ABSTRACT
The electrostatic charging of the lunar surface is caused by its interaction with the local plasma environment and solar UV and X-ray induced photoemission of electrons. Probe equations are used here to calculate electrostatic lunar surface potentials as a function of angle from the subsolar point, thus giving a global perspective on charging processes. Since the Moon is in the solar wind plasma flow for most of its orbit, surface potentials are first determined for typical fast and slow stream conditions. They are then calculated using data from the Electron Reflectometer aboard Lunar Prospector. The latter reveals how the hot tenuous plasma of the lunar wake drives large negative surface potentials (up to ~−200 V) on the nightside of the Moon. Lunar surface charging in the Earth’s magnetosphere is also discussed, with initial predictions indicating that the nightside charges to ~−600 V in the plasma sheet. The ability to predict surface potentials is vital for understanding the lunar environment; in particular, processes such as ion sputtering and electrically-driven dust transport. The latter is especially important since dust significantly interfered with Apollo exploration activities.

1. INTRODUCTION
The surface of the Moon, like any object in a plasma, charges to an electrostatic potential that minimizes the total incident current [1]. The charging currents come from four main sources: photoemission of electrons ($J_{ph}$), plasma electrons ($J_{e}$), plasma ions ($J_{i}$), and secondary electrons ($J_{sec}$). ($J_{sec}$ arises primarily from surface ionization by plasma electrons.) The lunar dayside typically charges positive, since $J_{ph}$ usually dominates (see Fig. 1). As a result a “photoelectron sheath” forms above the surface, which in the solar wind extends ~1 m, and effectively shields the charged surface from the surrounding plasma [2]. On the nightside, the lunar surface usually charges negative since $J_{e}$ typically dominates. In this case a “Debye sheath” shields the surface potential [3] and can extend from meters to possibly ~1 km above the surface [4]. However, there are significant uncertainties in lunar surface charging processes, and very little is known about either spatial or temporal variations.

Surface charging processes are thought to drive the transport of lunar dust grains with radii <10 μm, particularly near the terminator [5,6]. The Surveyor landers observed ≈5 μm grains levitating ~10 cm above the surface [7,8]. During the Apollo missions 0.1 μm-scale dust in the lunar exosphere was observed up to ~100 km altitude [9,10,11]. The most viable mechanisms proposed to explain these observations have been based on the principle that the like-charged surface and dust grains act to repel each other such that dust is lifted away from the surface. Under certain conditions, the heavier grains are predicted to electrostatically levitate near the surface [3,12], while the smaller grains are electrostatically “lofted” to ~10 km in altitude [5,13,14]. These phenomena could present a significant hazard to future robotic and human exploration of the Moon [6,15,16].

Figure 1. Schematic of the lunar electrostatic environment in the solar wind (not to scale).
Our objective here is to determine the global scale variation of electrostatic potentials and electric fields on the surface of the Moon. The electrostatic surface potentials are calculated using the probe equations from [17]. We first focus on typical fast and slow solar wind conditions, before using moments of the electron distribution function derived from Lunar Prospector Electron Reflectometer (LP/ER) data [18]. Also discussed is lunar surface charging in the magnetosphere, in particular during the Moon’s traversals through the plasma sheet.

2. SPACECRAFT AND INSTRUMENTATION

The LP spacecraft was in a rapidly precessing polar orbit about the Moon (period ~2 hours), which gave full coverage of the lunar surface twice every lunation. LP collected data for 18 months, with its altitude varying between 20 and 115 km, thus providing good coverage under most conditions. ER data is used to calculate the electrostatic surface potential, such that the net incident current is approximately zero, i.e., \( J_e \approx 0 \). (\( J_{sec} \) is not included here since for solar wind conditions it is expected to be less significant than either \( J_e \) or \( J_{ph} \), as argued by [3].) The current density equations are different for positive (\( \phi > 0 \)) and negative (\( \phi < 0 \)) surface potentials [e.g., see appendix in 17]. On the lunar dayside in the solar wind, we use the charging equations for a flowing plasma (most significant for \( J_i \)); while on the nightside, we use the equations for a static plasma. Photocurrent density from normally incident sunlight is assumed to be \( 4.0 \times 10^{-6} \text{ A m}^{-2} \) [20] (given a surface photoelectron emission efficiency of 0.1). \( J_{ph} \) varies with the angle from the subsolar point, \( \theta \), and so is highest at the equator at local noon (\( \theta = 0^\circ \)) and drops off to zero at the terminator (\( \theta = 90^\circ \)). The Debye lengths, \( \lambda_D \), used in this model are for the species attracted to the surface (e.g., where \( \phi > 0 \) we use the electron Debye length). It is important to note that the dominant source of electrons over most of the lunar dayside is from photoemission (at ~100 cm\(^{-3} \) this is ~10 times greater than in the solar wind). Assuming 1-D Debye shielding above a plane, the vertical lunar surface electric field is simply given by \( E_S = \phi_b / \lambda_D \).

