Large negative lunar surface potentials in sunlight and shadow

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[1] We survey Lunar Prospector Electron Reflectometer measurements from times when the Moon was located in the geomagnetic tail, in order to characterize the occurrence of large (>500 V) negative lunar surface potentials, as identified by upward-going electron beams. We find that charging to these levels is rare, but that such charging events do occasionally occur in both sunlight and shadow. Large surface potentials are found primarily in the plasma sheet, and their occurrence depends mainly on the incident electron spectrum rather than surface properties. Most examples occur in shadow, where the current from energetic electrons dominates. However, some occur in sunlight, suggesting the occasional presence of either lower photoemission than expected or non-monotonic potentials. Depending on the electric field scale height, significant electric fields of up to ~100 V/m may sometimes exist at the lunar surface. **Citation:** Halekas, J. S., R. P. Lin, and D. L. Mitchell (2005), Large negative lunar surface potentials in sunlight and shadow, *Geophys. Res. Lett.*, *32*, L09102, doi:10.1029/2005GL022627.

1. Introduction

[2] Previous investigations using Lunar Prospector Electron Reflectometer (LP ER) data demonstrated that the lunar surface, when shadowed, typically charges to ~35 V negative with respect to the LP spacecraft in the lunar wake and the geomagnetic tail lobes [*Halekas et al.*, 2002]. LP likely also charges negative in shadow, and therefore this potential drop represents a lower limit on the magnitude of the surface potential, with the absolute surface potential probably on the order of ~100 V negative. However, these measurements were made during appropriate conditions for electron reflectometry - namely, in quiet and steady plasma environments. In this study, we survey all data taken when the Moon was located in the geomagnetic tail (including tail lobe, plasma sheet, and magnetosheath regions), in both sunlight and shadow, to determine if more significant negative lunar surface potentials occur, and if so, under what conditions.

[3] In general, an object in space charges to a potential such that the total current to it is zero, with the main current sources usually ambient electrons and ions, and photoelectron emission. In a very rough sense, an object usually charges to a potential on the order of the temperature of and with the sign of the plasma population which comprises the most significant current source [*Whipple*, 1981]. In the case of the Moon, this means that the lunar surface will usually charge to a negative potential on the order of the electron temperature in shadow, and a positive potential on the order of the photoelectron temperature (a few eV) in sunlight [*Manka*, 1973]. In sunlight, if the ambient electron density is very low, a larger positive surface potential of up to ~100 V may be reached [*Reasoner and Burke*, 1972]. On the other hand, if the electron density and/or temperature is very high, the surface can charge negative even in sunlight. Finally, for primary electron energies of ~100–500 eV, secondary electron emission can significantly affect the charging balance [*Horanyi et al.*, 1998]. Regardless of these complications, though, one expects to find the most significant negative lunar surface potentials when the ambient electron temperature is high and the surface lies in shadow.

2. Basic Observations

[4] We present LP ER measurements (of differential electron energy flux vs. energy and pitch angle, which is the angle between electron velocity and magnetic field) that provide evidence for large negative lunar surface potentials in shadow (Figure 1) and in sunlight (Figure 2). Figures 1 and 2 both show a characteristic loss cone at the highest energies, though on different sides of the distribution, due to opposite magnetic polarities. The electrons that would fill the loss cone have instead overcome the effects of both electrostatic and magnetic reflection to travel down the magnetic field line to the lunar surface, where they were absorbed and lost from the distribution. The observed loss cone depends on energy, which is diagnostic of the presence of parallel electric fields. Meanwhile, a bright ~1 keV electron beam is seen traveling up the magnetic field line inside the loss cone. We have previously interpreted these beams as secondary electrons emitted from the surface at low energies and accelerated through the potential drop to the spacecraft, and shown that the energy of the electron beam agrees with the potential difference inferred from the loss cone energy dependence [*Halekas et al.*, 2002]. In previous investigations we have mainly relied on loss cone measurements to characterize the potential drop between LP and the surface, since these were already used to infer surface magnetic fields. In this work, however, we will instead rely on direct observations of upward-going electron beams.

