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Lunar Prospector measurements of secondary electron emission from lunar regolith

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ABSTRACT

We present the first in situ measurements of the secondary electron emission efficiency of lunar regolith, utilizing Lunar Prospector measurements of secondary electrons emitted from the negatively charged night side and accelerated upward by surface electric fields. By comparing measurements of secondary currents emitted from the surface and incident primary electron currents, we find that the secondary yield of lunar regolith is a factor of ~3 lower than that measured for samples in the laboratory. This lower yield significantly affects current balance at the lunar surface and the resulting equilibrium surface potentials. This information must be folded into models of the near-surface plasma sheath, in order to predict the effects on dust and other components of the lunar environment, and ultimately determine the importance for surface exploration and scientific investigations on the Moon.
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1. Introduction

Like any object in space, the lunar surface charges in response to incident currents, reaching a floating potential with respect to the surrounding plasma such that positive and negative currents to the surface balance (Whipple, 1981). The currents to an object in space include those from charged particles in the surrounding plasma, independent of material properties. Typically, currents from lighter and faster electrons dominate over ion currents, acting to drive the surface negative. However, photoelectron and secondary electron emission currents, which depend on material and surface properties, also significantly affect the charging balance and the equilibrium potential. In sunlight, photoemission usually dominates, leading to a small positive potential. In shadow, depending on the secondary electron yield, surfaces can float either positive or negative. Indeed, early predictions of nightside lunar surface potentials ranged from near zero to −1800 V, for different assumed regolith secondary emission (Knott, 1973). Secondary electron emission from lunar materials has been measured in the laboratory, but not in situ.

The charging of the lunar surface has both scientific and practical interest. Charging of surfaces in space represents a fundamental physical process, worthy of study in its own right. In addition, near-surface electric fields resulting from surface charging strongly affect the plasma environment near the surface, as well as possibly significantly affecting the motion of lunar dust and ionized exospheric gases. Electric fields and dust near the surface may have important practical implications for robotic and human lunar exploration, as well as scientific observations from the surface (Stubbs et al., 2007). In order to understand and predict the charging characteristics of the surface, and the effects of lunar electric fields on dust and other components of the environment, we need in situ measurements of secondary electron yields from lunar regolith. To this end, we now present direct measurements of secondary electrons by Lunar Prospector (LP), and the resulting constraints on lunar secondary yields.

2. Methods

LP, which orbited the Moon in 1998–1999, included an Electron Reflectometer (ER) and a magnetometer (MAG). The ER provided 3-d electron data from ~7–40 eV (adjustable) to ~20 keV. This paper focuses on data from times when the Moon passed through the terrestrial magnetosphere in 1999, when the ER energy sweep reached the lowest energies (lowest energy bin centered at ~7 eV), allowing the best measurements of secondary electrons.

The ER was designed to measure the distribution of electrons adiabatically reflected from lunar crustal magnetic fields, thereby determining their magnitude; however, the reflectometry technique also proved capable of measuring electrostatic potential

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differences between the surface and the spacecraft (Halekas et al., 2002). In addition, the ER measured secondary electrons produced at the surface and accelerated up to the spacecraft through these potential drops (Halekas et al., 2002). Both of these measurements provided diagnostics of the presence of significant negative lunar surface potentials (occasionally reaching kilovolt values) particularly in the terrestrial plasmasheet (Halekas et al., 2005). However, without spacecraft potential data, quantitative measurements were at first impossible. Therefore, we recently developed new techniques to estimate the LP spacecraft potential, allowing the first quantitative measurements from orbit of lunar surface potentials and the incident electrons which, in part, drive surface charging (Halekas et al., 2008). We now show that these techniques also allow the first in situ measurements of the secondary electron emission efficiency of lunar regolith. In order to measure the secondary electron emission efficiency, we must accurately measure both the electron flux incident on the surface, and the secondary flux from the surface. The latter does not require us to know the LP spacecraft potential or the surface potential, but for the former knowledge of both quantities proves critical.

Measuring secondary electrons from the lunar surface proves conceptually simple. Parallel electric fields accelerate secondary electrons (generated at initial energies of a few eV (Whipple, 1981)) along magnetic field lines up to the spacecraft, forming a field-aligned beam of electrons, with a center energy (measured at the spacecraft) corresponding to the potential difference between surface and spacecraft. We show a typical electron distribution measured above the lunar night side in Fig. 1. The combination of magnetic and electric fields below the spacecraft acts to reflect much of the incident electron population. However, the reflected flux at energy E and pitch angle $180-\alpha$ cannot exceed the incident flux at energy E and pitch angle α, assuming no net acceleration/deceleration of electrons during their round trip between the spacecraft and the reflection point (i.e. assuming adiabatic behavior, generally a good approximation). Therefore, upward-going flux that significantly exceeds the corresponding downward-going flux, as shown by the contours in Fig. 1, indicates a secondary electron population. The beam contains the great majority of the secondary flux (as determined by a straightforward integration), but some secondary flux also scatters to other

