MODEL-BASED CONSTRAINTS ON THE LUNAR EXOSPHERE DERIVED FROM ARTEMIS PICK-UP ION OBSERVATIONS. A. R. Poppe[1,2], J. S. Halekas[1,2], M. Sarantos[2,3,4], G. T. Delory[1,2], [1]Space Sciences Laboratory, University of California at Berkeley, Berkeley, CA, 94720 (poppe@ssl.berkeley.edu), [2]NASA Lunar Science Institute, Ames Research Center, Mountain View, CA [3]NASA Goddard Space Flight Center, Greenbelt, MD, [4]Goddard Planetary Heliophysics Institute, University of Maryland, Baltimore County, Baltimore, MD

Introduction: We use ARTEMIS measurements of lunar exospheric pick-up ions in the terrestrial magnetotail lobes combined with a particle-tracing model to constrain the source species and distributions of the lunar neutral exosphere. These pick-up ions, generated by photoionization of neutral species in the magnetotail, undergo acceleration from both the magnetotail convection electric field and the lunar surface photoelectric field, giving rise to distinct pick-up ion flux, pitch angle, and energy distributions. By simulating the behavior of lunar pick-up ions in the magnetotail lobes and the response of the twin ARTEMIS probes under various ambient conditions, we can constrain several physical quantities associated with these observations, including the source ion production rate and the magnetotail convection velocity (and hence, electric field). Using the model-derived source ion production rate and established photo-ionization rates, we present upper limits on the density of several species potentially in the lunar exosphere. In certain cases, these limits are lower than those previously reported. We also present evidence that the lunar exosphere is displaced towards the lunar dawnside in the terrestrial magnetotail based on fits to the observed pick-up ion distributions.

ARTEMIS Observations: The ARTEMIS mission consists of two identical probes in elliptical orbits around the Moon with comprehensive plasma and electromagnetic field instrumentation [1]. As reported in [2], the ARTEMIS spacecraft have observed ions originating from the tenuous lunar exosphere while the Moon was transiting the terrestrial magnetotail. These ions were detected above the lunar dayside, at relatively low energies (< 200 eV), were highly focused in velocity, and came at a range of angles with respect to the magnetic field. Based on these observations, [2] concluded that these ions result from photo-ionization of neutrals in the lunar exosphere that subsequently undergo interaction with both the magnetotail convection electric field and the lunar photoelectric field. Figure 1 shows a cartoon outlining the various processes believed to operate for pick-up ions in the terrestrial tail lobes, including ions that simply convect at 90° pitch angle (“high-altitude ions”), ions born within the photoelectron sheath that gain parallel velocity (“low-altitude ions”), and ions that while born above the photoelectron sheath, are driven into the photoelectron sheath and are “reflected” onto non-90° pitch angle trajectories.

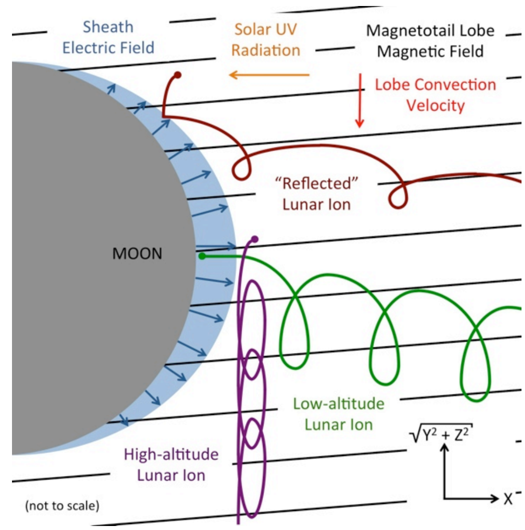

Figure 1: A cartoon of the various processes operating on pick-up ions above the lunar dayside surface in the terrestrial magnetotail. Adapted from [2].

Pick-up Ion Modeling: We have developed an ion tracing model in order to further explore the charateristics of the lunar pick-up ion flux in the terrestrial magnetotail. Ions are started in a Monte Carlo-type fashion within several typical exospheric scale heights above the lunar dayside surface and subjected to both magnetotail and surface electric and magnetic fields. The position and velocity of each ion is output regularly and the ensemble of trajectories is summed and appropriately weighted for a desired exospheric distribution. We typically assume a Chamberlain-type model with an added angular dependence from the subsolar point [3].