[5] The selected observations in shadow (Figure 1) and sunlight (Figure 2) are almost identical (excepting the opposite magnetic polarities and instrument modes with slightly different energy sweeps), other than the presence of a significant low energy (<~30 eV) electron population in sunlight. This component is ubiquitous in sunlight in the geomagnetic tail, and likely consists primarily of photoelectrons. The ER instrument is on a boom and should not measure a large population of photoelectrons from the spacecraft. Therefore, these likely consist primarily

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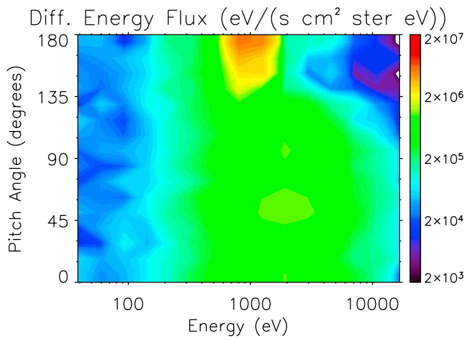

Figure 1. Energy pitch angle spectrogram obtained in the plasma sheet on March 11, 1998 at 15:31 UT. Both LP and the location of magnetic connection to the lunar surface lie in shadow. The LP position in SSE coordinates is (−0.92, −0.38, 0.36) R_L.

of photoelectrons emitted from the instrument and/or nearby regions of the boom, and attracted back to the ER by electric fields. The population is most significant when the ambient electron density and temperature are low, consistent with positive charging by photoemission in a low density plasma. These observations therefore imply that the potential of the ER reaches ~20–100 V positive in sunlight in the geomagnetic tail. Since we can only observe the potential difference between LP and the surface, the sunlit observation implies a (negative) lunar surface potential 20–100 V smaller than the energy of the upward-going electron beam. In shadow, on the other hand, the LP spacecraft may also charge significantly negative, implying that the electron beam energy provides a lower limit on the magnitude of the negative surface potential.

3. Distribution of Surface Locations

[6] We searched through all of the full 3-d electron distributions (integrated over 2.5 s once every 80 s) from ~68 days in 1998–1999 when LP was in orbit and the Moon was in the geomagnetic tail for upward-going electron beams with energies >500 eV. This survey yielded 496 observations of such beams, of which 47 had energies >1 keV, with a maximum energy of 2 keV. The location on the surface from which each beam originates is approximated by using the measured magnetic field at the spacecraft and performing a straight-line trace to the surface. LP orbits at an altitude of <115 km, so the error from this approximation is generally small. The surface locations thus approximated are shown in Figure 3, in selenocentric solar ecliptic coordinates (SSE, analogous to GSE, but Moon-centered). The north-south aligned sets of observations are a result of the polar orbit of LP, and demonstrate that charging events can have a duration of tens of minutes or more. Most observations lie in shadow (longitudes of 90–180), but some are found in sunlight. We find no significant clustering of observations in SSE coordinates or in selenographic Moon-fixed coordinates (which are only rotated slightly from SSE when the Moon is in the geomagnetic tail), other than that due to multiple observations on the same orbit or consecutive orbits. We find no clear associations with magnetic fields or surface features, though low data density makes a determination difficult.

4. Ambient Electron Spectra

[7] We calculated electron spectra from times when energetic beams were observed. Since the upward-going (reflected) part of the distribution depends strongly on both magnetic and electric fields (and contains the upward-going beam), we only used the downward-going (incident) half of the distribution. For comparison, we also roughly identified all data from the tail lobes and plasma sheet, and calculated median incident spectra for these regions as well (no interesting events were found in the magnetosheath, so we elected to omit magnetosheath spectra for the sake of figure clarity). We select results from solar zenith angles (SZA) of 0–80 and 110–180 and present median spectra in Figures 4 and 5. This selection ensures that both the LP spacecraft and the location of magnetic connection lie in shadow (SZA of 110–180) or in sunlight (SZA of 0–80), even if significant errors in field-line tracing exist. This yields 83 sunlit observations, of which 7 have energies >1 keV, and 278 shadowed observations, of which 25 have energies >1 keV. Each set of observations is also separated into two groups depending on the instrumental energy sweep, which went down to a lower energy (7 eV instead of 40 eV) in the geomagnetic tail for the last 5 months of the 18 month LP mission.

