RESEARCH ARTICLE

10.1002/2014JA020938

Key Points:

- Reflected protons produced by solar wind/lunar magcon interaction
- Reflected protons exist over a scale larger than magcon
- Simulations generally agree well with observations

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Citation:

Giacalone, J., and L. L. Hood (2015), Hybrid simulation of the interaction of solar wind protons with a concentrated lunar magnetic anomaly, *J. Geophys. Res. Space Physics*, 120, 4081–4094, doi:10.1002/2014JA020938.

Received 11 DEC 2014

Accepted 29 APR 2015

Accepted article online 7 MAY 2015

Published online 3 JUN 2015

Hybrid simulation of the interaction of solar wind protons with a concentrated lunar magnetic anomaly

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Abstract Using a two-dimensional hybrid simulation, we study the physics of the interaction of the solar wind with a localized magnetic field concentration, or “magcon,” on the Moon. Our simulation treats the solar wind protons kinetically and the electrons as a charge-neutralizing fluid. This approach is necessary because the characteristic scale of the magcon is of the same order or smaller than the proton inertial length—the characteristic scale in the hybrid simulation. Specifically, we consider a case in which the incident solar wind flows exactly normal to the lunar surface, and the magcon is represented by a simple dipole whose moment is parallel to the surface, with a center just below it. We find that while the magcon causes the solar wind to be deflected and decelerated, it does not completely shield the lunar surface anywhere. However, protons which impact the surface in the center of the magnetic anomaly have energies well below the solar wind ram energy. Thus, in this region, any backscattered neutral particles resulting from the interaction of solar wind protons with the lunar regolith would have energies lower than that of the solar wind. Moreover, very few neutrals, if any, would emanate from within the magcon with energies comparable to the solar wind energy. This may explain recent observations of lunar energetic neutral atoms associated with a strong crustal magnetic anomaly. Our study also finds that a significant fraction of the incoming solar wind protons are reflected back into space before reaching the surface. These particles are reflected by a strong electrostatic field which results from the difference in the proton and electron inertia. The reflected particles are seen at very high altitudes above the Moon, over 200 km, and over a much broader spatial scale than the magcon, several hundred kilometers at least. Our simulation also revealed a second population of reflected particles which originate from the side of the magcon where the interplanetary and magcon magnetic fields are directed opposite to one another, leading to a magnetic topology much like magnetic reconnection. As previously reflected particles move through this region, they are deflected upward, away from the surface, forming a second component. Our simulation has a number of similarities to recent in situ spacecraft observations of reflected ions above and around magcons.

1. Introduction

While our Moon does not possess a large global-scale magnetic field such as that of the Earth, Mercury, and the gas giant planets, it does have localized magnetic fields near its surface due to permanent magnetization in its upper crust [e.g., Hood, 2015]. These magnetic concentrations, or magcons, have field strengths that are considerably larger than the average interplanetary magnetic field at 1 AU [Dyal et al., 1974; Halekas et al., 2001; Hood et al., 2001; Mitchell et al., 2008]. It has been known for some time that magcons may present a barrier to the penetration of solar wind in the lunar regolith [Hood and Schubert, 1980]. The shielding of the solar wind over small regions on the Moon may be also related to surface albedo features such as lunar “swirls,” which are seen to be coincident with magcons [e.g., Hood et al., 1979; Blewett et al., 2011].

In situ measurements by instruments on Lunar Prospector reported the first observations of a density cavity in the solar wind plasma above a concentrated lunar magnetic anomaly which suggested the presence of a lunar “minimagnetosphere” [Halekas et al., 2008]. Later, high-resolution observations of backscattered neutral atoms from the Moon revealed the existence of a minimagnetosphere spatially coincident with a magcon. Chandrayaan-1/Sub-keV Atom Reflecting Analyzer (SARA) observations of 0.15–0.6 keV neutral atoms emanating from the Moon showed a significant depletion at the center of a magcon [Wieser et al., 2010]. The solar wind ram energy was within this energy range during the observation period strongly suggesting that the surface in the vicinity of the magcon was not impacted by solar wind ions of this energy. In contrast, Wieser et al. [2010] noted that there was an enhancement of lower energy (0.03–0.15 keV) neutral atoms emanating

from both within and around the magcon, consistent with the deceleration and deflection of solar wind ions by the strong magnetic field there.

The physics involved in the interaction of the solar wind with magcons is a problem of considerable interest. The solar wind standoff distance, H_{so} , can be estimated using ideal MHD by balancing the magnetic pressure of the magcon with the solar wind dynamic pressure. For typical parameters, one finds H_{so} to be ~ 50 km or so. This is comparable to the gyroradius of a proton moving with the solar wind speed U_{sw} in a field associated with the magcon at the surface, as noted in the review by *Halekas et al.* [2011]. The gyroradius of a solar wind proton in the weaker interplanetary magnetic field (IMF) far from the Moon is even larger still. Ideal MHD only applies when the scales of interest are much larger than the gyroradii of the particles, which is not the case here. Thus, kinetic physics must be included to adequately model the solar wind interaction with a lunar magnetic field. *Kallio et al.* [2012] performed three-dimensional, fully kinetic plasma simulations and found that solar wind ions are deflected toward the sides of the magcon, forming a “halo” around it, which may explain the backscatter of low-energy neutral atoms by *Wieser et al.* [2010]. Another recent kinetic simulation performed by *Poppe et al.* [2012] noted that the so-called “cusp” region of the magcon may provide direct access of solar wind to the surface. *Deca et al.* [2014] also used a fully kinetic simulation and found that small scales associated with strong electron pressure anisotropies can result in the minimagnetosphere being unstable over time. They suggested that the shielding of the solar wind at the lunar surface by the magcon was not uniform and steady but is variable.

A rather straightforward extension of ideal MHD is to include the Hall effect, which arises because of the difference in inertia of the electrons and protons in a plasma. As a rather simple illustrative example, consider the conservation of momentum of a collection of electrons by neglecting their inertia and any forces related to the resistivity of the ions. The resulting equation gives

$$\mathbf{E} = -\frac{1}{c}\mathbf{v}_e \times \mathbf{B} - \frac{1}{n_e}\nabla P_e \quad (1)$$

where $\mathbf{E}$ is the electric field, $\mathbf{v}_e$ is the average electron speed, $\mathbf{B}$ is the magnetic field, n_e is the electron number density, and P_e is the electron pressure. Noting that the current density is defined $\mathbf{J} = e(n_i\mathbf{v}_i - n_e\mathbf{v}_e) = (c/(4\pi))\nabla \times \mathbf{B}$ and by taking the condition of quasi-neutrality, $n_i = n_e = n$, we obtain

$$\mathbf{E} = -\frac{1}{c}\mathbf{v}_i \times \mathbf{B} + \frac{1}{4\pi ne}(\nabla \times \mathbf{B}) \times \mathbf{B} - \frac{1}{n}\nabla P_e \quad (2)$$

The first term on the right is the usual motional electric field of ideal MHD, and the second term on the right is the Hall term. The Hall term is important when the scale of the problem is of the same order or smaller than the proton inertial length. The term can be separated into components associated with magnetic pressure and magnetic tension. Because the magnetic field of the magcon near the lunar surface is nearly parallel to the surface (at the center), the magnetic pressure gradient dominates, leading to a significant electric field, directed upward and normal to the surface. This field is explicitly shown in the diagram of *Saito et al.* [2012, Figure 7] for the case of the solar wind/magcon interaction. A recent three-dimensional hybrid simulation reported by *Jarvinen et al.* [2014] has shown that the magnitude of this electric field is consistent with spacecraft observations [*Saito et al.*, 2012; *Futaana et al.*, 2013]. This electric field plays a critical role in the reflection of a fraction of the incident protons back into space, away from the Moon, before reaching the surface. Such reflected ions have been seen in situ by spacecraft in orbit above magnetic field concentrations on the Moon [*Futaana et al.*, 2003; *Saito et al.*, 2008, 2012]. The ion-reflection process is very similar to that which produces specularly reflected ions near collisionless shock waves such as Earth's bow shock [e.g., *Asbridge et al.*, 1968; *Gosling et al.*, 1978; *Leroy et al.*, 1981]. These reflected ions possibly play a role in the growth of electromagnetic fluctuations in the plasma environment above lunar magcons [*Tsugawa et al.*, 2011, 2012; *Halekas et al.*, 2013].

