THE DYNAMIC LUNAR ENVIRONMENT: PLASMAS, NEUTRALS, AND DUST. G. T. Delory[1], W. M. Farrell[2], J.S. Halekas[1], T. Stubbs[2,3], R. P. Lin[1], S. Bale[1], and R. Vondrak[2] [1]Space Sciences Laboratory, University of California, Berkeley, CA 94720 (gdelory@ssl.berkeley.edu) [2]NASA/GSFC, Greenbelt, MD 20771. [3]University of Maryland, Baltimore County, MD 20228.

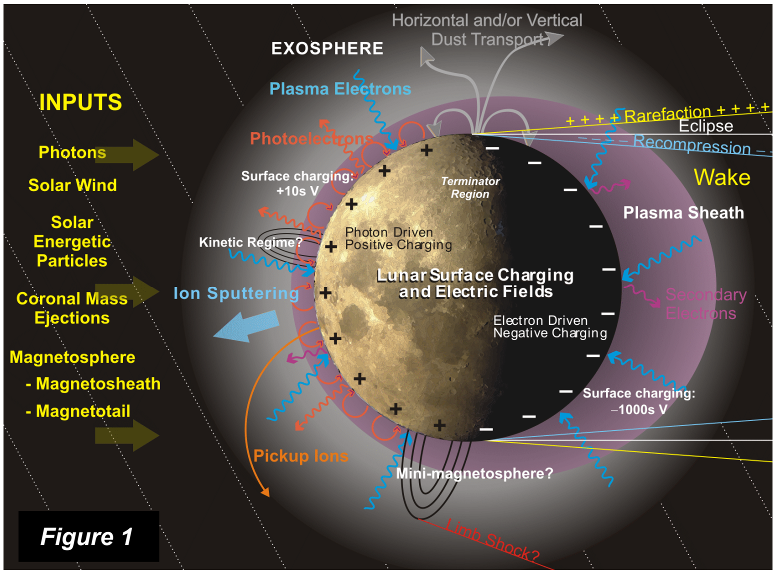

Figure 1

Introduction: The Moon is a convenient natural laboratory to study the interactions between solid bodies with tenuous atmospheres and the dynamic space environment. Ever changing plasma conditions combined with cycles of solar illumination are likely responsible for a myriad of effects that impact the dynamics of lunar plasmas, neutrals, and dust. Here we review what Lunar Prospector (LP) and Apollo era missions have revealed regarding both the space environment and surface-plasma interactions at the Moon, and discuss the implications of these processes for the planning of a renewed program of lunar science and exploration.

Global View: Results from LP and Apollo are the first hints at which may be a complex, coupled system linking plasmas, neutrals, and dust at the Moon. (Figure 1) At the largest scales, the average space environment around the Moon is highly asymmetric. Over most of the lunar orbit the environment is dominated by the impact of the solar wind and illumination on the dayside, and the formation of the lunar wake on the nightside. Thus conditions on the dayside lunar surface resemble those of the solar wind, with proton and electron densities between 5-20/cc convecting at an average speed of 400 km/sec, combined with a significant photo-electron population generated by incident solar UV on the surface. The role of the isolated magnetic anomalies in perturbing this environment remains unclear; while upstream signatures of the anomalies may indicate a shock structure [1], their ability to produce mini-magnetospheres (and thus alter the plasma environment above the lunar surface) is still debated [2, 3]. On the nightside, the lunar wake forms as a result of the supersonic flow of the solar wind around the solid obstacle presented by the Moon. Originally thought to be an MHD structure [4], results from both Wind and LP indicate that it is more likely a kinetic ion sonic disturbance [5, 6]. Within the central wake itself, plasma conditions are markedly different compared to the dayside; in addition to the absence of photocurrents, plasma densities are significantly depleted (~0.01/cc) and hotter (~100 eV) [5]. The detailed mechanisms underlying both the wake and the interaction of the magnetic anomalies with the solar wind remains an open question in our understanding of fundamental space plasma physics in both kinetic and fluid regimes.

