FRACTIONATION OF SOLAR WIND MINOR ION PRECIPITATION BY THE LUNAR PALEO-MAGNETOSPHERE. A. R. Poppe[1], I. Garrick-Bethell[2,3], and S. Fatemi[4,5], [1]Space Sciences Laboratory, University of California at Berkeley (poppe@berkeley.edu), [2]Dept. of Earth and Planetary Sciences, University of California at Santa Cruz, [3]School of Space Research, Kyung Hee University, South Korea, [4]Swedish Institute of Space Physics, Kiruna, Sweden, [5]Dept. of Physics, Umeå University, Sweden

Introduction: The analysis of solar wind material implanted within lunar soil has provided significant insight into the makeup and evolutionary history of the solar wind and by extension, the Sun and the proto-solar nebula [1,2]. These analyses often rely on the tacit assumption that the Moon has served as an unbiased recorder of solar wind composition over its 4.5 billion-year lifetime. Recent work, however, has shown that for more than 75% of its lifetime, the Moon possessed a dynamo that generated a global magnetic field with surface field strengths of at least 5 μT [3]. In turn, the presence of such a field has been shown to significantly alter the lunar-solar wind interaction via the formation of a lunar 'paleo-magnetosphere' [4]. This paleo-magnetosphere has implications for the flux of solar wind minor ions to the lunar surface and their subsequent implantation in lunar soil grains. Here, we use a three-dimensional hybrid plasma model to investigate the effects of the lunar paleo-magnetosphere on the dynamics and precipitation of solar wind minor ions to the lunar surface. The model results show that the lunar paleo-magnetosphere can suppress minor ion fluxes to the lunar surface by more than an order-of-magnitude and strongly fractionates the precipitating solar wind in a complex, non-linear fashion with respect to both the minor ion charge-to-mass ratio and the surface paleo-magnetic field strength. We discuss the implications of these results with respect to both the analysis of trapped material in lunar grains and the semi-quantitative $^{40}Ar/^{36}Ar$ antiquity indicator for lunar soils [5,6].

Hybrid Model Results: In order to investigate the effect of the lunar paleo-magnetosphere on the flux of solar wind minor ions to the surface of the Moon, we have used a quasi-neutral hybrid plasma model, Amitis [7], that tracks the interaction of both the core solar wind protons and heavy, solar wind minor ions with the lunar paleo-magnetosphere. In addition to the core solar wind protons, we simultaneously modeled the behavior of eight additional ion species with increasing mass-per-charge ratios. As an example, Figure 1 shows the relative density of (a) protons and (b) heavy minor ions with mass-per-charge of ~8 within the lunar paleo-magnetosphere. For both species, the uniform upstream densities are highly disturbed by the presence of the lunar paleo-magnetosphere. A bow shock and magnetopause form upstream of the Moon, generally diverting ions away from the Moon. Despite this, the model shows ions precipitating through the magnetic cusp regions and ions that are quasi-trapped in the inner, dipolar magnetosphere. As we will discuss further in our presentation, the overall precipitation rates of solar wind protons and minor ions are highly affected by the presence of the lunar paleo-magnetosphere, with some species decreasing their relative overall flux to the lunar surface and some species actually increasing their overall flux.

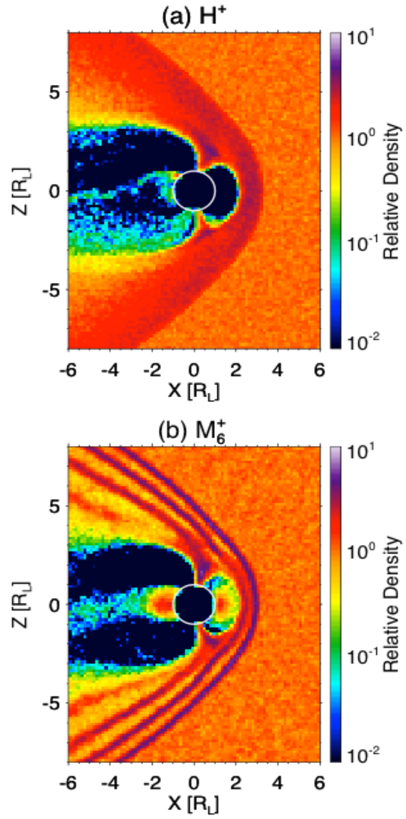

Figure 1: The relative ion density for (a) protons and (b) an example heavy minor ion for a paleo-magnetic field strength of 1 μT.

