations above and below the current sheet is 2–4 nT, and $\sim$1 nT in the sheath (Figure 2a). The magnetic field magnitudes in the inner magnetosphere are comparable to statistical averages [e.g., *Fairfield*, 1986], as is the core magnetic field of the plasmoid [e.g., *Moldwin and Hughes*, 1994].

[19] The stronger magnetic field strengths mean the gyroradii of the SEPs are approximately an order of magnitude smaller in the sheath for the storm case than in the quiet case. This is particularly important for the particles incident from the both the duskside and dayside. The low-energy SEPs cannot even enter the magnetosphere for either case. The high-energy particles incident from the dayside can cross the magnetopause, with 1.4% impacting the Earth. The SEPs that do not precipitate, travel downstream, at first primarily in the plasma sheet, where they can impact the Moon on the dayside, then spread out to higher latitudes as they continue past the Moon and interact with the plasmoid (Figure 6c). Some of these particles are deflected back earthward by the plasmoid. They gyrate out into the solar wind and then can reenter the magnetosphere near the Earth before being lost downtail. When the Moon is moved to the duskside, the number of impacts increases as many of the particles traveling downtail in the postmidnight midnight sector are scattered to higher latitudes by the earthward edge of the plasmoid. Most of the particles in the pre-midnight sector remain in the plasma sheet until after that pass the Moon.

[20] The high-energy particles incident from the duskside of the magnetosphere will gyrate directly towards the Earth, where they then interact with the inner magnetosphere (Figure 6d), either precipitating into the terrestrial polar caps or scattering downtail where they can impact the Moon. The particles that impact the Moon do so after they have scattered off the inner magnetosphere. When the Moon is on the duskside of the magnetosphere, the number of impacts is smaller but the reduction is not statistically significant. The flux of SEPs traveling downtail after they interact with the inner magnetosphere is roughly evenly spread out across the tail. Thus, the likelihood of impact is somewhat independent of the local time of the Moon within the tail for this case. As the particles are also scattered to high latitudes when interacting the inner magnetosphere, moving the Moon to above the plasma sheet results in a similar number of impacts as when it is in the plasma sheet.

[21] Entry of low-energy particles incident from the dawnside is greatly inhibited by the enhanced magnetic field strengths, but some does occur. The low-energy particles gyrate into the magnetosphere, experiencing two encounters with the bow shock and magnetosheath. The guiding center of the collection of particles moves sun-ward with each encounter until the third orbit where the particles encounter the dayside magnetopause and enter the magnetosphere (Figure 5a). The particles begin scattering downtail where they can then impact the Moon. Therefore, few impact Moon because of the fact that prior to entering the magnetosphere, the particles are effectively scattered high above and below the equatorial plane by the first two interactions with the bow shock and sheath. Thus, once they interact with the dayside and begin entering the magnetosphere, many of the particles are in excess of 30 $R_E$ above and below the equatorial plane (Figure 5a). Those particles remain at high latitudes once they enter the magnetosphere, and thus cannot impact the Moon. The particles are roughly evenly spread out across the tail after they are scattered to high latitudes, thus the number of impacts when the Moon is on the duskside will be similar to when the Moon is on the dawnside, both when the Moon is within the plasma sheet and when it is above the plasma sheet.

[22] The Moon is unprotected from high-energy particles entering from the dawnside of the magnetosphere. The high-energy particles can enter the magnetosphere, and once inside the enhanced magnetic field magnitudes lead to focusing of the particles as they travel across the plasma sheet, similar to the focusing that occurs when low-energy particles enter from the dawnside for the quiet conditions (Figure 6a). The high-energy SEPs entering from the dawnside for storm conditions will also travel downtail due to gyromotion, but because of the focusing effect, travel primarily in the plasma sheet where they can impact the

**Table 3.** Number of Impacts at the Moon When 120 Million Particles Launched Toward the Moon[a]

| | Impacts |
|---|---|
| 35 MeV | |
| Quiet (case 1) | 807 |
| Storm (case 2) | 511 |
| Outside | 688 |
| 760 MeV | |
| Quiet (case 1) | 1078 |
| Storm (case 2) | 174 |
| Outside | 921 |

[a]Cases 1 and 2 are when the Moon is in the dusk sector of the magnetosphere, above the plasma sheet.

Moon. The particles then interact with the plasmoid and are deflected to high latitudes, where they exit the magnetopause and are lost to the solar wind out of the dawnside of the magnetosphere far downtail. When the Moon is moved to the duskside of the magnetosphere, the number of impacts from high-energy particles decreases. As the motion of the particles is both downtail and across the tail due to the gyromotion, only the sunward edge of the particle stream impacts the Moon. Moving the initial launch position of the SEPs sunward increases the number of impacts when the Moon is on the duskside to 1797, as the particle stream is centered around the Moon.

