Mapping the Predicted Solar Wind Hydrogen Flux in Lunar South Pole Craters

Dov J. Rhodes and William M. Farrell
NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA; dovjr6@gmail.com
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Abstract

The solar wind hydrogen flux is mapped onto the topography of four lunar south pole craters: Shackleton, Haworth, Shoemaker and Faustini. Using altimetry data from the Lunar Reconnaissance Orbiter, we apply an analytic plasma model to map the hydrogen flux onto the surface, time-averaged over a lunar rotation cycle. We present a series of maps including the average flux, geomagnetic modulation, and ion flow energy. These results are intended to inform further studies of dynamic lunar surface processes, such as volatile implantation, sputtering, and weathering. As an example, we also present a map of a surface ice sheet lifetime based on ion sputtering.

Unified Astronomy Thesaurus concepts: Space plasmas (1544); Earth-moon system (436); Solar wind (1534); Lunar craters (949); Lunar surface (974)

1. Introduction

The present study presents flux maps of the long-term (lunation) solar wind hydrogen flow into lunar polar craters. It is part of an ongoing effort to understand the dynamic processes affecting lunar surface composition, including implantation (Starukhina 2006), sputtering (Farrell et al. 2013), weathering (Zuber et al. 2012), and micrometeoroid bombardment (Farrell et al. 2015). This line of research is largely motivated by the anticipated demand for volatile materials that could sustain human existence on the Moon. Polar craters are of particular interest to human exploration, seeing as they can act as cold traps for volatiles, most notably water ice, which is prevalent at temperatures below 110 K (Gladstone et al. 2012; Hayne et al. 2015). Unlike on Mercury, however, there appears to be limited correlation between temperature and volatile density within the Moon’s cold polar regions (Fisher et al. 2017; Li et al. 2018). In this paper, we examine one of the additional factors, namely the interaction of the varying lunar topography with the solar wind plasma.

As the solar wind plasma flows outward from the Sun, it creates unique wake patterns around airless bodies such as the Moon (Farrell et al. 1998; Halekas et al. 2005). On a smaller scale, similar wake patterns are created as the plasma flows horizontally over local topography features, as is the case with lunar polar craters (Farrell et al. 2007, 2010). In order to map out the flux of solar wind hydrogen ions in these permanently shadowed regions of the Moon, we apply an analytic plasma wake model by Rhodes & Farrell (2019), making use of topography data from the Lunar Orbiter Laser Altimeter (LOLA) instrument on the Lunar Reconnaissance Orbiter Mission (LRO; Smith et al. 2010). The 2D vertical plane model is extended across a crater width and then time-averaged over an entire lunar rotation. Besides the varying topography, rotational asymmetries are introduced by density modulations as the Moon crosses Earth’s magnetosphere (Poppe et al. 2018).

The average flux, geomagnetic modulation, and ion flow energy are individually mapped for four south pole craters; Shackleton, Haworth, Shoemaker, and Faustini. Owing to a departure in its characteristic width-to-depth ratio, Shackleton exhibits substantially different flux patterns than the other three craters. The Shackleton crater map is compared with a weathering study by Zuber et al. (2012), resulting in possible insights into the observed surface brightness pattern. More quantitative comparison with existing studies remains challenging owing to the low data resolution and are left for future investigation.

To demonstrate the power of this simple flux-mapping analysis, we provide an example calculation of ice sheet sputtering lifetimes. Based on the spatial distribution of flux, we predict the lifetime of a half-micron layer of surface H2O ice, as it is eroded by solar wind protons. Our results generalize the single-point predictions of Farrell et al. (2019), showing that the surface ice lifetime may be limited by either plasma sputtering or micrometeoroid bombardment, as the sputtering rate varies along the surface. Similar calculations can be performed for other dynamical surface processes such as implantation and weathering.

We begin below in Section 2 with a review of the plasma wake model by Rhodes & Farrell (2019), which provides an instantaneous snapshot of the plasma in a 2D vertical cross-section of a crater, resulting in the flux along a line of the crater floor. Section 3 then sweeps this solution about the span of the crater floor and presents the results of a rotation-averaged calculation, including maps of the total flux (Section 3.1), geomagnetic modulation (Section 3.2), ion flow energy (Section 3.3), and ice sheet sputtering lifetimes (Section 3.4).