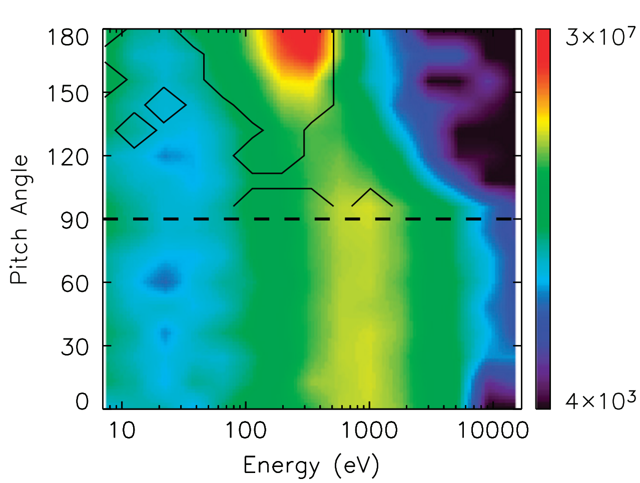

Fig. 1. Electron differential energy flux in eV/(cm^2 sr s eV) measured at 20:10:31 UT on April 29, 1999, with downward-going electrons at pitch angles $<90°$, and upward-going electrons at pitch angles $>90°$. Contours outline regions where upward flux exceeds corresponding downward flux by >2.5 standard deviations, indicating the presence of a significant secondary electron population in addition to adiabatically reflected primary electrons. The "loss cone" region of low upward-going flux above ~1 keV indicates an electron population lost to the surface.

(mostly nearby) pitch angles and energies, possibly indicating the effects of beam-plasma instabilities.

Our measurement of the total secondary electron current J_{SEC} does not depend on the potential of the surface U_M or the spacecraft U_{LP}, provided that all secondary electrons escape the near-surface region and reach the spacecraft. This requires a monotonic potential variation above the surface, and a large enough negative surface potential such that the beam (with a center energy of $-U_M$) can overcome any potential barrier at the spacecraft and arrive with sufficient energy for us to measure it, i.e. $(U_M - U_{LP}) < \sim 10$ V. We assume that the first requirement is satisfied. Though some authors have suggested non-monotonic potential variation above the dayside surface, to our knowledge no one has predicted non-monotonic potential variation on the night side. Meanwhile, we can confirm the second requirement observationally, and find that it is often satisfied on the lunar night side, allowing us to routinely measure secondary electrons in shadow. However, in order to determine the secondary emission yield, we also need to know the primary current to the surface, which requires quantitative measurements of plasma electron fluxes and lunar surface electrostatic potentials. We can now calculate these quantities using the methods of Halekas et al. (2008).

In order to calculate the primary electron current incident on the surface, we determine the downward-going electron flux at the spacecraft, and utilize measurements of the lunar surface potential to determine the amount of flux reaching the surface. To adequately represent the full downward-going electron distribution, we fit the measured spectrum, after correcting for spacecraft potential (as described by Halekas et al., 2008), to a kappa distribution of the form:

$$f(v) = \frac{\Gamma(\kappa+1)}{(\pi\kappa)^{3/2}\Gamma(\kappa-1/2)}\frac{n_0}{\Theta^3}[1+v^2/(\kappa\Theta^2)]^{-\kappa-1} \quad (1)$$

For this distribution, n_0 represents the density, κ the kappa index, and the temperature $T_0 = \kappa/(\kappa-3/2)^* m\Theta^2/(2k)$, where Θ is the thermal velocity. From this distribution, we can calculate the total current incident on the lunar surface, integrating to find the formula:

$$J_0 = n_0 q\sqrt{\frac{kT_0}{2\pi m}}\frac{\sqrt{\kappa-3/2}\,\Gamma(\kappa-1)}{\Gamma(\kappa-1/2)} \quad (2)$$

In fitting to the measured electron distribution to determine the quantities in Eqs. (1) and (2), we self-consistently took into account the spacecraft potential (see Halekas et al., 2008). However, we have not yet taken lunar surface charging into account, so we can only use Eq. (2) as is if the surface lies at zero potential with respect to the plasma. Our observations show that the nightside surface usually floats at a negative potential—therefore repelling electrons and preventing those at low energies from reaching the surface. By shifting the distribution in energy according to the lunar surface potential, and re-calculating the moments with the correct limits, one can show that this changes the density, temperature, and current of the electron population reaching the surface as follows:

$$n = n_0\left(1+\frac{qU_M}{(\kappa-3/2)kT_0}\right)^{1/2-\kappa} \quad (3)$$

$$T = T_0\left(1+\frac{qU_M}{(\kappa-3/2)kT_0}\right) \quad (4)$$

$$J = J_0\left(1+\frac{qU_M}{(\kappa-3/2)kT_0}\right)^{1-\kappa} \quad (5)$$

In Fig. 2, we show LP ER data from a typical series of orbits around the Moon in the terrestrial magnetosphere. We determine

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