[23] For the storm case, Moon is protected from both lower and higher energy SEPs traveling up the tail when it is in the dawn sector due to the formation of the plasmoid (Figure 1b). The SEPs experience little deflection prior to encountering the plasmoid due to the weak magnetic field, but once they encounter the plasmoid, they are all deflected to the duskside of the magnetosphere (Figures 5b and 6b). The plasmoid is very effective at deflecting SEPs to the duskside of the magnetosphere as they travel earthward, so much so that not only is the Moon protected from the SEPs, the Earth is also protected. The maximum energy of SEPs that experiences the duskward deflection is $\sim$1.5 GeV. Particles with a mean energy above this can punch through the plasmoid and impact both the Moon and the Earth. As the SEPs are deflected to the duskside, the Moon is not protected when it is in the dusk sector.

## 4. Cumulative Impact

[24] To determine any net shielding by the magnetosphere, 20 million particles were also launched toward the Moon from each edge of the simulation grid (thus a total of 120 million particles) when the Moon was both inside and outside the magnetosphere. Table 3 shows the count statistics of the total number of impacts for both solar wind cases and energy ranges. When inside the magnetosphere, the Moon was in the dusk sector, above the plasma sheet. When outside, the location of the Moon within the simulation grid remained the same, but the ambient magnetic field was reduced by a factor of 0.001.

[25] For the quiet magnetosphere (case 1), more high-energy particles impact the Moon when it is inside the magnetosphere as opposed to when it is outside. This is entirely because of the fact that particles incident from the tail scatter off the inner magnetosphere back toward the Moon. The flux from all other directions is reduced when the Moon is in the magnetosphere, with the largest reductions for particles incident from the dayside (a 92% reduction in impacts). The enhancement due to backscatter of particles initially traveling up the tail is dependent on the location of the Moon, though. When the Moon is in the dusk location, the number of impacts while in the magnetosphere from particles incident from the tail is 3.1 times larger than when the particles do not backscatter off the inner magnetosphere. The enhancement in impacts due to backscatter reduces to 1.7 when the Moon is at a dawn location.

[26] The number of impacts of low-energy particles for case 1 is also larger when the Moon is within the magnetosphere. Particles incident from the tail still backscatter off the inner magnetosphere, but for low-energy particles this does not lead to an enhanced flux relative to when no particles backscatter. When the Moon is in the magnetosphere, the number of impacts from particles initially incident from the tail is reduced by 23% when the Moon is in the dusk sector and 99% when the Moon is in the dawn sector. For low-energy particles, the enhanced flux while the Moon is in the magnetosphere is due to particles incident from the dawnside. For both high and low energies, the particles incident from the dawnside scatter off the inner magnetosphere and move downtail, but in the case of the high-energy particles, the particles penetrate further into the magnetosphere before they scatter, leading to and reduction in impacts at the Moon relative, for the dusk location, to when the Moon is outside the magnetosphere. For low-energy particles, this scattering leads to an 3.4 more impacts when the Moon is within the magnetosphere.

[27] The larger magnetic field strengths for the storm-time magnetosphere (case 2) means that the number of both high- and low-energy impacts is reduced when the Moon is with in the magnetosphere. The reduction is smaller for the low-energy particles, even though few particles enter from the dayside or the dawn and dusk flanks, due to an enhanced number of impacts for particles incident from above and below the ecliptic plane. The largest enhancement is from particles incident from above the ecliptic plane. These particles travel parallel to the IMF and then scatter off the plasmoid. The particles gyrate into the magnetosphere after they scatter, becoming temporarily trapped, as they undergo multiple gyrations within the magnetosphere before they exit once again and are lost to the solar wind. Those particles originating from the dusk sector impact the Moon, while trapped. The larger gyroradius of the high-energy particles means they do not become trapped within the magnetosphere, after they scatter off the plasmoid, and thus no enhancement in impacts for high-energy particles from above the ecliptic plane occurs.