2. Instantaneous Solar Wind Plasma Wake

To obtain a snapshot of the solar wind hydrogen flux associated with a specific Sun–Moon orientation, we apply the plasma wake model of Rhodes & Farrell (2019). This model adopts a self-similar plasma expansion (Gurevich et al. 1966) wake formulation from Farrell et al. (2010) to include an explicit expansion front. The front represents a cutoff for the bulk ion flow, beyond which the plasma is dominated by an electron cloud. Owing to the solar wind’s high Mach number, M, the topography of a large lunar polar crater is predicted to produce a substantial spatial void in the ion surface flux. While the study by Rhodes & Farrell (2019) is primarily concerned...
with the resulting negative surface potential in the electron cloud region, the present work is focused upon the proton flow to the surface, influenced by the lunar topography.

The present work approximates the solar wind by a pure proton–electron plasma, which represents most (over 90%) of the solar wind composition. Although beyond the scope of this work, we note that the plasma wake electric field has a smaller effect on heavier ions. This means that even accounting for multiple species, it is mostly protons that are substantially diverted into polar craters.

The physical process of plasma expansion into a crater can be understood as follows. As the quasi-neutral solar wind plasma flows over the lunar surface, a large void such as a crater will first be filled by the plasma electrons, which are lighter and have a relatively fast diffusion speed. The ion diffusion speed, in contrast, is two orders of magnitude slower, and in the absence of other forces, the bulk ion flow would remain roughly unchanged on the length scale of a crater. However, the electrostatic charge separation created by electron diffusion creates an ambipolar electric field, which accelerates the ions downward toward the surface. This mechanism creates a non-negligible ion flux along the crater interior. These protons striking the surface are generally implanted, with only ~1% backscattered into the solar wind or electron cloud (Saito et al. 2008).

The resulting 2D plasma wake structure, in terms of the vertical and horizontal parameters z and x, is characterized by the self-similar formulation of Farrell et al. (2010):

$$\frac{v_z}{C_i} = -\ln(n/n_0) = 1 - \frac{M_x}{x},$$  
(1)

for the vertical speed, $v_z$, and ion density, $n$, respectively, scaled by $C_i$ as the ion acoustic speed and $n_0$ as the ion density of the undisturbed plasma. The resulting 2D spatial structure depends solely upon the (dimensionless) Mach number, $M = v_x/C_i$. This solution assumes a horizontal solar wind flow over the top of the crater, with $x = z = 0$ defined by the top left point of the crater (see the diagram in Figure 1 of Rhodes & Farrell 2019). This assumption is reasonably accurate for craters in the Moon’s polar regions. It also assumes that the horizontal flow speed, $v_x$, remains constant as the plasma expands into the crater.

The local flux is determined by projecting to the total velocity ($v_x$, $v_z$) onto the normal of the surface slope ($\Delta x$, $\Delta z$):

$$\mathcal{F} = v_x n, \quad v_n = \frac{v_x \Delta z - v_z \Delta x}{(\Delta x^2 + \Delta z^2)^{1/2}},$$  
(2)

Note that $v_z$ is negative in the present system, with the plasma expanding downward toward the crater floor. As in the work of Rhodes & Farrell (2019), we enforce a wake front expansion boundary, below which no ions are found:

$$z_f = \left[ 1 - 2 \ln \left( \frac{x}{\lambda_{D0} M} \right) \right] \frac{x}{M}.$$  
(3)

Here $\lambda_{D0}$ is the Debye length of the undisturbed plasma. Additional information about the expansion front may be found in the review by Samir et al. (1983). In addition to this constraint on the main wake front, we also constrain the ion surface flow around small secondary obstacles within a crater. To this end, we apply a linear interpolation of the flow angle and speed at the top edge of secondary obstacles, so that a finite region beyond them may also exhibit an ion void.