3. SURFACE CHARGING MODEL

We calculate the electrostatic surface potential, \( \phi_b \), using the method and equations given in [17]. We solve numerically to find \( \phi_b \) such that the net incident current is approximately zero, i.e., \( J_e + J_i + J_{ph} \approx 0 \). (\( J_{sec} \) is not included here since for solar wind conditions it is expected to be less significant than either \( J_e \) or \( J_{ph} \), as argued by [3].) The current density equations are different for positive (\( \phi > 0 \)) and negative (\( \phi < 0 \)) surface potentials [e.g., see appendix in 17]. On the lunar dayside in the solar wind, we use the charging equations for a flowing plasma (most significant for \( J_i \)); while on the nightside, we use the equations for a static plasma. Photocurrent density from normally incident sunlight is assumed to be \( 4.0 \times 10^{-6} \text{ A m}^{-2} \) [20] (given a surface photoelectron emission efficiency of 0.1). \( J_{ph} \) varies with the angle from the subsolar point, \( \theta \), and so is highest at the equator at local noon (\( \theta = 0^\circ \)) and drops off to zero at the terminator (\( \theta = 90^\circ \)). The Debye lengths, \( \lambda_D \), used in this model are for the species attracted to the surface (e.g., where \( \phi > 0 \) we use the electron Debye length). It is important to note that the

\[
T_e = \left( \frac{K-1}{K} \right) T_k \approx \frac{2}{3} T_k
\]

Since there is no ion data available, we assume that the plasma environment at the orbit of LP is quasi-neutral and that the electrons and ions have the same temperature, i.e., \( n_i = n_e \) and \( T_i = T_e \).

4. MODEL PREDICTIONS

4.1 Fast and slow solar wind conditions

Solar wind flow can be broadly divided into two main types: fast and slow streams. The fast streams tend to be sourced from the poles of the Sun, while the slow streams come from the equatorial regions [21]. Fig. 2 shows predictions for \( \phi_b \) as a function of \( \theta \), given the typical fast and slow stream solar wind conditions shown in Table 1. As expected, charging on the dayside is photo-driven (\( \phi_b > 0 \)), while on the nightside it is electron-driven (\( \phi_b < 0 \)). A variation in surface potential is seen on the dayside due to the decrease in solar illumination (and surface photocurrent), as the terminator is approached. No variation is shown past the terminator on the nightside, since there is no solar illumination and the plasma environment there is assumed to be both uniform and stationary.

![Figure 2](image-url)

**Figure 2.** Lunar surface charging predictions for typical fast and slow stream solar wind conditions. Shown are (a) surface potentials, \( \phi_b \) (V), and (b) electric fields, \( E_S \) (V m\(^{-1} \)). The grey shading indicates the lunar nightside.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fast stream</th>
<th>Slow stream</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n_i ) [cm(^{-3} )]</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>( T_e ) [K]</td>
<td>( 1.4 \times 10^5 ) (12 eV)</td>
<td>( 1.4 \times 10^5 ) (12 eV)</td>
</tr>
<tr>
<td>( T_i ) [K]</td>
<td>( 1.5 \times 10^5 ) (13 eV)</td>
<td>( 1.0 \times 10^5 ) (9 eV)</td>
</tr>
<tr>
<td>( V_{\infty} ) [km s(^{-1} )]</td>
<td>650</td>
<td>400</td>
</tr>
</tbody>
</table>

Interestingly, Fig. 2 also shows that on the global scale the transition from positive to negative surface potential is predicted to be well dayside of the terminator. This transition occurs at \( \theta \approx 70^\circ \) for the fast stream and \( \theta \approx 35^\circ \) for the slow stream conditions. This means that
under slow stream conditions ≈40% of the lunar surface on the dayside has a negative surface potential. We also note that the rate of change of surface potential (i.e., the electric field along the surface) is still greatest just dayside of the terminator. This result is consistent with earlier predictions by [17] and shows that under typical conditions the lunar surface just dayside of the terminator will not be positively charged, as has often been assumed. However, lunar topography near the terminator, such as mountains or crater rims, could cause an increase in the solar illumination incident on the surface, thus locally enhancing the photocurrent such that a positive surface potential could occur.