[28] These results are in agreement with some of the results from the previous work [*Winglee and Harnett*, 2007] that used the integrated magnetic field along a straight path to estimate that some geographic locations on the Moon would be protected from galactic cosmic ray flux. Both indicate that stronger total magnetic field strengths will lead to greater protection. The previous results also indicated that the dawnside (or duskside) of the Moon is the least protected when the Moon is in the dawn (dusk) sector. For example, in the case when 120 million particles are

launched toward the Moon, the reduction in high-energy particles incident from the duskside because of the Moon being within a quiet magnetosphere (case 1) is 7% when the Moon is in the dusk sector, but 82% when it is in the dawn sector. But the previous method indicated that the Earth-facing side of the Moon is the most protect region and the farside of the Moon would experience moderate exposure. The particle tracking results show that, a shadow is present for particles incident from the dayside, scattering of SEPs off the inner magnetosphere eliminates the shadow of protection on the Earth-facing side previously predicted. The previous method also could not capture how effective plasmoids can be in deflecting SEPs.

[29] These results do not agree with assertion by *Huang et al.* [2009] that particles with energies equal to 1 MeV or greater will undergo little or no deflection by the terrestrial magnetic field outside of the innermost portion of the magnetosphere. An issue with the results by *Huang et al.* [2009] is that a 1 MeV particle will have a gyroradius of $\sim 2\ R_E$ in the lobe (assuming 10 nT magnetic field). This is much smaller than the scale size of the lobes, and thus a 1 MeV particle will undergo deflection within the lobe. Further discussion can be found in the work of R. M. Winglee and and E. M. Harnett (Comment on assessing access of galactic cosmic rays at Moon's orbit, submitted to *Geophysical Research Letters*, 2009).

[30] While the storm conditions may offer more protection from SEPs, those particles that do impact the Moon will have a slightly higher energy than for quiet conditions. The initial energy distribution of the particles is identical for both the quiet and storm conditions. Using the set of cases analyzed in section 3 as the basis for analysis, the mean energy of the high-energy SEPs that impact the Moon for case 1 (when considering both dusk and dawn locations) is 759 MeV with a standard deviation of 1.2 MeV. The mean energy of the impacts for case 2 is 764 MeV with a standard deviation of 1.7 MeV. In both cases the mean energy of the particles impacting the Moon when it is in the dusk sector is $\sim$1 MeV higher than (but within 1 sigma of) the mean energy of the impactors when the Moon is in the dawn sector. This behavior of higher-energy impactors for storm conditions remains true for the low-energy SEPs that impact the Moon as well. The mean energy of the low-energy SEPs that impact the Moon for both dawn and dusk locations combined is 35.2 MeV (±0.1 MeV) in case 1 and 35.7 MeV (±0.4 MeV) in case 2. The low statistics of low-energy particle impacts in case 2 makes the difference less significant than in the high energy case.

## 5. Conclusions

[31] The results from particle tracking studies show that structures within the terrestrial magnetosphere can deflect SEP-type particles with mega electron volts of energies away from regions in which the Moon orbits. The deflection is most pronounced for storm conditions. The protection for storm conditions comes from two sources. Impacts incident from the dayside or dawn and dusk terminators are greatly reduced as the increased magnetic field magnitudes in the sheath inhibits entry of SEPs into the magnetosphere. Impacts from SEPs traveling up the tail are deflected by the formation of a plasmoid and the enhanced magnetic field in the core. The plasmoid does not act to completely reduce flux from all directions, though. Lower-energy articles incident from above and below the ecliptic plane can be scattered by the plasmoid into the magnetosphere, thus enhancing the flux at the Moon. This partially confirms earlier work by *Winglee and Harnett* [2007] that indicated that the case with the strongest magnetic field magnitude within the magnetosphere resulted in the most protection at the Moon.

[32] At some locations the flux of SEPs will be enhanced, though. This enhanced flux can be due to scattering of particles toward the Moon. It also occurs when the gyroradius of the particles is large compared to the size of the magnetosphere and the direction of the particle velocity leads to gyromotion directed toward the current sheet. During these times, the largest number of impacts will occur when the Moon is closest to the current sheet. This focusing also occurs primarily for SEPs incident from the dawnside of the magnetosphere, though it also occurred in a portion of the magnetotail for SEPs traveling up the tail. *Hapgood* [2007] has shown that because of the 5° inclination and precession of the Moon's orbit around the Earth, the average time the Moon spends within the plasma sheet will vary with an 18 year cycle, the last peak occurring in 1999. Flapping of the plasma sheet due to dynamics of the tail will add a short times scale variability to this long-term average. Although the results are for two specific set of solar wind conditions, the types of structures within the magnetosphere that can modify particle trajectories, such as a plasmoid or the current sheet, make the conclusions applicable to a wide range of cases as the current sheet is always present and plasmoids form for a variety of changes in the IMF.