As an example, Figures 1 and 2 illustrate the solar wind ion flow into Shackleton crater at an instantaneous moment in time. As the plasma flows from left to right, the cross-section view in Figure 1 highlights the plasma wake structure described above. The dashed gray lines represent the rarefaction front separating the undisturbed plasma from the quasi-neutral wake and the expansion front separating the quasi-neutral wake from the electron cloud below. In this view, we observe how the ions—owing to their high Mach number—flow above much of the crater floor and only reach the surface along the far wall downstream.

For the undisturbed solar wind at 1 au, we take the flow speed, density, and temperature to be, respectively, $v_x = 400 \text{ km s}^{-1}$, $n_0 = 5 \text{ cm}^{-3}$, and $kT = 11 \text{ eV}$. All of the length and depth units are expressed in kilometers, and the flux is mapped on a logarithmic scale relative to the undisturbed solar wind flow flux: $n_0 v_x = 2 \times 10^{12} \text{ m}^{-2} \text{ s}^{-1}$. Since the solar wind is taken to flow horizontally over the surface, the flux outside the crater is given by the thermal flux: $n_0 C_i/\sqrt{2\pi} = 6.5 \times 10^{10} \text{ m}^{-2} \text{ s}^{-1}$, or ~3% of the flow flux. Note that in order to highlight the crater topography, we have artificially flattened...
the exterior region and neglected associated perturbations in the initial solar wind conditions.

Figure 2 extrapolates the cross-section view shown in Figure 1 across the entire crater surface, maintaining a fixed Sun–Moon orientation. The crater topography is characterized by the overlaid contour lines. Axes and contour lines are measured in kilometers. The results in Figure 2 demonstrate how the relatively fast flow speed \( M = v_x/C_i = 12.3 \) creates a void on the left-hand side as the plasma slowly expands downward while being carried by the horizontal flow. As a consequence, the bulk of the ions entering Shackleton crater strike the crater surface far downstream. Just below the far wall rim, we observe a peak of approximately half of the flux: \( \approx 6 \times 10^{11} \text{ m}^{-2} \text{s}^{-1} \), or \( \approx 3.4 \text{ km of hydrogen per m}^{-2} \) over 100 million years. Moving down into the crater basin, the predicted flux rapidly diminishes.

In the following section, we rotate and average the instantaneous flux over a lunation, which is an entire lunar rotation cycle. In addition, we account for the density modulations introduced as the Moon passes through the Earth’s geomagnetic field (Poppe et al. 2018). The geomagnetic effect on the resulting flux distribution is presented, as well as the incidence flow energy distribution, which plays an important roll in secondary processes such as weathering and sputtering. An example sputtering computation is also presented, predicting the lifetime of a half-micron surface ice sheet.

3. Average over Lunar Rotation

Looking at the average incident plasma wake over a complete lunar rotation, we compare four south pole craters: Shackleton, Shoemaker, Faustini, and Haworth. We assume that all four craters experience a horizontally flowing solar wind, neglecting variations of up to 4% in latitude or the out-of-ecliptic polar angle. The present calculations apply a rotation average over 30 steps, or every 6°.

3.1. Flux

Comparing Figures 3 and 2, we observe how the lunar rotation relative to the Sun creates a ring of the flux along the rim of each crater. The smooth bowl-like Shackleton crater portrays a nearly perfect rotation of the image in Figure 2. In contrast, the other craters in Figure 3 exhibit many pockets of sharp flux variation corresponding with the local topographical

 Rotation and interpolation onto a fixed Cartesian grid is performed with the Python package scipy.ndimage.interpolation.rotate.
features. Peaks create dark spots (higher density), and valleys create light spots (lower density). For reference, typical values around the crater rim and base are listed in Table 1. Even the peak values just below the rim, $\sim 10^{11} \text{ m}^{-2} \text{s}^{-1}$, are an order of magnitude below the solar wind flux. This is a real effect, which occurs because much of the time the near-rim region resides in the void depicted in Figure 2. As discussed in the previous section, only the solar wind electrons diffuse fast enough to fill this void, while the bulk of the ions flow over it without striking the surface.

