ARTEMIS OBSERVATIONS OF ANISOTROPIC ION SPUTTERING OF THE LUNAR SURFACE: IMPLICATIONS FOR LADEE A. R. Poppe[1], J. S. Halekas[1], G. T. Delory[1], and V. Angelopoulos[2] [1]Space Sciences Laboratory, Univ. of California at Berkeley, Berkeley, CA, 94720 (poppe@ssl.berkeley.edu), [2]IGPP/ESS, Univ. of California at Los Angeles, Los Angeles, CA

Introduction: The lunar exosphere is a tenuous, collisionless combination of various neutral species derived from a variety of sources, including charged particle sputtering, micrometeoroid impact vaporization, internal gas release, and photon-, electron-, and thermally-stimulated desorption. Each of these processes produces various neutral species with differing spatial and temporal variability. Here, we investigate anisotropies in charged-particle sputtering of the lunar surface by both reflected solar wind protons and pick-up ions born from the exosphere itself. We use observations from the Acceleration, Reconnection, Turbulence, and Electrodynamics of the Moon's Interaction with the Sun (ARTEMIS) probes combined with particle modeling to investigate the nature of these anisotropies. Finally, we also discuss the possible implications of exospheric measurements currently on-going by the Lunar Atmospheric and Dust Environment Explorer (LADEE) mission.

ARTEMIS Observations: The two-probe ARTEMIS mission has been in orbit around the Moon since July 2011 observing plasma of both external and lunar origin [1]. Both spacecraft are in elliptical, 28-hr orbits and possess an extensive suite of plasma instrumentation (with the exception of an ion mass composition spectrometer). Figure 1 shows an ARTEMIS P1 observation on February 12, 2013 of reflected protons while the Moon was in the solar wind as described in the caption. As ARTEMIS P1 crossed the lunar dayside and approached the lunar dawn terminator, it observed both the main solar wind proton beam and multiple secondary ion beams traveling both toward and away from the Moon (panel (e)). Ions traveling away from the Moon and against the electric convection field are assumed to be solar wind protons reflected off either the lunar surface or crustal magnetic anomalies. Ions traveling toward the lunar surface are presumed to be a combination of reflected solar wind proton executing cycloidal motion about the interplanetary magnetic field and freshly-ionized heavy pick-up ions traveling directly along the electric convection field. This hypothesis is supported by simultaneous observations by ARTEMIS P2 near lunar dusk, which observed no ion populations besides the main solar wind beam.

We traced ion trajectories both forwards and backwards in time using the observed ion energy and direction along with the prevailing interplanetary magnetic and electric fields in order to understand the behavior of these ions. Backward-traced ions exhibit trajectories that intersect the lunar surface with energies between 0.3-1.0 times that of the incident solar wind, consistent with previous observations of protons scattered from the lunar surface or anomalies [2,3]. Back-traced trajectories show a range of reflection angles from the lunar surface with respect to both the local normal and the incident solar wind velocity. Such a wide range of angles could indicate that solar wind protons scatter isotropically from the lunar surface or that some of the observed ion flux is due to heavy ions from the lunar exosphere. Under the assumption of proton composition, forward-tracing of the trajectories from ARTEMIS to the Moon shows that all the moonward-directed flux impacts the lunar surface at energies ranging from 0.05 to 5 times the solar wind energy. Surface impact angles also span the entire range between 0° and 90°, an important factor in calculating neutral sputtering yields, as previous work has shown a

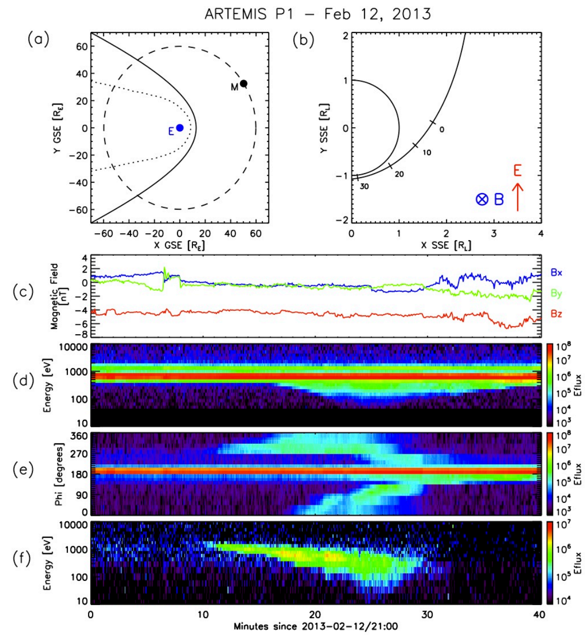

Figure 1: An ARTEMIS observation of anisotropic plasma sputtering of the lunar surface. Panels (a) and (b) show the Moon's position relative to the Earth and the ARTEMIS orbit relative to the Moon, respectively. Panels (c)-(f) show the magnetic field components, angle-averaged ion energy spectrum, spin-plane angular spectrum, and the ion energy spectrum along the electric convection field, respectively.

ten-fold increase in sputtering yield for highly-oblique impact angles [4,5].