4.2 Solar wind observations from Lunar Prospector

Fig. 3 shows predictions for lunar surface charging given (a) \( n_e \) and (b) \( T_e \) derived from LP/ER data as a function of \( \theta \). On the dayside, \( n_e \approx 7 \text{ cm}^{-3} \) and \( T_e \approx 12 \text{ eV} \), and so the predicted values for \( \phi_s \) and \( E_s \) are consistent with those shown in Fig. 2 for the fast and slow solar wind streams. However, nightside of the terminator the plasma conditions vary significantly from the previous results discussed in section 4.1. As the anti-subsol lar point (\( \theta = 180^\circ \)) is approached, \( n_e \) decreases rapidly while \( T_e \) increases. This variation is caused by the lunar wake.

On the global scale the Moon is effectively an unmagnetised dielectric body, therefore its interaction with the supersonic solar wind flow forms a void or “wake” in the antisinward direction [22]. The thermal motion of the solar wind particles allows them to fill in the wake from the flanks [23]. For any given temperature, the thermal velocity of the electrons is significantly greater than that of the ions due to the smaller electron mass. Therefore, it is the electrons that lead the infilling of the wake (note that the differential motion of the electrons and ions generates an ambipolar electric field at the terminator [6,23]). The number of electrons with sufficient energy to reach the centre of the wake (i.e., \( \theta = 180^\circ \) at the surface) decreases exponentially [19], which explains the trend in Fig. 3a. Since it is only the most thermally energetic electrons that can make it deep into the wake, this causes an increase in ambient \( T_e \) [19], as seen in Fig. 3b. Note that this increase in \( T_e \) toward the center of the wake is caused by the suprathermal tail of the solar wind electron distribution (described by the kappa function), and would not occur if it were truly Maxwellian [19].

Fig. 3c reveals that this increase in \( T_e \) in the wake results in surface potentials of up to almost −200 V. The decrease in \( n_e \) and increase in \( T_e \) also results in a significant increase in \( \phi_s \) at the surface. In turn, this leads to a much weaker \( E_s \), as shown in Fig. 3d.

4.3 The Moon in the Earth’s magnetosphere

It is important to realize that the Moon is not always in the solar wind, as indicated in Fig. 4. For about one-quarter of its orbit, the Moon is either in the tenuous plasma of the magnetospheric tail lobes, or the turbulent and energetic plasmas encountered in the geomagnetic plasma sheet and magnetosheath. At the orbit of the Moon, the plasma conditions in the magnetosheath are not significantly different from those in the solar wind. However, inside the magnetosphere, the plasma environments are typically much more tenuous and significantly hotter than the solar wind. Since the geomagnetic plasma sheet is much hotter than the tail lobes, which is an important factor for surface charging, we limit our discussion here to that region.

Practically no variation was observed in \( n_e \) and \( T_e \) as function of \( \theta \) when LP was in the plasma sheet. Given this apparent lack of dependence on \( \theta \), we assumed that the plasma flow, \( V = 0 \). On average, it was found that \( n_e \approx 0.016 \text{ cm}^{-3} \) and \( T_e \approx 1.9 \times 10^6 \text{ K} \) (161 eV) in the plasma sheet. For these observations, initial predictions indicate that on the dayside \( \phi_s \approx +10 \text{ V} \) and \( E_s \) can be as large as +12 V m\(^{-1}\), while on the nightside \( \phi_s < -600 \text{ V} \) and \( E_s \approx -1 \text{ V m}^{-1} \). These predictions are for average conditions, which suggests that during periods of enhanced geomagnetic activity, lunar surface potentials could be much greater.

![Figure 3. Lunar surface charging predictions based on LP/ER data in the solar wind. Shown are observations of (a) electron concentration, \( n_e \) \( \text{cm}^{-3} \) and (b) electron Maxwellian temperature, \( T_e \) \( \text{eV} \); and predictions for (c) surface potential, \( \phi_s \) and (d) electric field, \( E_s \).](image-url)
50 eV) and the plasma sheet (Te ≈ 160 eV), and the plasma sheet (Te = 50 eV) and the plasma sheet (Te ≈ 160 eV), as shown in Fig. 2, with variations in n_e and T_e being particularly important.

- The lunar wake plays a major role in the charging of the lunar nightside in the solar wind, as shown in Fig. 3. This is due to the exponential drop in n_e and increase in T_e toward the centre of the wake. On average, we predict nightside surface potentials of up to −200 V.

- Lunar surface charging is considerably different in the magnetosphere than in the solar wind. For example, in the plasma sheet surface potentials are predicted to be much greater, especially on the lunar nightside (~ −600 V).

The results presented here have begun to reveal the global scale variations in lunar surface charging and the strong dependence on the ambient plasma conditions in the solar wind or magnetosphere.

6. REFERENCES