The last term in equation (2), associated with a gradient in the electron pressure, also contributes to the electric field. For the simulation presented in this study, however, this term is considerably smaller than that associated with the Hall term. This is because we assume that the electrons behave adiabatically, which is reasonable when variations in the field are on scales larger than the thermal electron gyroradius. This is indeed the case for our simulation which has a characteristic length scale of the order of the ion inertial length. Simulations in which the electrons are also treated kinetically, such as those performed by *Deca et al.* [2014], have shown that electron pressure gradients associated with the solar wind/magcon interaction can be large enough that this term is very significant.

The purpose of this paper is to study the ion-kinetic physics of the interaction between the solar wind and a localized, crustal magnetic anomaly. We perform a numerical simulation which treats protons kinetically and electrons as a charge-neutralizing fluid. This approach is adequate for studying processes occurring on scales associated with the protons. Our work is similar to that of other recent kinetic simulations [Kallio *et al.*, 2012; Poppe *et al.*, 2012], but our focus is primarily on the physics involved in the creation of reflected solar wind protons and their properties in the plasma environment near the magcon. We also examine carefully the properties of the protons incident on the lunar surface. Some of our conclusions are consistent with the results of these previous studies, but we also present some new results which give new insights.

2. Numerical Model

We utilize the self-consistent “hybrid” simulation which treats solar wind protons kinetically and the electrons as a massless charge-neutralizing fluid. This approach is ideal for studying processes on scales comparable to the proton inertial length, which is similar to the scale of a large lunar magcon. Electron kinetic effects may also be important for scales smaller than the proton inertial length, but we do not consider such effects here.

The basic algorithm and governing equations of the hybrid simulation are discussed in considerable detail elsewhere [see Winske and Omidi, 1996, and references therein], but here we describe some salient details of our method.

We assume a two-dimensional spatial domain in the x - z plane. The lunar surface is defined at $x = x_{\max}$ and $-z_{\max}/2 < z < z_{\max}/2$. Solar wind plasma initially flows normal to this surface with a speed U_{sw} and is injected continuously at the side of the domain opposite to the lunar surface at $x = 0$. Plasma moments and fields are functions of x and z only.

For our study, electric and magnetic fields associated with the solar wind/magcon interaction are determined from the vector potential $\mathbf{A}$. This ensures that the divergence of the magnetic field is zero everywhere in the simulation domain, including the boundaries.

We solve the following equations for the vector potential and the component of the magnetic field out of the plane of the simulation:

$$\frac{\partial A_y(x, z, t)}{\partial t} = -cE_y(x, z, t) \quad (3)$$

$$\frac{\partial B_y(x, z, t)}{\partial t} = -c \left(\frac{\partial E_x(x, z, t)}{\partial z} - \frac{\partial E_z(x, z, t)}{\partial x} \right) \quad (4)$$

The x and z components of the magnetic field are obtained from $\mathbf{B} = \nabla \times A_y \hat{y}$.

The electric field appearing in equations (3) and (4) is obtained from the electron (fluid) momentum equation by assuming the electrons have no inertia. This is given by equation (2), plus an additional term representing the macroscopic coupling between the electrons and ions, $\eta \mathbf{J}$, where η is the phenomenological resistivity. This term helps damp high-frequency fluctuations that form near the surface boundary ($x = x_{\max}$) in our calculation. It is commonly used in hybrid simulations, particularly of the physics of collisionless shocks [e.g., Winske and Omidi, 1996]. Equation (2) (+ $\eta \mathbf{J}$) provides means of determining the electric field from the proton bulk velocity, which is determined from the first moment of the proton distribution. Note that the proton motions are determined by numerically integrating their equations of motion, which includes both the electric and Lorentz forces. We use a very large number of protons to ensure reasonable statistical accuracy. Finally, we assume that the electrons behave adiabatically so that $P_e \propto n^{5/3}$, where n is determined from the zeroth moment of the proton distribution.

The initial magnetic field in our model is a combination of two separate fields: one carried into the lunar surface with the solar wind, and another representing the lunar magnetic anomaly. The field carried with the solar wind is assumed constant and makes an angle of 225° with the surface, which is consistent with the angle between the average Parker spiral magnetic field and solar wind velocity vector at 1 AU. Table 1 shows the assumed parameters for our simulation. The values are consistent with those observed in the solar wind

Table 1. Simulation Parameters^a

n_p	2cm^{-3}
B_{IMF}	4 nT
U_{sw}	$3 \times 10^7 \text{ cm/s}$
$\beta_{e,\text{sw}}$	0.36
$\beta_{p,\text{sw}}$	0.18
m_{dipole}	$7.5 \times 10^{16} \text{ G cm}^3$
D_{dipole}	$4.2 \times 10^6 \text{ cm}$
ω_p	1861.89 s^{-1}
Ω_p	$\Omega_p = 0.383 \text{ s}^{-1}$
c/ω_p	$1.61 \times 10^7 \text{ cm}$
$V_{A,\text{sw}}$	$6.17 \times 10^6 \text{ cm/s}$
$M_{A,\text{sw}}$	$U_{\text{sw}}/V_{A,\text{sw}} = 4.86$
$\eta_p U_{\text{sw}}$	$6 \times 10^7 \text{ cm}^{-2} \text{ s}^{-1}$

^a n_p is the ambient solar wind proton number density, B_{IMF} is the ambient interplanetary magnetic field strength, U_{sw} is the solar wind speed, $\beta_{e,\text{sw}}$, $\beta_{p,\text{sw}}$ are the ratios of the electron and proton thermal pressure to the ambient interplanetary magnetic field pressure, respectively, m_{dipole} is the dipole moment of the magcon, D_{dipole} is the depth below the lunar surface to the center of the magcon dipole, Ω_p is the proton cyclotron frequency, c/ω_p is the proton inertial length, and $V_{A,\text{sw}}$ is the Alfvén speed in the ambient solar wind.

near 1 AU on 17 June 2009, when the spacecraft Chandrayaan-1 flew above a lunar magcon and measured energetic neutral atoms backscattered from the lunar surface with SARA [Wieser *et al.*, 2010]. The lunar magcon is modeled as a dipole field whose center is located just below the surface. The assumed dipole strength and location of its center below the surface are also given in Table 1. We note that our chosen values are representative of a particular situation on the Moon which occurred during a particular time period, but the general conclusions from our analysis are robust to minor changes in these values.