Highlighted in Figure 3 is the extreme proton void covering the central plane of Shackleton, spanning a radius of approximately 3 km around the center. The extensive flux void highlights the smaller width-to-depth ratio of Shackleton relative to the other three south pole craters. As Shackleton crater is 15 km wide and 5 km deep, roughly speaking, its characteristic width-to-depth ratio is 3/1. The other south pole craters, on the other hand, exhibit a characteristic width-to-depth ratio of around 7/1. The crater geometry uniquely characterizes the plasma wake electric field and thus the extent to which solar wind ions are diverted into the crater. The near absolute flux void in Shackleton’s central plane shows that, at this relatively low width-to-depth ratio, it is associated with an ever present electron cloud. As a consequence, such a permanent electron cloud may result in an extremely negative surface potential, maintained in steady state (Rhodes & Farrell 2019).

The dichotomy in characteristic shape is sharply visible in our calculated flux maps. In contrast with Shackleton, crater Shoemaker, Faustini, and Haworth all exhibit a finite central region flux. Typical values around the crater base fall lower to around $\sim 10^{10} \text{ m}^{-2} \text{s}^{-1}$, in agreement with the studies in Farrell et al. (2013, 2015, 2019). Our results suggest that these studies of the dynamic volatile processes should be revisited to incorporate the effect of this time-integrated plasma inflow on hydrogen retention (Starukhina 2001) and surface volatile/plasma sputtering (Farrell et al. 2019). Considering the variability of characteristic geometries (e.g., Shackleton versus other three south pole craters), with different width-to-depth ratios, may reveal new insights into the local environments and associated surface properties.

The central flux void for Shackleton crater may provide an explanation for the anomalously bright colored crater floor relative to the external region, discussed by Zuber et al. (2012). They suggested that the crater floor would receive less micrometeoroid bombardment due to the unusual width-to-depth ratio; crater walls effectively blocks meteoric infall. However, our study herein demonstrates that Shackleton’s width-to-depth ratio has a substantial effect on plasma ion inflow as well. Both volatile erosional processes—micrometeoroidal and ion—are diminished in comparison with nearby craters. On the other hand, the even brighter color of the crater walls cannot be explained by the calculated flux pattern, adding credence to the theory of Zuber et al. (2012) that the bright walls are more likely caused by another mechanism such as downslope regolith motion. In any case, it remains ambiguous whether the observed brightness patterns in Shackleton are due to water related hydrogen (hydroxyl) content or rather to surface minerals such as anorthosite (Haruyama et al. 2013), with the model results presented herein providing additional insight on one component of weathering on the crater floor.

Additionally, strong effects of local topography are visible, in particular in the Figure 3 maps of Haworth and Faustini. Small canyons are shown to be steep enough to be inaccessible to solar wind protons. While it is difficult to compare by eye with recent surface ice maps such as those found in Hayne et al. (2015) or Li et al. (2018), it would be informative for future studies to examine the correlation with these sharp surface features, as well as the macroscopic features. Such a reduced solar wind ion inflow into these “crater-in-crater” regions can have two competing effects on the volatile content. (1) If substantial icy regolith pre-exists, then reduced ion sputtering losses may afford greater longevity to the local ice compared to that of the surrounding surface. (2) If the ice in the regolith forms via solar wind implantation and subsequent OH formation (Starukhina 2001), then one would expect a lack of ice build-up in these doubly shadowed regions compared to the adjacent terrain. As previously mentioned, however, studies by Farrell et al. (2019) suggest that competing effects such as meteoric vaporization or particulate ejection may play a dominant role. We reiterate that to properly compare theory with experimental data from studies such as Hayne et al. (2015) or Li et al. (2018), integrated simulations are required to predict the combined spatio-temporal behavior of the entire system.

### 3.2. Magnetosphere Effect

Over the course of its orbit around Earth, the Moon experiences a periodic modulation in the solar wind plasma flux as it crosses through the tail of the magnetosphere. The central region of the magnetotail, i.e., the magnetopause, experiences a substantial drop in the solar wind plasma density. On its two flanks, however, i.e., in the magnetosheath, the plasma density is slightly boosted.