Solar Wind and Pick-up Ion Sputtering Models: To further explore the global consequences of these ARTEMIS observations, we have constructed a three-dimensional particle tracing model to follow the trajectories of reflected protons from the lunar surface and quantify the subsequent re-impact flux. Ambient solar wind conditions are defined including the solar wind proton energy and the interplanetary magnetic and electric field vectors. Protons are launched in a Monte Carlo fashion from the dayside lunar surface with an isotropic distribution of scattering angles and followed under Lorentz motion until they either strike the lunar surface or escape from the lunar vicinity.

Figure 2 shows the results for one example model run with **B** = [0, 0, -5] nT and a solar wind velocity of 450 km/sec (similar to the conditions observed by ARTEMIS in Figure 1). Panel 2(a) shows a family of proton trajectories that reflect from a single point on the lunar surface at different angles with respect to the surface normal, illustrating the wide range of proton motion after reflection. Panel 2(b) shows the resulting secondary impacting proton flux summed over the trajectories reflected from all locations on the lunar surface. For southward IMF, a large fraction (>85%) of protons that reflect from the near-equatorial lunar dawnside follow trajectories that re-impact the Moon a second time. As seen in Figure 2(b), the sum of all re-impacting proton trajectories yields a sputtering source centered at approximately -25° longitude from the sub-solar point (roughly 10:30 am local time). The absolute strength of this anisotropic sputtering source can be calculated using various maps of lunar proton reflection efficiency as measured by Chandrayaan-1 [3]. These observations have revealed that reflection efficiencies can reach nearly 50% over the strongest magnetic anomalies, which will in turn generate significant anisotropies in the neutral sputtered flux via secondary sputtering protons.

An additional source of anisotropic sputtering may also be the process of "self-sputtering", where newly-photoionized neutrals from the lunar exosphere itself are driven into the lunar surface at high energies by the convection electric field and in turn, sputter new neutral atoms from the surface. We have explored this process through a series of particle simulations and found that depending on the composition of the lunar exosphere and the prevailing solar wind conditions, local self-sputtering fluxes can potentially be an order-of-magnitude higher than the main solar wind proton flux to the lunar surface [6].

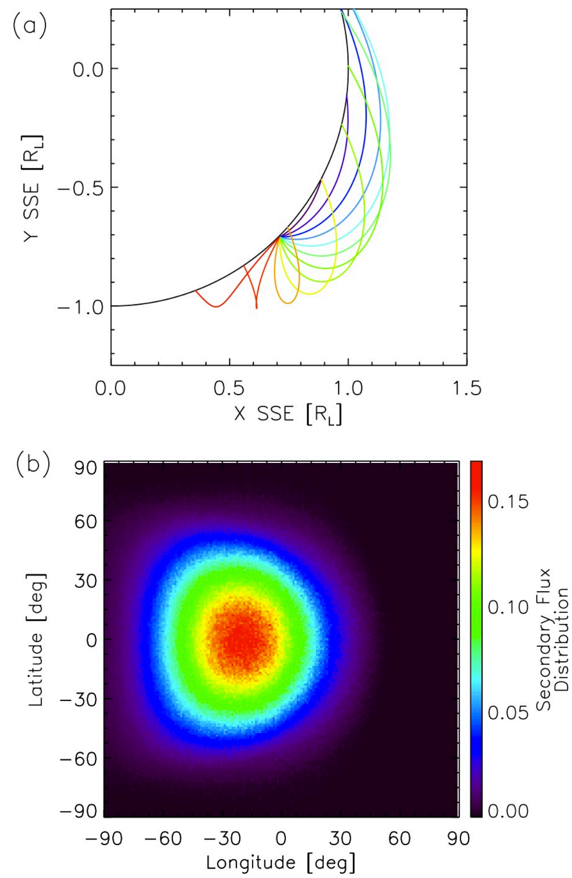

Figure 2: Model results for the re-impacting solar wind proton flux onto the lunar surface as described in the text.

Implications for LADEE: The processes described above may contribute to observed anisotropies in the distribution of lunar exospheric neutral species. The LADEE mission is currently in orbit around the moon taking in-situ and remote sensing measurements of exospheric composition and distribution. A correlative study between LADEE neutral and ARTEMIS plasma measurements may reveal the signature of anisotropic sputtering sources, which will in turn contribute to our knowledge of the fundamental sources and sinks of neutral exospheres around airless bodies throughout the solar system.

References:

[1] Angelopoulos, V. (2011) *Space Sci. Rev.* [2] Saito et al., (2008), *Geophys. Res. Lett.*, **35**(L24205) [3] Lue, C. et al. (2011), *Geophys. Res. Lett.*, **38**(L03202) [4] Biersack, J. P. and W. Eckstein (1984) *Appl. Phys. A,* **34** [5] Behrisch, R. and W. Eckstein (2007) **110**, *Springer*, Berlin, Germany [6] Poppe, A. R. et al. (2013) *J. Geophys. Res. Planets,* **118**