Other simulation parameters are as follows: $x_{\text{max}} = 3c/\omega_p$, $z_{\text{max}} = 6c/\omega_p$, where c/ω_p is the proton inertial length, $N_x = 960$, and $N_z = 1920$, where $N_{x,z}$ is the number of grid cells in the x and z direction, respectively. For the assumed values given above, this corresponds to a region of $483 \times 966 \text{ km}$. The assumed electron ($\beta_{e,\text{sw}}$) and proton ($\beta_{p,\text{sw}}$) plasma

beta, which are the ratio of the electron and proton thermal pressures to the magnetic pressure, are 0.36 and 0.18, respectively, and the anomalous resistivity is $5 \times 10^{-5} 4\pi\omega_p^{-1}$, where ω_p is the proton plasma frequency in the ambient solar wind. We assume a time step of $10^{-5} \Omega_p^{-1}$, where Ω_p is the proton cyclotron frequency in the ambient interplanetary magnetic field, and advance the simulation forward in time for 72,000 time steps or a total time of about 0.2 s of real time using the values given above. There is nothing special about our choice of the maximum simulation time; results presented in this paper are not significantly different if the simulation were run longer. We also use 125 simulation particles per grid cell.

All kinetic particles incident on the lunar surface are assumed to be absorbed. Moreover, we assume that the total current density is zero at the lunar surface. The boundaries at the sides of the simulation ($z = -z_{\text{max}}/2$ and $z = +z_{\text{max}}/2$) are assumed to be “open” in that any flow crossing one of them leaves the system. We inject new solar wind particles at the inflow boundary, as well as at the sides of the simulation domain, to ensure that the appropriate (constant) solar wind flux is maintained.

Because of the reduced dimensionality of our simulation, the component of the canonical momentum in the ignorable direction is conserved. This has the consequence that all protons are unphysically forced to remain within one gyroradius of the field line on which it starts its motion [e.g., Jokipii *et al.*, 1993; Jones *et al.*, 1998]. It is not likely that this limitation will have much of an effect on our conclusions since the scale of the simulation domain is of the same order as the gyroradii of the particles of interest. Moreover, it has been noted in simulations of shocks using a reduced dimensionality that the downstream distribution of heated ions across the shock is different in the directions perpendicular and parallel to the magnetic field. Three-dimensional simulations show the temperature distribution to be more isotropic. We do not expect this to play a role in our case since no shock is formed in our calculation. There may be other issues related to our assumed reduced dimensionality, but there is no obvious reason to suspect that our primary results and conclusions will be much different than if we performed a fully three-dimensional simulation.

3. Simulation Results

Figure 1 shows the solar wind flux, normalized to the ambient flux that is injected into the system, for a portion of the simulation domain. We note that the vertical axis on this plot corresponds to the height above the lunar surface, h . h is related to the simulation coordinate x by $h = x_{\text{max}} - x$. The color code scale, shown at the right of the figure, is such that blue represents a 25% depletion of the flux relative to the ambient value, and

Figure 1. Solar wind flux over a portion of the simulation domain, normalized to the ambient solar wind flux. The color code legend is at the right. Deep blue represents values of the flux that are less than 25% of the ambient value, and deep red are values greater than 50% of the ambient value. The black lines are magnetic lines of force which show both the interplanetary magnetic field and lunar magcon. Far from the magcon, the magnetic field points toward the upper left of the figure, as indicated. Near the magcon itself, the field is directed toward the left ($-z$ direction), as indicated. The vertical axis, h , is the height above the lunar surface which is related to the simulation coordinate, x , by $h = x_{\text{max}} - x$. Note the solar wind flux depletion at the center of the magcon and the enhancements on either side of it.

depletion at the center of the magcon is also partly the result of the deflection of the protons; however, in addition, the enhanced magnetic field above the magcon, with a length scale comparable to the proton inertial length, leads to a significant electrostatic field (see section 1) that decelerates the protons and reduces the flux striking the surface. This is discussed further below.

Figure 2 shows the solar wind flux (bottom), magnetic field strength (middle), and two components of the magnetic field vector (top) at $x = x_{\text{max}}$ ($h = 0$), the lunar surface, as a function of the horizontal distance along

Figure 2. Various simulation parameters at the lunar surface as a function of horizontal distance. The center of the magcon is located at $z = 0$. (top) Components of the magnetic field vector in the simulation plane. The solid line is the vertical or h component of the magnetic field (which is related to $B_x = -B_h$), and the dashed line is the horizontal or z component. (middle) The magnitude of the magnetic field. (bottom) The total proton flux striking the lunar surface, normalized to its ambient value, far from the magcon.

red is a 50% increase. Several representative magnetic field lines are also shown. These are contours of the y component of the vector potential. The magnetic anomaly is clearly evident as the mini-magnetosphere at the bottom center of the plot. There is a significant depletion of solar wind flux inside the magnetic anomaly, but, as is shown in Figure 2, the flux does not vanish. Moreover, there are enhancements in the plasma flux on either side of the anomaly. This was also noted by Kallio *et al.* [2012] who referred to this as a halo region around the magcon. The physical interpretation for this enhancement is that solar wind protons that are directed toward the center of the magcon are deflected by the enhanced magnetic field toward the sides of the magcon and add to the ambient flux of protons striking the surface there. The

depletion at the center of the magcon is also partly the result of the deflection of the protons; however, in addition, the enhanced magnetic field above the magcon, with a length scale comparable to the proton inertial length, leads to a significant electrostatic field (see section 1) that decelerates the protons and reduces the flux striking the surface. This is discussed further below.

Figure 2 shows the solar wind flux (bottom), magnetic field strength (middle), and two components of the magnetic field vector (top) at $x = x_{\text{max}}$ ($h = 0$), the lunar surface, as a function of the horizontal distance along the surface. The center of the magcon is located at $z = 0$. Note that where the magnetic field is the strongest, the solar wind flux is the lowest. We note, however, that the flux is not zero, indicating that solar wind protons impact the surface in this region. The flux depletion at the center of the magcon is about a factor of 4. Note also that there are 30–50% enhancements in the flux peaking about ~ 30 km on either side of the magcon. This is the halo discussed above.

Figure 3 (top) shows the kinetic energy for all protons that impact the surface at $x = x_{\text{max}}$ ($h = 0$) as a function of distance along the surface. In this plot, we used only particles absorbed by the surface late in the simulation between $0.68 < \Omega_p t < 0.72$ when the flux at the surface was no longer changing with time. Note that within the magcon ($-30 \text{ km} < z < +30 \text{ km}$), the particles that strike the surface have significantly lower energy than those impacting the surface far from the magcon. This indicates that solar wind protons are significantly decelerated, as expected. Figure 3 (bottom) shows the

Figure 3. (top) the kinetic energy of every proton striking the lunar surface late in the simulation between 0.68 and $0.72 \Omega_p^{-1}$ as a function of horizontal distance along the surface. (bottom) The partial solar wind flux due to protons in two different energy intervals, as indicated, at the lunar surface. Note that the protons which strike the surface near the magcon have lower energy than those that strike the surface far from it.

partial fluxes within two different energy intervals. Note that far from the magcon, the greatest contribution to the total flux is from protons within the 0.15 – 0.6 keV energy range which is large enough to include nearly all ambient solar wind protons. The kinetic energy of a proton moving with the solar wind speed of 300 km/s is 0.47 keV. It is noteworthy that the flux of protons impacting the lunar surface in this energy range, near the nominal solar wind ram energy, is about a factor of 10 lower in the center of the magcon, compared to that far from it. In contrast, the flux due to 0.03 – 0.1 keV protons, at much lower energies than the nominal solar wind ram energy, is a maximum at the center of the magcon and is zero far away from it.