Figure 2 shows the relative density of mass 42 amu ions within 0.1 lunar radii of the plane containing the magnetic field and the convection velocity. As ions gyrate around the tail magnetic field, they also drift along with the convection velocity perpendicular to the magnetic field and, if an ion has interacted with the surface electric field, also drift parallel to the magnetic field. This results in a broad wedge of ion density trailing off of one side of the lunar dayside surface. While

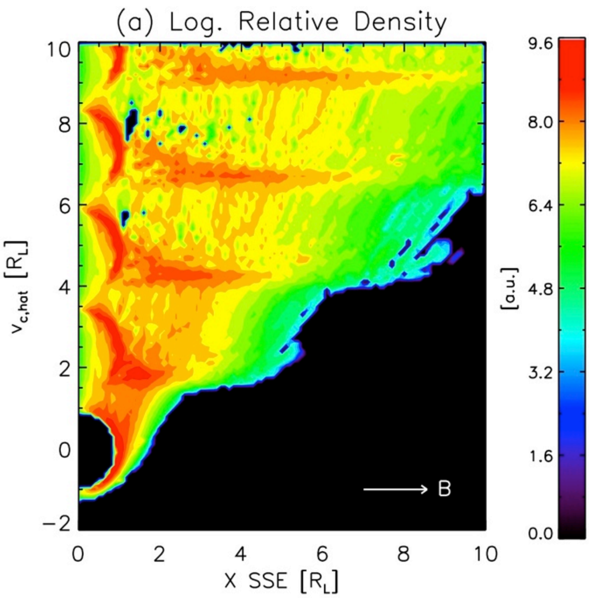

Figure 2: The relative density of mass 42 amu pick-up ions as they undergo acceleration from both the magnetotail convection field and the surface photoelectric field.

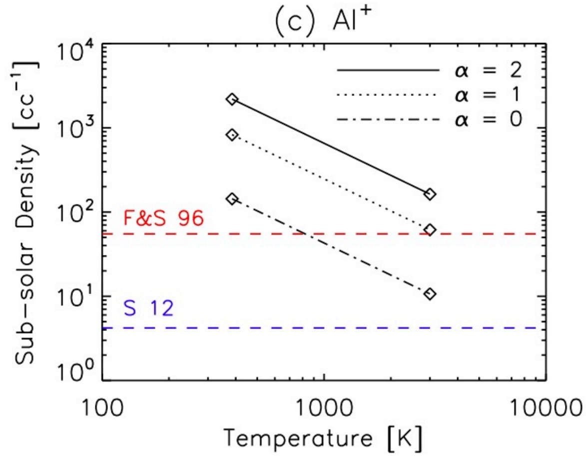

Figure 3: Limits on the exospheric neutral density of Al based on pick-up ion measurements as a function of exospheric temperature for three different angular distributions.

this simulation is only for one mass ion (amongst several known to be simultaneously present), the model nonetheless offers to opportunity to quantitatively compare to the ARTEMIS pick-up ion observations and place limits on the lunar neutral exosphere.

Exospheric Constraints: To place constraints on the distribution and density of the lunar neutral exosphere, we have run the pick-up ion model for a range of possible magnetotail and exospheric conditions for four specific ions masses representing groups of similar-mass ions. From the model outputs, we created synthetic ARTEMIS time-series spectra and compared these to the observed ARTEMIS spectra reported in [2]. By fitting to the spatial, energy, and angular distributions simultaneously, we can constrain several of the parameters associated with each individual ARTEMIS observation, including the magnetotail convection speed and direction, the source ion production rate, and any anisotropy in the neutral exospheric distribution. Finally, using photo-ionization rates calculated using the specific solar irradiation conditions on each of the dates where pick-up ions are observed, we can put limits on the density of several species thought to be in the lunar exosphere. These limits are dependent upon the assumed neutral exospheric distribution, including the neutral temperature, *T*, and the angular dependence, given by $cos^{\alpha}\theta$, where θ is the angle from the sub-solar point. Figure 3 shows the upper limit for Al neutral density as a function of exospheric temperature for three different values of α. The observational limit [4] and the most recent modeling estimate [5] are shown in red and blue, respectively. In this case, for hotter and more isotropic ($\alpha \rightarrow 0$) distributions, the upper limit for Al density is below the previously reported limits, although, in all cases, remains above the modeled estimate. We will present a similar analysis for several species thought to be in the lunar exosphere. Finally, our modeling has also indicated that the ARTEMIS pick-up ions observations are best fit when the neutral exospheric distribution contains a bulk angular offset from the sub-solar point in the dawnward direction. We will present the evidence for such an offset, which we tentatively ascribe to micrometeoroid impact vaporization, which is the dominant neutral production mechanism for most species while the Moon is in the magnetotail and is known to have distinct anisotropies [6,7].

References:

[1] Angelopoulos, V. (2010) *Space Sci. Rev*. [2] Poppe, A. R., et al. (2012) *Geophys. Res. Lett., 39*(L17104). [3] Chamberlain, J. W. (1963) *Planet. Space Sci.*, *11*, 901-960. [4] Flynn, B. C. and S. A. Stern (1996) *Icarus, 124*, 530-536. [5] Sarantos, M. et al. (2012) *J. Geophys. Res.*, *117*(A03103) [6] Janches, D., et al. (2006), *J. Geophys. Res.*, 111. [7] Poppe, A. et al. (2011), *Planet. Space Sci.*, *59*, 319-326.