While the previous section flux maps in Figure 3 do include geomagnetic density variations, the effect is difficult to see. In order to highlight this effect, Figure 4 presents the difference between the calculation results with and without the geomagnetic density variation. As described by Poppe et al. (2018), the solar wind plasma density is perturbed by the Earth’s geomagnetic field, while the energy remains approximately unchanged. Thus the geomagnetic effect is easily incorporated by varying the value of $n_0$ in Equation (1) over the course of a lunar rotation cycle.

The Acceleration, Reconnection, Turbulence and Electrodynamics of the Moon’s Interaction with the Sun (ARTEMIS) data presented in Poppe et al. (2018) result in the following plasma density characteristics for the two different magnetosphere regions. (1) As the Moon spends an average of five days per cycle in the magnetopause, it experiences a diminished density of $0.55 \text{ cm}^{-3}$, or 11% of the normal value used to produce Figures 1 and 2. The Earth-ward direction in our figures is $u_p$, which coincides with the Sun-ward direction during the tail crossing. This results in a substantial flux decrease along the Earth-facing crater wall, which is clearly visible on the lower half in the difference plots shown in
Figure 4. (2) The moon spends another five days crossing the two magnetosphere flanks (2.5 days each), where the density increases to 6.0 cm$^{-3}$, or 120% of the normal value. The result is a slight flux increase along the crater wall regions on the sides, just bordering the flux-depleted regions.

The observed flux asymmetry introduced by the Earth’s magnetosphere may produce a measurable effect upon the volatile distribution in lunar polar craters. Owing to the reduced magnetopause plasma density, the flux along the Earth-ward facing crater wall (the lower half in Figure 4) is predicted to decrease by approximately 30% relative to the opposite side of the crater. The magnetosheath, on the other hand, introduces only a small flux increase at the edges of the magnetopause region, just barely visible as light purple dimples on the sides of each crater.

### 3.3. Ion Incidence Energy

In addition to the effect of the net surface flux, dynamic processes such as implantation and weathering may depend upon the incident ion energy. Figure 5 shows the spatial distribution of ion flow energy gained by ambipolar acceleration, relative to the flow energy of the undisturbed solar wind ions, 0.84 keV. Ion flow is only accelerated by this plasma expansion process, not slowed. Note that the flow energy is distinct from the thermal energy, which is assumed to be constant throughout the plasma and is comparatively small (∼0.01 keV). The incidence angle may also have an effect but is difficult to quantify for a granular surface and is not presently addressed.

Once again, comparing Shackleton crater with the other three, we observe a qualitatively different distribution generated by the alternate topography. The negligible surface flux in Shackleton’s central plane is coupled with a high energy annulus, over 30% more energetic than the solar wind. The wider craters also exhibit a substantial energy gain of incident ions in the central plane, on the order of 15%–20% higher than the solar wind.

Comparing Figures 5 and 3, it is apparent that the ion incidence energy and flux density are anticorrelated. This is because the diffuse but highly deflected ions near the crater center undergo the most ambipolar acceleration (see Rhodes & Farrell 2019 for further explanation). The combined effect of the two opposite factors, namely flux density and energy, depends upon the specific process of interest: hydrogen accumulation, sputtering, weathering, etc. Further studies are required to examine the combined effects of the flux and energy upon dynamic surface processes.
3.4. Sputtering Lifetime of Surface Ice

The lifetime of H2O ice on the lunar surface is limited, among other effects, by sputtering from solar wind ions. While a study by Farrell et al. (2019) predicts that this effect is inconsequential relative to impact vaporization and ejecta (with lifetimes on the order of $10^5$ versus $10^3$ yr, respectively), their model does not account for the varying spatial distribution of the ion flux. Note that the latter effects, caused by micrometeoroid bombardment, are anticipated to be uniformly spread across the surface. We now revisit the sputtering lifetime calculation and demonstrate the role of the presently studies plasma–surface interactions. Our calculations focus solely on plasma sputtering and do not include competing effects such as the creation of new water molecules by implanted hydrogen. The results presented in Figure 6 show the spatial variability of an ice sheet lifetime to be substantial.