At the center of the magnetic anomaly, the flux of solar wind protons at low energies is about the same as that at higher energies associated with the solar ram energy. This has important implications for any resulting backscattered neutral atoms whose flux is observed to be proportional to the solar wind flux, with an “albedo” of about 10% [McComas *et al.*, 2009]. Our simulation results may help explain the high spatial resolution observations made by Chandrayaan-1/SARA reported by Wieser *et al.* [2010] who noted that maps of the flux of neutrals emanating from the lunar surface within the 0.15 – 0.6 keV energy range showed a distinct depletion coincident with the strongest magnetic fields of the lunar magcon. This is the minimagnetosphere. However, the flux of lower energy neutrals, within the 0.03 – 0.1 keV energy range, did not show such a depletion, and, in fact, revealed an enhancement emanating from within the magcon. The authors noted that this was puzzling but offered one suggestion: “To generate it, solar wind protons would need to be decelerated inside the minimagnetosphere, prior to interaction with the surface.” This is consistent with our simulation results. We note that the parameters of the solar wind and lunar magcon chosen for this study were based on observations made at the time Chandrayaan-1 observed neutrals coming from the lunar surface above a magcon.

Also evident in the top plot of Figure 3 is a deceleration of the solar wind to the left side of the magcon. This deceleration is not as large as the one that occurs directly coincident with the magcon but is significant. The reason for this is related to a secondary electric field produced in this region and is discussed further below (Figure 8).

Figure 4 shows profiles of magnetic field magnitude (bottom), vertical component of the electrostatic electric field (middle), and v_h versus h phase-space scatterplot, as functions of vertical distance, h , above the lunar surface starting from the center of the magcon ($z=0$). For the phase-space scatterplot, we show all protons whose z position is within $0.004 c/\omega_i$ (corresponding to 0.24 km, using the parameters of this simulation) of the center of the magcon. By 50 km, the magnetic field magnitude has dropped by a factor of 5 from its value at the surface, and by 100 km it is very near its value in interplanetary space. The electric field in Figure 4 (top) shows both an instantaneous profile taken at the end of the simulation ($t = 0.72 \Omega_p^{-1}$) as a light-gray curve, and a profile that has been averaged over both space and time as a darker, thick, solid curve. In the case of the latter, we averaged E_h from the simulation at 10 separate equally spaced times starting at $t = 0.36 \Omega_p^{-1}$ and ending with $t = 0.72 \Omega_p^{-1}$, and then performed a 20 -point running average on the time-averaged profile. We note that the instantaneous electric field profile is quite noisy, especially very near the lunar surface, but generally looks similar to the profile that is averaged. We also note that the averaging is only for diagnostic purposes. The positive field that exists from a few kilometers above the surface to heights greater than 50 km, reaching a maximum at about 10 km, results from the difference in inertia of the protons and electrons over a scale of about the proton inertial length. The physics of this electric field is discussed in section 1. It is similar to the so-called “cross-shock” electric field seen in simulations of collisionless shocks which contributes to the reflection of ions within the shock layer providing an additional source of shock dissipation [Leroy *et al.*, 1981]. These reflected ions have been observed upstream of Earth’s bow shock [Paschmann *et al.*, 1982;

Figure 4. (bottom) Profiles of magnetic field magnitude, (middle) vertical component of the electric field, and (top) phase-space scatterplot of the velocity of protons as functions of height above the lunar surface, directly above the center of the magcon ($z = 0$). For the case of the phase-space scatterplot, all protons with positions in the horizontal direction such that $|z| < 0.004c/\omega_i$ are shown. The thin gray curve in the Figure 4 (middle) is the instantaneous $E_h (= -E_x)$ at the end of the simulation at $\Omega_p t = 0.72$, and the thick solid curve is a spatially and temporally averaged profile (see text for details).

Gosling *et al.*, 1982]. While there is no evidence of a shock in our simulation of the solar wind/magcon interaction, this electric field exists nevertheless and, like the case at supercritical shocks, leads to the reflection of protons within the magcon prior to their reaching the surface. Their flux at high altitudes can be significant, and they can be seen over a spatial scale that is far greater than that of the magcon.

Figure 4 (top) shows that a fraction of the protons incident on the magcon is reflected back into space before ever reaching the lunar surface. Note that any proton incident on the surface is absorbed and removed from the system; hence, none of the protons in this plot hit the surface. The presence of a significant number of protons with upward directed velocities indicates that they are reflected within the magcon/solar wind interaction region. These particles are reflected by the large electrostatic field discussed above.

Figure 5. The density of reflected protons within a spatial region near the magcon, normalized to the ambient solar wind density, at the end of the simulation ($\Omega_p t = 0.72$). Black curves are magnetic lines of force, similar to those shown in Figure 1. The white arrows represent the reflected proton bulk velocity. The magnitude of each of these vectors are all about $0.85 V_{sw}$. The bottom portion of the plot, below the horizontal dashed line at 25 km near the lunar surface, indicates the region over which our method for identifying reflected particles is not reliable. See the text for more details.

Figure 5 shows the density of reflected protons over a small spatial region near the magcon. A reflected proton is identified in this case as any kinetic particle in the simulation with $v_h > 0$. The black lines represent magnetic field lines, as in Figure 1. The white arrows represent the average velocity vector of reflected ions within a $20 \text{ km} \times 20 \text{ km}$ square region centered at the large circle at the base of the arrow. For each of the vectors shown, the (v_h, v_y, v_z) components of the bulk velocity, normalized to the ambient solar wind velocity, are, respectively: A: (0.27, -0.11, -0.79), B: (0.65, -0.27, -0.56), C: (0.84, -0.31, 0.02), D: (0.59, -0.35, 0.59), and E: (0.19, -0.29, 0.82). Note that in all cases the arrows point out of the plane

which is consistent with a negative y component of the bulk velocity and for our assumed coordinate system. The reflected particle density below the dashed line at 25 km in Figure 5 should be interpreted with some care because our method of identifying reflected particles is not reliable in this region. For one, the populations of decelerated solar wind and reflected particles tend to overlap in phase space in this region, particularly very near the magcon. Second, on the sides of the magcon the reflected particles are moving with large horizontal speeds, but smaller, and even negative vertical speeds. Thus, plotting only the density of particles with positive vertical speeds misses a considerable number of reflected particles near the surface. This is the reason for the very abrupt drop in the density close to the surface, just below the red “bands” seen on either side of the magcon in Figure 5.

Figure 5 indicates that the number density of reflected protons is of the order of a few percent over a fairly large spatial region near the magcon. The density can be even larger near the magcon itself, even approaching a value close to 10%.

