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# Dependence of lunar surface charging on solar wind plasma conditions and solar irradiation

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ABSTRACT

The surface of the Moon is electrically charged by exposure to solar radiation on its dayside, as well as by the continuous flux of charged particles from the various plasma environments that surround it. An electric potential develops between the lunar surface and ambient plasma, which manifests itself in a near-surface plasma sheath with a scale height of order the Debye length. This study investigates surface charging on the lunar dayside and near-terminator regions in the solar wind, for which the dominant current sources are usually from the photoemission of electrons $J_p$, and the collection of plasma electrons $J_e$, and ions $J_i$. These currents are dependent on the following six parameters: plasma concentration $n_0$, electron temperature $T_e$, ion temperature $T_i$, bulk flow velocity $V$, photoemission current at normal incidence $J_{P0}$, and photoelectron temperature $T_p$. Using a numerical model, derived from a set of eleven basic assumptions, the influence of these six parameters on surface charging – characterized by the equilibrium surface potential, Debye length, and surface electric field – is investigated as a function of solar zenith angle. Overall, $T_e$ is the most important parameter, especially near the terminator, while $J_{P0}$ and $T_p$ dominate over most of the dayside. In contrast, $V$ and $T_i$ are found to be the least effective parameters. Typically, lunar surface charging in the solar wind can be reduced to a two-current problem: on the dayside in sunlight, $J_p+J_e=0$, since $|J_p| \gg |J_e| \gg |J_i|$, while near the terminator in shadow, $J_e+J_i=0$. However, situations can arise that result in a truly three-current problem with some important consequences; e.g., very cold $T_e$ and/or very fast $V$ can result in $|J_p| \gg |J_e| \approx |J_i|$ on the dayside. The influence of surface charging pervades the environments of the Moon and other airless bodies, and the investigation presented here provides insights into the physical processes involved, as well as being useful for interpreting and understanding more complicated simulations.



## 1. Introduction

The surface of the Moon is electrically charged by solar irradiation on its dayside and the highly variable plasma environment that surrounds it. The main electric current sources that charge the lunar surface come from the photoemission of electrons by solar ultraviolet (UV) and soft X-ray radiation $J_p$, the collection of plasma electrons $J_e$ and ions $J_i$, and the secondary emission of electrons from the lunar surface $J_s$. As a result of these incident currents, an inhomogeneous region, referred to as a plasma sheath, forms above the lunar surface to shield the charged surface from the surrounding plasma, as shown in Fig. 1. When the lunar surface is in shadow, it typically charges negative with respect to the ambient plasma due to the incident flux of electrons being much greater than the flux of ions (see Sections 2.3 and 3); the sheath in this case is also referred to as a Debye sheath. In sunlight the surface typically charges positive with respect to the plasma because the current generated by the photoemission of electrons dominates; in this case the sheath is also referred to as a photoelectron sheath. All four current sources can be highly variable, which in turn results in electrostatic potentials and electric fields above the lunar surface being very changeable, both temporally and spatially.

Predictions that the dayside of the Moon is positively charged by the photoemission of electrons were made prior to the Apollo landings (e.g., Singer and Walker, 1962; Grobman and Blank, 1969). Analyses of measurements from the Suprathermal Ion Detector Experiments (SIDE), deployed on the Moon by the

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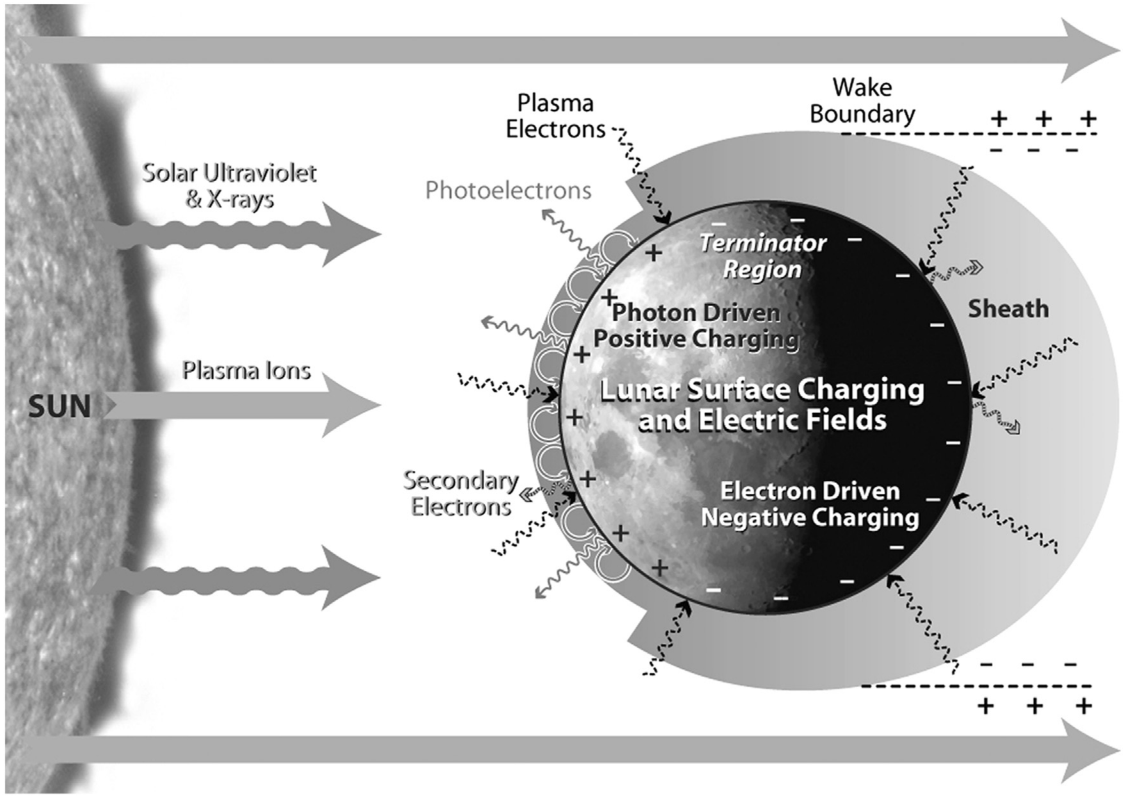