[8] Commensurate with expectations, large upward-going electron beams are only seen in very energetic plasma environments. In both shadow and sunlight, the median incident spectrum is clearly much more like the plasma sheet spectrum than the tail lobe spectrum. In fact, ~95% of the beam observations come from regions tentatively identified as plasma sheet, though the Moon is only in the plasma sheet ~44% of the time in the tail. Even in the plasma sheet we only observe energetic beams ~1.5% of the time, though. We attempted to determine approximate densities and temperatures by fitting the spectra to Maxwellian and Kappa distributions [*Halekas et al.*, 2002]. The plasma sheet spectra we observe often appear somewhat bi-Maxwellian or bi-Kappa, with the lower-energy portion not well covered by our energy sweep, rendering density estimates unreliable. Furthermore, in sunlight,

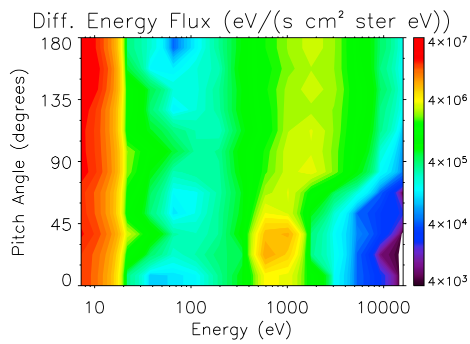

Figure 2. Energy pitch angle spectrogram obtained in the plasma sheet on May 1, 1999 at 11:17 UT. Both LP and the location of magnetic connection to the lunar surface lie in sunlight. The LP position in SSE coordinates is (0.28, −0.16, 0.97) R_L.

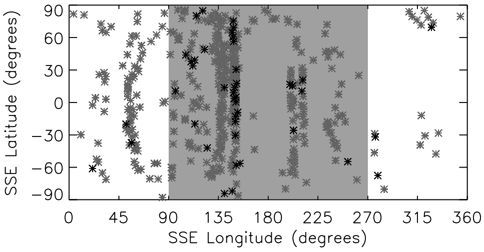

Figure 3. Locations of magnetic connection to the lunar surface when beams of energies >500 eV (grey) and energies >1 keV (black) are observed, in SSE coordinates. Background corresponds to illumination condition.

photoelectron contamination below $\sim$100 eV makes density estimation impossible. However, the temperature of the higher-energy component can still be reliably estimated. In both shadow and sunlight, we find a median plasma sheet temperature on the order of a few hundred eV. When we observe energetic upward-going beams, on the other hand, we find higher temperatures on the order of $\sim$1 keV. When beams with energies >1 keV are present, we find an even slightly higher temperature ($\sim$1.5–2 keV). These temperature values remain roughly the same in sunlight and shadow. In sunlight, however, it appears that we also require somewhat higher incident energy fluxes to cause large negative charging events.

[9] In shadow, our observations correspond well with theoretical expectations, with evidence for large negative lunar surface potentials in the most energetic plasma environments. In sunlight, it appears that we also require high electron temperatures, and even higher energy fluxes than in shadow. This makes sense, since we need a very large electron current to overcome the effects of photoemission. However, if we estimate the relevant currents, we find a puzzling situation. Total lunar photoemission currents of $\sim 4.5\ \mu A/m^2$ were estimated from measurements on lunar samples [*Willis et al.*, 1973], with slightly larger values inferred from in situ observations by other authors [*Reasoner and Burke*, 1972; *Goldstein*, 1974]. This value is an order of magnitude less than that for typical metals [*Whipple*, 1981], implying that the lunar surface will more easily charge negative in sunlight than a typical spacecraft (thus explaining how the surface could charge negative while LP charges positive). While electron density is not easy to determine from our measurements, though, we estimate that it is only on the order of 0.1 cm^{-3} when we see beams in sunlight. Along with temperature estimates, this allows us to calculate an approximate incident thermal current from the electrons. Unfortunately, we find that this current is approximately fifty times too small to balance the expected photoelectron current. Even if the density is much higher than we think, the electron current cannot possibly overcome the expected photoelectron current.