The higher-density collection of reflected particles on either side of the magcon, seen as red “bands,” is related to the enhanced flux of solar wind protons striking the lunar surface seen in Figure 1 and Figure 2 (bottom). The enhanced flux striking the surface, as we noted previously, arises because of the deflection of solar wind protons to the sides of the magcon (the halo). A fraction of these particles is reflected away from the surface before striking it, and this leads to the enhanced reflected particle density seen as the red bands in Figure 5. We also note that on the left side of the magcon, the magnetic fields of the solar wind and magcon are directed opposite to one another. This leads to a magnetic topology that is very reminiscent of magnetic reconnection. As can be seen in this figure, there appears to be two populations of high-density reflected particles starting about 100 km to the left of the magcon (seen as a separation of the red band into two parts, just below the base of the arrow labeled “A”). As we discuss below, this is related to the magnetic topology.

Reflected ions can have significant densities even very far from the magcon. The process is analogous to reflected particles from Earth’s bow shock in which a fraction of the incident solar wind protons is reflected by the cross-shock electric field. When the incident magnetic field is sufficiently oblique to the shock normal, these reflected particles have sufficient velocity parallel to the magnetic field to escape upstream of the shock. There have been numerous observations of these particles in Earth’s foreshock [e.g., *Asbridge et al.*, 1968; *Gosling et al.*, 1978]. For the case of the solar wind/magcon interaction, when a spacecraft crosses interplanetary magnetic field lines which are magnetically connected to the region near the magcon, reflected ions will be seen to be moving away from the Moon along these field lines. Their flux will depend on, among other things, the angle of the magnetic field relative to the lunar surface at the point of the magcon [e.g., *Burgess*, 1987]. If there is little pitch angle scattering due to interplanetary magnetic field turbulence, field-aligned reflected particles would be seen very far upstream from the Moon. Field-aligned beams in Earth’s foreshock are typically seen several Earth radii from the bow shock; thus, we might expect field-aligned ion beams emanating from the solar wind/lunar magcon interaction to be seen at similar distances from the Moon (i.e., several tens of thousands of kilometers). However, since the interaction region is spatially quite small, the ions seen very far from the Moon would only be seen very briefly and, therefore, would likely be difficult to detect. Note that it would take a bundle of field lines spanning the size of a typical solar wind/magcon interaction region (~ 100 km) less than a second to advect past a spacecraft assuming they were moving with a 400 km/s solar wind.

Figure 6 shows the partial flux of reflected particles at various altitudes above the lunar surface as a function of horizontal distance. The flux is normalized to the ambient solar wind value. Plotted is the component directed vertically upward. It peaks directly above the magcon in all cases shown, although the spatial distribution is considerably broader at higher altitudes. The sharp drop in the flux to the right of the magcon is due to the interaction of particles reflected by the magcon with the IMF. Note that in our case, the IMF makes a 135° angle relative to the lunar surface in the $h - z$ plane (a 225° angle in the $x - z$ plane) so that it has a negative z component. Thus, the parallel velocity of the reflected particles is directed vertically upward and toward negative z . Particles moving from the magcon toward positive z will be turned around by their gyromotion in the IMF. Thus, we expect there to be no particles beyond $z \sim r_g$, where r_g is the reflected particle gyroradius. Taking $r_g \sim 0.8U_{sw}/\Omega_p \sim 600$ km, for the parameters in our simulation. This is similar to, but somewhat larger than that shown in Figure 6.

We note also from Figure 6 that the reflected proton flux is significant over a spatial scale that is considerably larger than the scale of the magcon. Note that at 100 km altitude, the flux exceeds 0.1% of the solar wind

Figure 6. The vertical component of the partial flux of reflected particles at various altitudes above the lunar surface as a function of horizontal distance. The flux is normalized to the ambient solar wind value.

emerged from these observations is that the reflected ions are related to the solar wind/magcon interaction, which leads to an electrostatic field that reflects incident solar wind ions [Halekas *et al.*, 2011; Lue *et al.* 2011], which is consistent with our simulations, as discussed above. Saito *et al.* [2012] noted that the reflected ions were observed over a much larger area than that of the magcon, which is also consistent with our simulations. Also, by comparing Figures 1 and 3 of the Saito *et al.* paper, the reflected ions are observed to be somewhat more concentrated near the magcon at 25 km altitude (their Figure 3) than at 100 km altitude (their Figure 1). This is also consistent with our simulations as shown in our Figure 6. Saito *et al.* also reported on the magnitude of the observed differential flux of ions seen by sensors that were either pointed toward the Moon (Kaguya/IMA), or away from it (Kaguya/IEA). The authors noted that at ~ 25 km, the “density of magnetically reflected ions sometimes reaches as high as $\sim 50\%$ of the incident solar wind ion density” (see also Lue *et al.* [2011]). This is considerably higher than we see in our simulations. We note that the simulated flux of reflected protons in our simulation is generally consistent with that seen in simulations of high-Mach collisionless shocks [e.g., Leroy *et al.*, 1981], despite the fact that there is no shock in our case (this is discussed further below). It is also consistent with observations near Earth’s bow shock which typically show that the specularly reflected ion density is 1–3% of the solar wind density when the solar wind Alfvén Mach, M_A , is about 2 and 15–25% when M_A is 8–12 [Sckopke *et al.*, 1983]. The dependence on Mach number suggests that the ions are part of the shock dissipation process—e.g., more reflected ions are needed to dissipate the higher incident ram energy of higher-Mach shocks. Note that in our case, $M_A = 4.7$. It is not clear to us why the observations presented by Saito *et al.* [2012] and Lue *et al.* [2011] show such high reflected ion densities, but this disagreement is possibly due to physics not included in our simulation or responsible for shock dissipation at Earth’s bow shock.

Phase-space scatterplots of the three components of the proton velocity at two different altitudes as functions of horizontal distance are shown in Figure 7. All protons that are within ± 1 km of the indicated altitude are shown. The velocity vector is that in the frame of the Moon. The incident beam of solar wind protons is clearly visible as the densely packed dots centered on a vertical speed of -300 km/s, and horizontal components centered on 0. The spread about the center is due to the finite thermal speed of the solar wind protons. Note that nearer the lunar surface, at 25 km, the solar wind protons are seen to be decelerated. This is also seen in the scatterplot of the energy of protons incident on the surface that was shown in Figure 3. Figure 7 (middle) in the left column also indicates that the decelerated solar wind above the magcon is also deflected toward the positive y direction (into the plane of Figure 5).

Reflected ions are seen as a much less densely populated scatter of dots in each of the plots shown in Figure 7. Figure 7 (top row) indicates that they are moving nearly with opposite speed to the solar wind above the magcon with little horizontal speed. Thus, they are specularly reflected protons. Note also that compared to the solar wind, reflected particles are rather narrowly distributed relative to their bulk motion, suggesting they have a smaller temperature (defined relative to the reflected proton bulk velocity, rather than the combined solar wind, reflected proton center of mass velocity) than the solar wind. This is not consistent with observations of reflected proton distributions near the Moon reported by Saito *et al.* [2012]. We are not entirely certain of the reason for this, but suggest that our rather small and short simulation, as well as our nonkinetic treatment of the electrons, is not sufficient to allow for the growth of magnetic fluctuations, such as whistler waves, that could thermalize these particles. Enhanced magnetic wave activity seen simultaneously with

flux over a range of 800 km starting from about 500 km to the left of the magcon, to 300 km to the right of it. There is only a slight reduction in the reflected-particle flux at the higher altitude of 200 km. In contrast, when an observer crosses above a magcon at low altitudes, the reflected-particle flux will be more closely concentrated near the magcon and will be larger than it is at higher altitudes.