[33] Besides the direct hazard of SEP exposure (e.g., electronics failure due to catastrophic memory upsets, and biological damage from ionizing radiation) *Halekas et al.* [2009] have shown that SEPs incident at the Moon, while it is in the solar wind, can lead to large negative surface potentials on the nightside (magnitude > kilovolts). They are far larger than typical nightside potentials when the Moon is in the solar wind or when it is in the current sheet, both of which are on the order of a hundreds of volts negative [*Halekas et al.*, 2005]. Large surface potentials can lead to electrostatic discharge and enhance dust transport. The magnetosphere may offer protection during periods when SEP exposure may be high and the average time the Moon spends in the plasma sheet will be low. This would represent a time when that hazards associated with both focusing of SEPs to lunar locations and surface charging would both be minimized, relative to when the Moon is in the solar wind. This may be observed by future lunar missions. The next solar maximum is predicted to occur around 2012, which will be when the average time the Moon spends in the plasma sheet is predicted to be near a minimum [*Hapgood*, 2007].

[34] The results have impact regarding the location of future lunar bases. The South Pole-Aitkins basin region in the southern portion of the farside of the Moon has been suggested as a potential site for a lunar base because of its proximity to geologically interesting areas, high crater rims for positioning solar arrays, and the possibility of ice deposits [e.g., *Staehle et al.*, 1993; *Vondark and Crider*,

2003]. This work suggests that an additional advantage for this region is that the SEPs flux may be a minimized at this location while the Moon is within the terrestrial magnetosphere as compared to other locations on the Moon. But to be certain, the next step in the work would be to model an actual SEP events. This would require a much larger number of particles incident from all directions, with a representative spread in energies.

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## References

Fairfield, D. H. (1986), The magnetic field of the equatorial magnetotail from 10 to 40 $R_E$, *J. Geophys. Res.*, *91*, 4238–4244.

Gaisser, T. K. (1990), *Cosmic Ray and Particle Physics*, Cambridge Univ. Press, Cambridge, U. K.

Halekas, J. S., R. P. Lin, and D. L. Mitchell (2005), Large negative lunar surface potentials in sunlight and shadow, *Geophys. Res. Lett.*, *32*, L09102, doi:10.1029/2005GL022627.

Halekas, J. S., et al. (2009), Lunar surface charging during solar energetic particle events: Measurement and prediction, *J. Geophys. Res.*, *114*, A05110, doi:10.1029/2009JA014113.

Hapgood, M. (2007), Modeling long-term trends in lunar exposure to the Earth's plasmasheet, *Ann. Geophys.*, *25*, 2037–2044.

Huang, C.-L., H. E. Spence, and B. T. Kress (2009), Assessing access of galactic cosmic rays at Moon's orbit, *Geophys. Res. Lett.*, *36*, L09109, doi:10.1029/2009GL037916.

Mewaldt, R. A., et al. (2005), Solar-particle energy spectra during the large events of October-November 2003 and January 2005, paper presented at 29th International Cosmic Ray Conference, Tata Inst. of Fundam. Res., Pune, India.

Moldwin, M., and W. Hughes (1994), Observations of earthward and tailward propagating flux rope plasmoids: Expanding the plasmoid model of geomagnetic substorms, *J. Geophys. Res.*, *99*, 183–198.

Reames, D. V., L. M. Barbier, and C. K. Ng (1996), The spatial distribution of particles accelerated by coronal mass ejection-driven shocks, *Astrophys. J.*, *466*, 473–486.

Robbins, D. E. (1997), The space radiation environment, in *National Council on Radiation Protection Symposium Proceedings, No. 3: Acceptability of Risk from Radiation—Application to Human Space Flight*, pp. 5–32, Natl. Counc. on Radiat. Prot. and Meas., Bethesda, Md.

Staehle, R. L., et al. (1993), Lunar base siting, *Spaceflight*, *35*, 402.

Winglee, R. M. (2003), Circulation of ionospheric and solar wind particle populations during extended southward interplanetary magnetic field, *J. Geophys. Res.*, *108*(A10), 1385, doi:10.1029/2002JA009819.

Winglee, R. M. (2004), Ion cyclotron and heavy ion effects on reconnection in a global magnetotail, *J. Geophys. Res.*, *109*, A09206, 10.1029/2004JA010385.

Winglee, R. M., and E. M. Harnett (2007), Radiation mitigation at the Moon by the terrestrial magnetosphere, *Geophys. Res. Lett.*, *34*, L21103, doi:10.1029/2007GL030507.

Vondark, R. R., and D. H. Crider (2003), Ice at the lunar poles, *Am. Sci.*, *91*, 322–329.

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