**Fig. 1.** Overview of the lunar plasma environment in the solar wind (not to scale) indicating the various charging processes acting on the Moon's surface: photoelectrons emitted by solar UV and soft X-rays, incident thermal plasma electrons and beam-like plasma ions, as well as the secondary emission of electrons. The curled arrows on the lunar dayside indicate the "return" photoelectrons that are unable to escape the positively charged surface. The discontinuity in the extent of the plasma sheath just dayside of the terminator indicates the transition from a cool, dense photoelectron sheath above a positively charged surface ($\lambda_D \sim 1$ m) to a hotter, more tenuous Debye sheath above a negatively charged surface ($\lambda_D \sim 10$ m).

Apollo 12, 14, and 15 missions, indicated that in the solar wind the lunar surface charged positive on the dayside ($\approx +10$ V), and typically charged negative near the terminator and on the nightside ($\sim -100$ V); see Freeman and Ibrahim (1975) and discussion in Section 5.1. These limited observations are in rough agreement with theoretical predictions of surface charging calculated using a "current balance" approach (Manka, 1973; Stubbs et al., 2007b). More recently, lunar surface potentials derived from Lunar Prospector (LP) Electron Reflectometer (ER) measurements have been broadly consistent, within uncertainties, with the Apollo era observations under typical solar wind conditions (Halekas et al., 2002; 2008). However, during solar energetic particle (SEP) events Halekas et al. (2007, 2009) have shown that the lunar surface can charge up to $\sim -4$ kV with respect to the ambient plasma at LP altitudes (well above the plasma sheath).

The influence of surface charging pervades the lunar environment, and can have a significant effect on a variety of natural phenomena. For example, surface charging has long been suggested as a mechanism for driving the transport of charged dust on the lunar surface (e.g., Gold, 1962). The finest component of the lunar dust ($< 10$ μm) is most susceptible to electrostatic forces (Colwell et al., 2007). The two modes of electrostatic transport of most interest are anticipated to be levitation (Nitter and Havnes, 1992; Nitter et al., 1998; Sickafoose et al., 2002; Poppe and Horányi, 2010; Poppe et al., 2012; Collier et al., 2013) and lofting (Stubbs et al., 2006, 2007c; Farrell et al., 2007, 2010). The most compelling evidence for the transport of charged dust on the Moon comes from the Lunar Ejecta and Meteorite (LEAM) experiment deployed on the surface by the Apollo 17 mission, which appeared to detect relatively slow-moving ($\sim 100$ m s$^{-1}$), highly-charged dust grains of lunar origin, particularly near lunar sunrise and sunset; see Berg et al. (1976), Colwell et al. (2007), and references therein, as well as O'Brien (2011) for an alternative interpretation of the LEAM measurements.

Similarly, surface charging could have important implications for science and exploration activities on the Moon. It is likely that many of the lunar dust problems experienced by the Apollo astronauts –such as adhesion to suits and equipment that can lead to increased abrasion and contamination of seals – were exacerbated by electrostatic processes (e.g., see Gaier, 2005; Stubbs et al., 2007a, and references therein). It is important to appreciate that the Apollo astronauts only experienced the near-surface dust-plasma environment in the relatively benign lunar morning sector under normal solar conditions; as opposed to either the more active regions that appear to surround the terminator, or conditions during an interval of extreme space weather (Stubbs et al., 2012). In addition, another potential hazard could arise from electrostatic discharges (ESD) caused by the differential charging of objects on the lunar surface (Farrell et al., 2008b; Jackson et al., 2011; Zimmerman et al., 2012).

The objective of this paper is to better understand surface charging on the lunar dayside and near terminator regions and how it varies under different plasma and solar UV conditions. This is achieved by using a numerical surface charging model to perform an extensive investigation of parameter space in order to provide a clear sense of the key factors. Our investigation is based around typical conditions in the solar wind, since this is where the Moon spends about 70% of its time (the other $\approx 30\%$ is spent in the Earth's magnetosphere and magnetosheath; e.g., see Stubbs et al., 2007b). We do not consider surface charging on the lunar nightside much beyond the terminator, since including the effects of the plasma wake that forms downstream of the Moon is