Our simulation results are qualitatively consistent with spacecraft observations of reflected ions near the Moon, first reported by Futaana *et al.* [2003] and later by Saito *et al.* [2008, 2012]. The basic picture that has

Figure 7. Phase-space scatterplots of the three components of the velocity vector of protons as a function of horizontal distance at two different altitudes. Every tenth proton that is within 1 km of the altitude indicated at the top of each set of plots is shown.

backstreaming electrons and protons has been reported by *Tsugawa et al.* [2011, 2012] and *Halekas et al.* [2013]. Also, more complex representations of the magcon, other than the simple dipole that we considered, such as quadrupolar or higher-order terms in the magnetic field expansion, could possibly lead to more thermalization of the reflected particles.

The population of particles seen at an altitude of 25 km, extending from $z \sim -100$ km to $z \sim -180$ km in Figure 7, is an additional component of reflected ions. They have a larger vertical speed than the “primary” reflected particles. That this population only exists on the left side of the magcon, where the magnetic field lines of the magcon and IMF are opposite one another, suggests that these particles are related to magnetic reconnection.

Figure 8 shows the magnitude of the magnetic field and vertical component of the electrostatic field over a small region to the left of the magcon. In this region, the magnetic field of the magcon is directed opposite to that of the IMF, leading to a topology that is reminiscent of that associated with magnetic reconnection. In magnetic reconnection, magnetic fields of opposite polarity separated by a current sheet are forced together at a small localized region where magnetic energy is converted into a plasma kinetic energy. The resulting plasma flow is directed outward along the current sheet representing an “exhaust flow.” It is a common feature in models of magnetic reconnection [cf. *Priest and Forbes*, 2000]. The exhaust flow moves at the Alfvén speed associated with magnetic field and plasma density outside the reconnection region. For our case, the largest magnetic field is near the surface and is larger than the IMF. Thus, the associated Alfvén speed is larger than

Figure 8. Color-coded representations of the (top) magnitude of the magnetic field and (bottom) vertical component of the electric field over a small spatial region to the left of the magcon. Magnetic field lines are shown as solid curves, and the direction of the field is indicated with small arrows in Figure 8 (top).

that in the ambient solar wind. Thus, we might expect an exhaust flow on either side of the point where the fields appear to “reconnect” that is comparable to the solar wind speed. However, in our case, we find that the bulk plasma flow velocity in this region is directed downward, into the surface. Thus, the plasma flow pattern is not consistent with what is expected from the standard MHD model of magnetic reconnection. It is important to note that this region is smaller than a proton inertial length, so our standard views of magnetic reconnection from either MHD, or even Hall MHD, are not necessarily applicable. Nevertheless, the magnetic topology leads to a secondary electrostatic electric field which influences the motion of previously reflected protons produced closer to the magcon, creating a secondary component of reflected protons.

Note that in Figure 8 (top) the magnetic topology leads to a magnetic depression at the location where the field lines seem to reconnect. The magnetic field is quite weak in this region, with a magnitude about 10–20% of the IMF value. The magnetic field closer to the surface is much stronger than this because this part of the surface is still rather near the magcon. This leads to a significant magnetic pressure gradient giving rise to a large electric field, pointed upward from the surface, similar to that already discussed in section 1 for the primary electric field. This electric field is shown in Figure 8 (bottom) and extends to the highest altitude just where the magnetic field is a minimum. Note that this is a secondary electrostatic field, which is spatially smaller and also weaker than the primary one seen toward the far right of this figure which we have discussed previously. There is also a magnetic pressure gradient above the magnetic depression, but any electric field produced by this would be smaller than the one below it and would not be visible in this plot. The reason can be understood by noting that the magnetic pressure gradient varies as $B^2/(nl_B)$, where B is the magnetic field strength, n is the proton density, and l_B is the scale of the gradient. The terms l_B and n are about the same above and below the magnetic depression, but B is stronger near the surface than the IMF; thus, the magnetic pressure gradient is larger below the magnetic depression, leading to a stronger electric field there (by a factor of ~ 10).

As reflected protons are created in the primary electrostatic field at the right, some of them move through the secondary electric field and are deflected upward. This is responsible for the second population of reflected particles seen in Figures 6 and 7. Although we do not find evidence of reflected protons originating directly from the secondary electric field, it is reasonable to expect that for a different choice of parameters, the secondary electric field could be sufficiently strong to produce its own reflected ions. The solar wind is clearly decelerated by this electric field as can be seen in Figure 3.

We note that the secondary component of reflected protons we see in our simulation is probably unrelated to the secondary component of reflected ions observed by Kaguya on the dayside of the lunar surface (not necessarily associated with a magcon) reported by Saito *et al.* [2008]. These authors interpreted this population as photoionized (backscattered) neutral atoms that, upon ionization, are “picked up” and accelerated by the motional electric field to velocities as high as twice the solar wind speed in the Moon reference frame. Our simulations do not include this pickup process, yet we still obtain a secondary reflected ion component as a result of the interaction of solar wind protons with the lunar magnetic anomaly, as described above.

4. Summary

We have performed a self-consistent, kinetic proton, fluid electron, numerical simulation of the interaction between the solar wind and a lunar magnetic anomaly. Our simulation used parameters that are typical of the solar wind, interplanetary magnetic field, and a strong lunar magnetic anomaly or magcon (magnetic concentration). We focused attention on the spatial variation of the flux of protons incident on the lunar surface, as well as at various altitudes near the surface. We also studied the properties of protons reflected by electromagnetic processes resulting from the solar wind/magcon interaction.

From our analysis we conclude the following:

1. The total solar wind flux incident on the lunar surface over a region the size of a typical lunar magnetic anomaly is significantly reduced, but is not zero. For the parameters of our simulation, the total solar wind proton flux is reduced by a factor of about 4 at the center of the magcon (a $\sim 75\%$ reduction).
2. The solar wind flux striking the surface is significantly enhanced at the sides of the magcon. This is due to the increased number of particles striking the surface there which were deflected by the strong magnetic fields above the magcon. This is consistent with results from a fully kinetic three-dimensional plasma simulation revealing a halo in the incident solar wind flux around the magcon reported by *Kallio et al.* [2012].
3. Solar wind protons which strike the lunar surface within the magcon are of considerably lower energy than the solar wind, indicating that they are significantly decelerated before reaching the surface. For the parameters in our simulation, protons which strike the surface have energies between ~ 0.05 and 0.3 keV, compared to ~ 0.5 keV for a proton moving with the undisturbed solar wind.
4. Directly above the center of the magcon, the scale height of the magcon magnetic field, or the distance above the surface in which it has decreased by a factor of e compared to the value at the surface, is about 20 km. The magnetic field is about twice as large as the ambient interplanetary magnetic field, 50 km above the surface.
5. A strong, vertically directed, static electric field exists within the solar wind/magcon interaction which is strongest at about 10 km altitude and extends to altitudes of about ~ 50 km. This electric field results from the large magnetic pressure gradient near the magcon arising from a significant difference in the inertia of the electrons and protons in the solar wind. In this case, there is a significant contribution from the Hall term in the magnetic induction equation. It is similar to the so-called "cross-shock" electric field known to exist in the ramp of supercritical collisionless shocks.
6. Specularly reflected solar wind protons are seen moving directly outward and away from the lunar magcon. These protons are reflected by the strong electric field discussed above and are similar to reflected ions seen near strong collisionless shocks.
7. Reflected protons are seen at very high altitudes and over a broad spatial range, much larger than the scale of the magcon itself. They can be seen with a significant flux at altitudes above 200 km from the surface and over a horizontal scale exceeding 500 km on either side of the magcon. The reason for this is that the specularly reflected protons have speeds comparable to the solar wind speed, in the Moon reference frame, and their motion parallel to the interplanetary magnetic field (IMF) will carry them large distances before they are ultimately scattered by turbulence (which is not included in our simulation). Moreover, their gyroradii in the weak IMF are considerably larger than the size of the magcon.
8. Our simulations also reveal a second component of reflected protons which exist only on the side of the magcon where the magnetic field of the magcon is directed opposite to the IMF. This is the "magnetic reconnection" side of the magcon. The second component of reflected protons results from the reacceleration of reflected protons by another, secondary, (primarily) vertically directed electric field which exists on this side of the magcon. This electric field also results from a significant magnetic pressure gradient. In this case, the oppositely directed IMF/magcon magnetic fields ~ 10 km above and ~ 60 km to the side of the magcon leads to a weakening in the magnitude of the field there, giving rise to a large magnetic pressure gradient between there and the surface. The resulting electrostatic field accelerates previously reflected protons to create a secondary component.
9. The "secondary" electrostatic field discussed in conclusion 8 also leads to a slight deceleration of the solar wind there. For the parameters of our simulation, the solar wind was decelerated by about 10% .

