CHARACTERIZING THE PLASMA SHADOWING AND SURFACE CHARGING AT THE MOON USING LOLA TOPOGRAPHIC DATA: PREDICTIONS FOR THE LCROSS IMPACT.
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Introduction: Since the Moon is an airless body, its surface is directly exposed to unfiltered solar UV and soft X-rays, as well as charged particles from the surrounding plasma environment – this causes it to become electrically charged [1]. In sunlight, the lunar surface typically charges to a positive electric potential of ~5 V with respect to the surrounding plasma, due to the dominant current being from the photoemission of electrons; while in shadow the plasma electrons usually provide the dominant current, and so the surface charges to a negative potential of ~100–1000 V [2,3]. The direct exposure of regolith to the space environment also results in space weathering, the generation of exospheric species (ion sputtering), and maybe the electrostatic transport of dust [1,4].

Plasma Shadowing: Clearly, solar illumination and shadowing are major factors in determining the lunar surface potential. However, to a first approximation, the Moon also casts a "plasma shadow" in the ambient solar wind flow, since most of the solar wind plasma is absorbed on the upstream side of the Moon. Plasma shadow calculations are similar to those for optical shadows [5], except that we must also account for the orbital motion of the Moon about the Sun and the non-radial component of the solar wind flow. The plasma shadow boundary provides a critical reference for the expansion of solar wind plasma into the void formed downstream of the Moon – referred to as the lunar wake [6,7].

The lunar regolith is a good insulator [4], so electric current conducts very slowly between regions in sunlight and shadow (i.e., at different surface electric potentials), which results in relatively abrupt changes at shadow boundaries.

Plasma shadowing of the lunar surface is complicated by topography over a wide range of spatial scales – from impact basins and mountain ranges to craters and boulders – which means that a highly accurate digital elevation model (DEM) is required in order to develop a reliable predictive capability. We also need to know about the orbital motion of the Moon, as well as the ambient plasma conditions.

We have developed a plasma shadowing model for the Moon, which we use here with a DEM of the southern lunar polar region produced from Lunar Orbiter Laser Altimeter (LOLA) data [8]. As a test case, we present shadowing predictions for the time at which the Lunar Crater Observation and Sensing Satellite (LCROSS) impacted into Cabeus crater, a permanently shadowed region (PSR) near the south pole [9]. We also show some *preliminary* surface charging predictions using some simple analytical solutions.

The Orbit and Spin of the Moon: The axial tilt of the Moon relative to the ecliptic plane is only 1.54°, so the solar wind is usually flowing parallel to the lunar surface near the poles. Since the Moon's spin rate is so slow (~10^{-4} ° s^{-1}), variations in shadowing occur over relatively long timescales (~hours); however, variations in surface charging, due to changes in ambient plasma conditions, are expected to have much shorter timescales (~10^{-3}–100 s).

LOLA DEM: The LOLA DEM that we use here has a resolution of 1/128° (≈240 m) in latitude and 1/4° (≈660 m at 85° latitude) in longitude. It is in Mean Earth (ME) coordinates (IAU Moon 2000) and heights are given relative to a reference radius of 1737.4 km. We use the SPICE Toolkit for the Sun location and related parameters.

Plasma Shadowing Model: For any given time and location on the lunar surface, we are able to calculate the following plasma shadowing parameters: (1) the direct exposure to the solar wind; (2) the solar wind incidence angle; (3) the normalized incident solar wind flux; (4) the radial distance to the plasma shadow boundary; (5) the closest distance to the plasma boundary, which is necessary for calculating the plasma expansion into the wake; and (6) the distance to the obstacle producing the plasma shadow. See figure.

Wake Model: Here we assume a basic isothermal expansion of a Maxwellian solar wind plasma into the lunar wake, which can be described by self-similar analytical equations [6].

Surface Charging Model: For speed and convenience, we have used simple analytical solutions for the lunar surface potential (see figure). In sunlight and the solar wind, we consider only the photoemission and plasma electron currents. In sunlight and the wake, we include the drop in plasma electron concentration at the surface. In shadow and the solar wind (close to the terminator), we just account for the plasma electron and ion thermal currents. In shadow and the wake, for incidence angles ≤ 90°, we use thermal plasma electron currents and ion beam currents. For incidence > 90° (ions flowing away from the surface), we include the thermal contribution to the ion current. As can be seen in the surface charging figure, for most of the wake the ions cannot reach the surface, so no surface charging solution can be obtained.

In reality, current balance at the surface is achieved – we have not accounted for the fact that the plasma expansion is not isothermal (electron temperatures increase in the wake) [10], or that secondary electrons get emitted from the surface (an additional current source) [1]. We are currently adapting our more sophisticated surface charging models to couple with the optical and plasma shadowing results presented here [see also 5], which will produce much more realistic suface charging predictions.

Predictions for the LCROSS Impact: On 9 October 2009 at 11:31:19 UT, the LCROSS Centaur upper stage impact occurred at latitude 84.675°S, longitude 48.719°W, and height of −3.83 km (indicated by black cross in figure). At this time, we estimate that the solar wind conditions at the Moon were: concentration = 5 cm^{-3}, ion temperature = 3.4 × 10^4 K (very low), electron temperature = 1.2 × 10^5 K, flow velocity = 300 km s^{-1}. The overall aberration angle of the solar wind flow from the Sun-Moon line was 5.74°, which is fairly large. Also see figure.

Summary: We have developed a highly versatile and accurate shadowing code that can be adapted to help address many questions about the Moon.

References: [1] Colwell et al. (2007) *Rev. Geophys*. [2] Freeman and Ibrahim (1975) *The Moon*. [3] Halekas et al. (2007) *GRL*. [4] Heiken et al. (1991) *Lunar Source Book*. [5] Stubbs et al. (2010) *LPSC 41*. [6] Samir et al. (1983) *JGR*. [7] Farrell et al. (1998) *JGR*. [8] Chin et al. (2007) *Space Sci. Rev*. [9] Ennico et al. (2009) *LPSC 40*. [10] Halekas et al. (2005) *JGR*.