Surface Interactions: The large scale structure of the lunar plasma environment has important implications for lunar surface processes, including surface charging, and the dynamics of the lunar atmosphere, ionosphere, and dust. The lunar surface acquires a potential relative to space due to the requirement that all currents from plasmas, secondary electrons, and photoelectrons are balanced. As a result, the lunar dayside typically charges positive by <+10V, a process dominated by the loss of photo-electrons [7]. Anti-sunward of the terminator, the absence of photo-electron currents combined with a more tenuous, hotter plasma produces negative surface potentials, dominated by electron plasma currents. LP has provided a wealth of data about the potential of the lunar surface under a variety of conditions. [8], and has confirmed that on the nightside potentials of −100V or less are common. Results from LP have also highlighted the importance of extreme solar events and the variable magnetospheric plasmas that the Moon traverses during its orbit. During solar energetic particle events and in the terrestrial plasma sheet, nightside potentials of up to –4.5 kV are possible [9].

The strong temporal and spatial variations in the lunar surface potential may cause electrostatic transport of dust, as suggested for other airless bodies [10]. Dust levitation almost certainly occurs within a few meters of the lunar surface, creating “Lunar Horizon Glow” (LHG), as captured by Surveyor lander cameras [11]. More controversial is a high-altitude component of lunar dust, which based on Apollo command module observations may extend to altitudes of 100 km [11, 12]. Visible to the naked eye, these dust concentrations are too high to be explained by impact-related processes alone, leading to the concept of dust fountains [13], in which large surface potentials expected near the terminator regions ballistically loft smaller dust grains to high altitudes. Whether LHG results from dust or perhaps another source such as emission from the sodium exosphere remains an open question; regardless, LP results do indicate that extreme surface charging occurs, which could in turn be responsible for dust levitation and lofting.

LP results are also yielding information about the secondary and photo-emissive properties of the lunar surface *in situ*. LP has shown that the yield of secondary electrons – produced by the impact of solar wind or other plasmas on the surface – is comparable to, but perhaps slightly lower than predicted by laboratory experiments on lunar samples and simulants [14]. This difference could be a result surface roughness effects that may scatter secondary electrons and cause re-absorption. There is some evidence that the effective large-scale photo-current emitted by the lunar dayside may be much lower in magnitude than expected. While still preliminary, one possibility is the formation of a trapped photo-electron layer contained in a plasma sheath structure that is non-monotonic [15]. Both secondary electrons and photo-emission are important processes to understand in order to successfully model and predict the structure and variability of the lunar plasma sheath.

Lunar surface-plasma interactions may be of great importance in the production of both the neutral atmosphere and ionosphere of the Moon. Sputtering by the solar wind and other plasmas will produce both neutrals and ions from the lunar surface [16]. The dominant processes involved in the sources, sinks, and dynamics of the neutral exosphere have been under considerable debate since Apollo, with numerous observation campaigns conducted in order to isolate the important processes at work. Photon-stimulated desorption (PSD), a leading mechanism for the production of neutrals from the surface, may also be enhanced by coincident plasma (ion) fluxes from the solar wind [17]. LP has provided a first look at the relevant plasma processes that will influence both neutral and ion dynamics. For ions generated at the surface, the negative surface potentials observed by LP may heavily influence the ability of these to escape due to the potential barrier. While LP did not carry an ion detector, the electron flux can be used to estimate the ion flux under the assumption of quasi-neutrality, and correlated with existing exospheric observations. In addition, LP observations of large surface potentials suggest that there are times when the ion current to the surface may be heavily modified, thus impacting neutral and ion generation from both PSD and sputtering.

Science & Exploration: While current data suggests that many of the processes shown in Figure 1 may be in operation, fundamental debates persist in terms of the dominant mechanisms influencing plasma, neutral, and dust populations at the Moon. These processes may have special importance in permanently shadowed regions (PSRs) [18], areas of interest to both science and exploration, where space plasmas, migrating neutrals, and dust may be the major factors (in addition to micro-meteorite bombardment) that alter the surface. Future explorers will be immersed in the lunar plasma/photo-electron sheath, including charged dust and electric fields, which we know from experience from other missions can pose a hazard to both electrical and mechanical systems. Ion and neutral measurements from Kaguya and future missions such as the proposed Lunar Atmosphere and Dust Environment Explorer (LADEE), and the Lunar-Solar Interactions Explorer (LuSIE) will be crucial in order to understand the present-day dynamics of the lunar space environment. This data, combined with results from the Lunar Reconnaissance Orbiter and plasma simulations of localized, critical regions on the Moon, will revolutionize our understanding of lunar-space weather.

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