Minor Ion Fractionation: In addition to modeling minor ions with varying mass-per-charge ratios, we also investigated the effect of varying paleo-magnetic field strengths. We ran a control case with no paleo-magnetic field (akin to today's Moon) and an

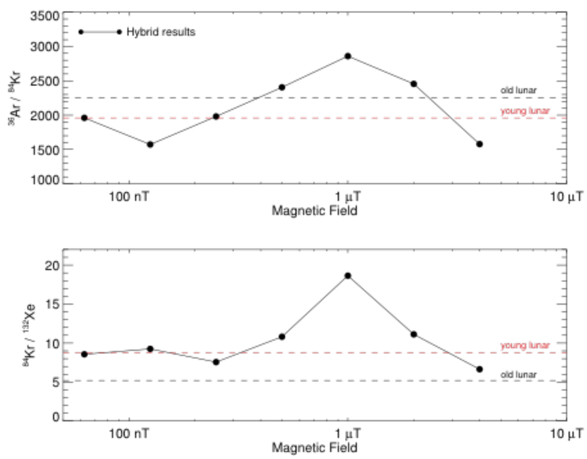

Figure 2: The ratios of (top) ^{36}Ar / ^{84}Kr and (bottom) ^{84}Kr / ^{132}Xe flux to the lunar surface as a function of paleo-magnetic field strength. Horizontal dashed lines denote the observed ratios in young and old lunar samples, respectively.

additional 8 cases with surface field strengths ranging from 125 nT to 4.0 μT. For each of these cases, we then computed the net precipitation of each minor ion, integrated over the entire lunar surface. Thus, with these calculations, we can compare the relative precipitation flux for each minor ion *and* the fractionation of various minor ions as a function of paleo-magnetic field strength.

Figure 2 shows the ratios of two modeled heavy minor ions: (top) ^{36}Ar / ^{84}Kr and (bottom) ^{84}Kr / ^{132}Xe as a function of paleo-magnetic field strength. Additionally, the horizontal black and red dashed lines denote the ratios observed in 'old lunar' samples and 'young lunar' samples, respectively [*adapted from* 2]. For the $^{36}Ar/^{84}Kr$ ratio, the predicted isotopic deviations from the hybrid model wholly encompass the deviation seen between 'young' and 'old' lunar samples. For the $^{84}Kr/^{132}Xe$, the negative isotopic ratio deviation seen in the 'old' lunar samples is nearly matched by the hybrid model for the 4 μT case. Intriguingly, the trend in the modeled $^{84}Kr/^{132}Xe$ seen in the 1, 2, and 4 μT suggests that paleo-magnetic field strengths of ~6-8 μT may yield a closer match to the observed ratio in 'old' lunar samples. We do note that the predicted isotopic ratios from the hybrid model do not appear to simultaneously match both the $^{36}Ar/^{84}Kr$ and $^{84}Kr/^{132}Xe$ ratios for a specific paleo-magnetic field strength.

Conclusion: Using the three-dimensional Amitis hybrid plasma model, we have simulated the interaction of solar wind protons and heavy minor ions with the lunar paleo-magnetosphere over a range of assumed paleo-magnetic field strengths. The hybrid model results show the successive growth of a lunar paleo-magnetosphere with increasing surface magnetic field strength, in line with previous results [4]. Simultaneous modeling of the dynamics of heavy, minor solar wind ions with the lunar paleo-magnetosphere have demonstrated that the fluence of these ions to the lunar surface is heavily altered by the presence of paleo-magnetic fields. While solar wind ions of all charge-to-mass ratios impact the dayside lunar surface directly for an un-magnetized Moon, the presence of paleo-magnetic fields shields the dayside lunar surface by up to an order-of-magnitude in fluence. Despite this dayside shielding effect, precipitation of solar wind minor ions through the paleo-magnetospheric cusps and from trapped ions in the inner magnetospheric dipolar region still allows solar wind minor ions to reach the lunar surface. Overall, the simulation results have extensive implications for the interpretation of implanted solar wind species in lunar regolith [e.g., 1, 2] and in reality, make an already difficult interpretation all the more challenging. Nevertheless, based on our findings presented here, we maintain that the presence of lunar paleo-magnetic fields, which are now well documented in the literature [e.g., 3, 8-11], and their subsequent effects must be accounted for in studies of trapped material in moderate-to-high antiquity lunar samples.

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