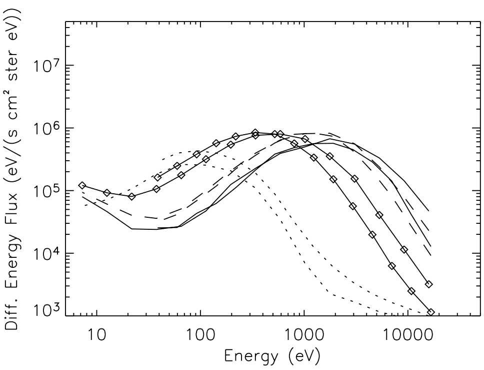

Figure 4. Median incident spectra in the tail lobes (dotted), plasma sheet (diamonds), and when beams of energies >500 eV (dashed) and energies >1 keV (solid) are observed, all in shadow.

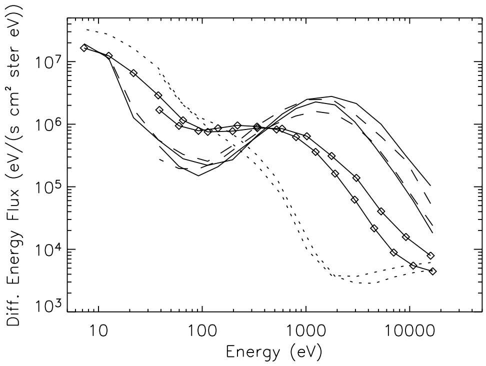

Figure 5. Median incident spectra in the tail lobes (dotted), plasma sheet (diamonds), and when beams of energies >500 eV (dashed) and energies >1 keV (solid) are observed, all in sunlight.

[10] We find evidence of large negative potentials in sunlight so infrequently that special circumstances must be required to generate them. One way out of our conundrum is to postulate the occasional existence of a greatly reduced photoemission current. Another possibility is provided by early theoretical work on this problem [*Fu*, 1971], which showed that non-monotonic potentials may exist at some times in sunlight. In the typical case, the potential is positive at the surface and monotonically decreasing with altitude. However, in some cases, due to space charge, another solution exists in which the potential decreases from the surface to a minimum and then increases again at greater distances. This creates a potential barrier which returns most photoelectrons to the surface, allowing the surface to charge more negatively than it would otherwise. For electron temperatures much larger than the photoelectron temperature, the surface potential for this case can be on the order of $-T_e/2$. Furthermore, in some cases this solution will even be energetically stable [*Fu*, 1971; *Nitter et al.*, 1998]. Unfortunately, for the extreme situation discussed here, a non-monotonic solution is almost certainly not stable. However, the potential distribution depends on the time history of the charging, and in rare situations, a non-monotonic potential could conceivably be momentarily present, which might explain some of our observations.

5. Conclusions

[11] We find evidence of negative lunar surface potentials of 500 V or more in both shadow and in sunlight. Potentials this large are about four times more likely in shadow than in

sunlight, though still rare. The large potentials almost all occur when the Moon lies in the geomagnetic plasma sheet, where the ambient electron temperature is at its highest, in agreement with theoretical expectations. In sunlight, however, estimates of the relevant charging currents show that the electron thermal current is still much lower than the expected photoemission current. The occasional presence of either much lower than expected photoemission or non-monotonic potentials may be required to explain the observations. In any case, our data show that the lunar surface can occasionally charge to rather large values in both shadow and in sunlight. The appearance of beams in many consecutive observations on certain orbits argues that charging events can last for some time. Depending on the scale height of the potentials, rather significant electric fields may occasionally be present at the lunar surface. For scale heights on the order of the Debye length (10's to 100's of m), surface electric fields as high as 100 V/m may exist. From the perspective of safety for astronauts and equipment on the surface, the plasma sheet is the most electrically hazardous plasma regime.

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