In our simulation, there is no shock wave standing in the solar wind flow above the magcon. This is not surprising given that the scale of the magcon is of the order of an ion inertial length, which is the characteristic ramp width of Earth's bow shock [e.g., *Russell and Greenstadt*, 1979; *Leroy et al.*, 1981]. However, there are a

couple of issues worth mentioning here that may relate to the possible existence of shocks associated with the solar wind interaction with lunar magcons, which has recently been reported by *Halekas et al.* [2014]. The first is that fine-scale structures, possibly associated with shock reformation, with scales smaller than the ion inertial length have been seen in the ramp of Earth's bow shock [Mazelle et al., 2010]. Such scales are associated with electron kinetic physics not included in our calculation. Second, whether a shock forms is not wholly determined by the strength of the magnetic barrier deflecting the incident flow, its spatial size is also very important. If the magnetic barrier extends over many tens to hundreds of ion inertial lengths, the enhanced field typical of strong lunar magcons is sufficient to decelerate and deflect the incident protons so that the plasma would pile up and lead to a standing bow shock, like at Earth. However, the required spatial scale is considerably larger than that of lunar magcons, and even larger than the radius of the Moon itself, so this probably has little to do with shock-like features observed near the Moon reported by *Halekas et al.* [2014]. Finally, we have only considered the case in which the solar wind moves exactly normal to the surface. It is not clear how our results would change if the incident flow were much more oblique, or even close to parallel to the surface.

Our study has focused on aspects of the interaction between the solar wind and a concentrated lunar magnetic field that leads to reflected ions and neutral atoms emanating from the surface, and variations in the electromagnetic field on the scale of the magcon itself. Variations in the solar wind flux on the lunar surface may also be related to surface albedo anomalies, which is a topic of considerable interest [e.g., *Hood and Schubert*, 1980; *Blewett et al.*, 2011; *Glotch et al.*, 2015], but we have not focused on that aspect of this problem. Our simulations have revealed a richness in the kinetic proton plasma physics associated with the interaction between the solar wind and lunar magcons [see also *Halekas et al.*, 2011]. Fully kinetic simulations, such as those performed by *Kallio et al.* [2012], are needed to study effects on smaller scales, such as the electron inertial length (~ 4 km) in the undisturbed solar wind, or even the Debye length ($\sim$ tens of meters). As one example, in our study, we noted that on the side of the magcon where its magnetic field is directed opposite to the IMF, the magnetic topology is very reminiscent of magnetic reconnection. However, our simulations do not reveal processes occurring in this region consistent with our current understanding of magnetic reconnection, by itself, such as plasma exhaust flows, or the formation of magnetic islands. Understanding this region better and its relation to magnetic reconnection, which is a topic of considerable interest, will likely require the consideration of electron kinetic physics.

Acknowledgments

We gratefully acknowledge useful conversations on this topic with J.R. Jokipii. This work was partially supported by NASA under grant NNX11AO64G. All results presented in this paper are from a numerical simulation.

The Editor thanks Yoshifumi Saito and Jasper Halekas for their assistance in evaluating this paper.

References

- Asbridge, J. R., S. J. Bame, and I. B. Strong (1968), Outward flow of protons from Earth's bow shock, *J. Geophys. Res.*, **73**, 5777–5782.
- Blewett, D. T., E. T. Coman, B. R. Hawke, J. J. Gillis-Davis, M. E. Purucker, and C. G. Hughes (2011), Lunar swirls: Examining crustal magnetic anomalies and space weathering trends, *J. Geophys. Res.*, **116**, E02002, doi:10.1029/2010JE003656.
- Burgess, D. (1987), Simulations of backstreaming ion beams formed at oblique shocks by direct reflection, *Ann. Geophys. A*, **5**, 133–145.
- Deca, J., A. Divin, G. Lapenta, B. Lembege, S. Markidis, and M. Horanyi (2014), Electromagnetic particle-in-cell simulations of the solar wind interaction with lunar magnetic anomalies, *Phys. Rev. Lett.*, **112**, 151102.
- Dyal, P., C. W. Parkin, and W. D. Daily (1974), Magnetism and the interior of the Moon, *Rev. Geophys. Space Phys.*, **12**(4), 568–591.
- Futaana, Y., S. Machida, Y. Saito, A. Matsuoka, and H. Hayakawa (2003), Moon-related nonthermal ions observed by Nozomi: Species, sources, and generation mechanisms, *J. Geophys. Res.*, **108**(A1), 1025, doi:10.1029/2002JA009366.
- Futaana, Y., S. Barabash, M. Wieser, C. Lue, P. Wurz, A. Vorburger, A. Bhardwaj, and K. Asamura (2013), Remote energetic neutral atom imaging of electric potential over a lunar magnetic anomaly, *Geophys. Res. Lett.*, **40**, 262–266, doi:10.1002/grl.50135.
- Glotch, T. D., J. L. Bandfield, P. G. Lucey, P. O. Hayne, B. T. Greenhagen, J. A. Arnold, R. R. Ghent, and D. A. Paige (2015), Formation of lunar swirls by magnetic field standoff of the solar wind, *Nat. Commun.*, **6**, 6189, doi:10.1038/ncomms7189.
- Gosling, J. T., J. R. Asbridge, S. J. Bame, G. Paschmann, and N. Scopke (1978), Observations of two distinct populations of bow shock ions in the upstream solar wind, *Geophys. Res. Lett.*, **5**, 957–960, doi:10.1029/GL005i011p00957.
- Gosling, J. T., M. F. Thomsen, S. J. Bame, W. C. Feldman, G. Paschmann, and N. Scopke (1982), Evidence for specularly reflected ions upstream from the quasi-parallel bow shock, *Geophys. Res. Lett.*, **9**, 1333–1336, doi:10.1029/GL009i012p01333.
- Halekas, J. S., D. L. Mitchell, R. P. Lin, S. Frey, L. L. Hood, M. H. Acuna, and A. B. Binder (2001), Mapping of crustal magnetic anomalies on the lunar near side by the Lunar Prospector electron reflectometer, *J. Geophys. Res.*, **106**, 27,841–27,852.
- Halekas, J. S., G. T. Delory, D. A. Brain, R. P. Lin, and D. L. Mitchell (2008), Density cavity observed over a strong lunar crustal magnetic anomaly in the solar wind: A mini-magnetosphere?, *Planet. Space Sci.*, **56**(7), 941–946.
- Halekas, J. S., Y. Saito, G. T. Delory, and W. M. Farrell (2011), New views of the lunar plasma environment, *Planet. Space Sci.*, **59**(14), 1681–1694.
- Halekas, J. S., A. R. Poppe, J. P. McFadden, and K. H. Glassmeier (2013), The effects of reflected protons on the plasma environment of the Moon for parallel interplanetary magnetic fields, *Geophys. Res. Lett.*, **40**, 4544–4548, doi:10.1002/grl.50892.
- Halekas, J. S., A. R. Poppe, J. P. McFadden, V. Angelopoulos, K. H. Glassmeier, and D. A. Brain (2014), Evidence for small-scale collisionless shocks at the Moon from ARTEMIS, *Geophys. Res. Lett.*, **41**, 7436–7443, doi:10.1002/2014GL061973.
- Hood, L. (2015), Lunar magnetic anomalies, in *Encyclopedia of Lunar Science*, edited by B. Cudnik, Springer, Heidelberg, Germany.
- Hood, L., P. J. Coleman, and D. E. Wilhelms (1979), The Moon—Sources of the crustal magnetic anomalies, *Science*, **204**, 53–57.
- Hood, L. L., and G. Schubert (1980), Lunar magnetic anomalies and surface optical properties, *Science*, **208**(4439), 49–51.