Consider a uniform sheet of solid H2O ice, 500 nm thick, across the crater region. The sputtering lifetime is defined as the number of years for the sheet to be completely eroded by the incoming solar wind protons. This timescale is predicted to be comparable for a mixed topsoil of icy regolith (Farrell et al. 2019). According to Johnson (1990, see Figure 3.22b), the sputtering yield of protons striking H2O ice is roughly fixed at 0.75 H2O/proton in the energy range of interest: 0.8–1.5 keV. Thus we can produce a sputtering prediction based solely on the flux distribution shown in Figure 3 and ignore the energy variability shown in Figure 4. Given a density of $10^{21}$ H2O molecules per square meter of half-micron ice sheet, the sputtering lifetime is given simply by

$$\text{sputtering lifetime} = \frac{\text{ice sheet density}}{\text{flux} \times \text{yield}}.$$  \hspace{1cm} (4)

The results in Figure 6, inversely correlated with the flux pattern in Figure 3, suggest that any ice in the topsoil of the crater walls will be eroded by sputtering on the timescale of hundreds of years. For all four craters shown, this relatively fast erosion time along the crater walls dominates over the micrometeoroid induced effects computed by Farrell et al. (2019). On the other hand, the central plane exhibits much longer sputtering lifetimes, typically several thousand years for the wider craters and virtually infinite for Shackleton (the color bar cuts off at $10^4$ to highlight details in the shorter timescale range). In addition, this image suggests that smaller canyons may contain local ice pockets within the larger craters, where sputtering by ions is scarce.

Figure 5. Percent energy gain of the flow energy of ions striking the surface, relative to the undisturbed solar wind flow energy, 0.84 keV. Spatial dimensions are in kilometers for axes as well as altitude contours. The observed ion energy pattern is opposite to the flux distribution shown in Figure 3.
Note that the present work does not address the case of icy regolith, also discussed by Farrell et al. (2019). Their work suggests that the water sputtering timescale for a surface with 1% ice is dominated by the majority species, which is a much slower process.

4. Conclusion

An analytic plasma model has been used to map the long-term (lunation averaged) solar wind hydrogen flux onto the surface of lunar polar craters. The model is based on the well-established self-similar formulation of plasma expansion. By sweeping a 2D (vertical slice) plasma wake across the surface and then rotating the system, we obtain the average flux over a complete lunar rotation cycle. In addition, we incorporate geomagnetic field effects by varying the solar wind density based on the rotation phase.

Our calculations are performed on four lunar south pole craters: Shackleton, Haworth, Shoemaker, and Faustini. The resulting hydrogen maps include the average surface flux, the magnetosphere flux modulation, flow energy of the surface incident ions, and an example calculation of the sputtering lifetime of a half-micron ice sheet. Averaging over a lunar rotation cycle is found to produce a striking ring shaped pattern for the flux, with high density along the walls (∼3 kg m⁻² per 100M yr) and much lower density on the crater floor.

An inverse ring pattern is observed for the flow energy as well as for the ice sputtering lifetimes. The magnitude of this effect depends upon the height-to-width ratio, clearly separating Shackleton from its neighbors: Shackleton’s central floor flux is predicted to be negligible, whereas the other three craters only drop two orders of magnitude along the floor relative to the surrounding crater walls. Also visible are the smaller topographical features such as small valleys or peaks within the larger craters, creating local pockets of modified flux. Observed sputtering lifetimes of a 500 nm ice sheet range between 100 yr along the crater walls to well over 10,000 yr in the deeper regions such as the floor of Shackleton and local canyons in the other craters.

Solar wind can be a source of surface hydrogen and OH for dry regolith (Starukhina 2006) or a loss mechanism to ice already present in the region (Zimmerman et al. 2012). The net effect is yet unknown. Further analysis is thus needed to correlate the ion influx with existing maps of water icy regolith in polar craters (as in Hayne et al. 2015). Our results suggest that correlations could also be made for secondary features.
found within the polar craters, such as small crater-in-crater regions. We present herein the time-integrated crater ion influx as a starting point to such future studies.

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ORCID iDs
Dov J. Rhodes @ https://orcid.org/0000-0002-7352-0758

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