- Hood, L. L., A. Zakharian, J. Halekas, D. L. Mitchell, R. P. Lin, M. H. Acuna, and A. B. Binder (2001), Initial mapping and interpretation of lunar crustal magnetic anomalies using Lunar Prospector magnetometer data, *J. Geophys. Res.*, *106*(E11), 27,825–27,839, doi:10.1029/2000JE001366.
- Jarvinen, R., M. Alho, E. Kallio, P. Wurz, S. Barabash, and Y. Futaana (2014), On vertical electric fields at lunar magnetic anomalies, *Geophys. Res. Lett.*, *41*, 2243–2249, doi:10.1002/2014GL059788.
- Jokipii, J. R., J. Kóta, and J. Giacalone (1993), Perpendicular transport in 1- and 2-dimensional shock simulations, *Geophys. Res. Lett.*, *20*(17), 1759–1761.
- Jones, F. C., J. R. Jokipii, and M. G. Baring (1998), Charged-particle motion in electromagnetic fields having at least one ignorable spatial coordinate, *Astrophys. J.*, *509*, 238–243.
- Kallio, E., et al. (2012), Kinetic simulations of finite gyroradius effects in the lunar plasma environment on global, meso, and microscales, *Planet. Space Sci.*, *74*, 146–155.
- Leroy, M. M., C. C. Goodrich, D. Winske, C. S. Wu, and K. Papadopoulos (1981), Simulation of a perpendicular bow shock, *Geophys. Res. Lett.*, *8*, 1269–1272.
- Lue, C., Y. Futaana, S. Barabash, M. Wieser, M. Holmstrom, A. Bhardwaj, M. B. Dhanya, and P. Wurz (2011), Strong influence of lunar crustal fields on the solar wind flow, *Geophys. Res. Lett.*, *38*, L03202, doi:10.1029/2010GL046215.
- Mazelle, C., B. Lembege, A. Morgenthaler, K. Meziane, T. S. Horbury, V. Genot, E. A. Lucek, and I. Dandouras (2010), Self-reformation of the quasi-perpendicular shock: Cluster observations, in *Twelfth International Solar Wind Conference*, vol. 1216, edited by M. Maksimovic et al., pp. 471–474, Am. Inst. Physics, Saint-Malo, France.
- McComas, D. J., et al. (2009), Lunar backscatter and neutralization of the solar wind: First observations of neutral atoms from the Moon, *Geophys. Res. Lett.*, *36*, L12104, doi:10.1029/2009GL038794.
- Mitchell, D. L., J. S. Halekas, R. P. Lin, S. Frey, L. L. Hood, M. H. Acuna, and A. Binder (2008), Global mapping of lunar crustal magnetic fields by Lunar Prospector, *Icarus*, *194*, 401–409.
- Paschmann, G., N. Sckopke, S. J. Bame, and J. T. Gosling (1982), Observations of gyrating ions in the foot of the nearly perpendicular bow shock, *Geophys. Res. Lett.*, *9*, 881–884.
- Poppe, A. R., J. S. Halekas, G. T. Delory, and W. M. Farrell (2012), Particle-in-cell simulations of the solar wind interaction with lunar crustal magnetic anomalies: Magnetic cusp regions, *J. Geophys. Res.*, *117*, A09105, doi:10.1029/2012JA017844.
- Priest, E. R., and T. G. Forbes (2000), *Magnetic Reconnection—MHD Theory and Applications*, Cambridge Univ. Press, New York.
- Russell, C. T., and E. N. Greenstadt (1979), Initial ISEE magnetometer results: Shock observations, *Space Sci. Rev.*, *23*, 3–37.
- Saito, Y., et al. (2008), Solar wind proton reflection and the lunar surface: Low energy ion measurement by MAP-PACE onboard SELENE (KAGUYA), *Geophys. Res. Lett.*, *35*, L24205, doi:10.1029/2008GL036077.
- Saito, Y., M. N. Nishino, M. Fujimoto, T. Yamamoto, S. Yokota, H. Tsunakawa, H. Shibuya, M. Matsushima, H. Shimizu, and F. Takahashi (2012), Simultaneous observation of the electron acceleration and ion deceleration over lunar magnetic anomalies, *Earth Planets Space*, *64*, 83–92.
- Sckopke, N., G. Paschmann, S. J. Bame, J. T. Gosling, and C. T. Russell (1983), Evolution of ion distributions across the nearly perpendicular bow shock—Specularly and non-specularly reflected-gyrating ions, *J. Geophys. Res.*, *88*, 6121–6136.
- Tsugawa, Y., N. Terada, Y. Katoh, T. Ono, H. Tsunakawa, F. Takahashi, H. Shibuya, H. Shimizu, and M. Matsushima (2011), Statistical analysis of monochromatic whistler waves near the Moon detected by Kaguya, *Ann. Geophys.*, *29*, 889–893.
- Tsugawa, Y., et al. (2012), Statistical study of broadband whistler-mode waves detected by Kaguya near the Moon, *Geophys. Res. Lett.*, *39*, L16101, doi:10.1029/2012GL052818.
- Wieser, M., S. Barabash, Y. Futaana, M. Holmstrom, A. Bhardwaj, R. Sridharan, M. B. Dhanya, A. Schaufelberger, P. Wurz, and K. Asamura (2010), First observation of a mini-magnetosphere above a lunar magnetic anomaly using energetic neutral atoms, *Geophys. Res. Lett.*, *37*, L05103, doi:10.1029/2009GL041721.
- Winske, D., and N. Omid (1996), A nonspecialist's guide to kinetic simulations of space plasmas, *J. Geophys. Res.*, *101*, 17,287–17,303.