FORMATION TIMESCALES OF AMORPHOUS RIMS ON LUNAR GRAINS DERIVED FROM ARTEMIS OBSERVATIONS. A.R. Poppe[1,2], W.M. Farrell[2,3], and J. S. Halekas[2,4], [1]Space Sciences Laboratory, Univ. California at Berkeley, Berkeley, CA (poppe@ssl.berkeley.edu), [2]NASA SSERVI, Ames Research Center, Mountain View, CA [3]NASA Goddard Space Flight Center, Greenbelt, MD, [4]Dept. of Physics and Astronomy, Univ. of Iowa, Iowa City, IA

Introduction: The weathering of airless bodies exposed to space is a fundamental process in the formation and evolution of planetary surfaces. At the Moon, space weathering induces a variety of physical, chemical, and optical changes including the formation of nanometer sized amorphous rims on individual lunar grains. These rims are formed by vapor redeposition from micrometeoroid impacts and ion irradiation-induced amorphization of the crystalline matrix. For ion irradiation-induced rims, however, laboratory experiments of the depth and formation timescales of these rims stand in stark disagreement with observations of lunar soil grains. We use observations by the ARTEMIS spacecraft in orbit around the Moon to compute the mean ion flux to the lunar surface between 10 eV and 5 MeV and convolve this flux with ion irradiation-induced vacancy production rates as a function of depth calculated using the Stopping Range of Ions in Matter (SRIM) model. By combining these results with laboratory measurements of the critical fluence for charged-particle amorphization in olivine, we can predict the formation timescale of amorphous rims as a function of depth in olivinic grains. This analysis resolves two outstanding issues: (1) the provenance of >100 nm amorphous rims on lunar grains and (2) the nature of the depth-age relationship for amorphous rims on lunar grains.

Amorphous Lunar Rims: Lunar regolith grains that are exposed to incident radiation undergo a complex series of physical, chemical, and optical changes, collectively termed “space weathering” [e.g., 1, 2]. An understanding of space weathering is critical for the interpretation of remote observations of airless solar system bodies. Among the various forms of space weathering, laboratory analysis of returned Apollo lunar soil grains via transmission electron microscopy showed that grains often possess amorphous outer rims ranging between 20-250 nm thick [3,4]. Later work showed that these amorphous rims can be either similar to the host grain with some elements preferentially depleted or can be compositionally distinct from the host grain [e.g., 5,6,7]. Both types of rims are occasionally present as overlapping layers. The former rim type has generally been attributed to ion irradiation, which can preferentially sputter away certain elements present in the host grain, while the latter rim type is believed to be due to the deposition of ion-sputtered or impact-vaporized material from neighboring, geochemically distinct grains. The width of the ion-irradiated amorphous grain rims should correspond to the 20-30 nm penetration depth of ≈1 keV solar wind protons, and indeed, a majority of grain rims are consistent with this [8]; however, [8] also reported ion-irradiated grain widths of up to ≈250 nm in some grains, a finding seemingly inconsistent with 1 keV solar wind proton irradiation as a cause. Furthermore [9] have recently shown a correlation between the solar wind amorphized rim width and the grain exposure age calculated from solar flare track densities for lunar anorthite grains, with 20-50 nm rim widths corresponding to ages of ≈1 Myr and 150-200 nm rim widths corresponding to ≈10-50 Myr. Both the provenance of the thicker amorphous grain widths and their correlation with surface exposure time has to date remained unexplained.

Mean Ion Flux at the Moon: Using approximately 5 years of ARTEMIS ion measurements in lunar orbit, we computed the mean ion flux to the Moon as a function of ion energy and lunar phase. ARTEMIS observations provide three-dimensional ion energy distributions from ≈10 eV to ≈5 MeV once every 4 seconds. As shown in Figure 1, the ARTEMIS observations show that while the solar wind core beam near 1 keV is indeed the dominant ion flux to the Moon, there exists flux at all observed energies. This additional flux comes from several sources, including the

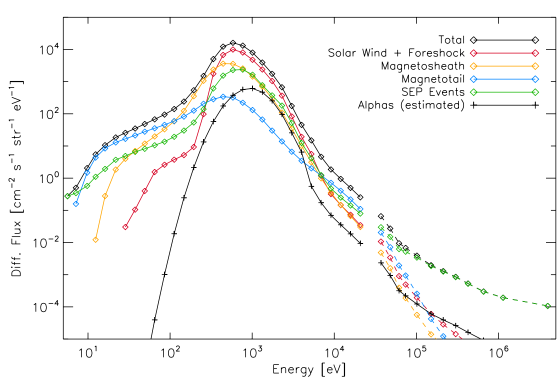

Figure 1: The mean ion flux to the Moon as observed by ARTEMIS as a function of ion energy and ambient plasma environment [14].

terrestrial ion foreshock, the terrestrial magnetosheath, terrestrial magnetotail, and occasional solar energetic particle events. These observations imply that charged-particle irradiation of the lunar surface occurs over a wide range of ion energies and, due to varying flux levels, over a wide range of timescales.

Weathering Timescales: To quantify the thickness of amorphous rims on lunar soil grains induced by the mean ion flux spectrum at the Moon, we used the Stopping Range of Ions in Matter (SRIM) Monte Carlo program [10] to calculate the damage produced in lunar soil grains as a function of incident ion energy, species, and depth. For our analysis, we injected 10^5 protons and alphas, respectively, at the center energy of each ARTEMIS ESA and SST energy bin into an olivine surface at 45° incidence angle. We used an Fo50 olivine composition ($MgFeSiO_4$) with a density of 3.8 kg m^{-3}. The surface, displacement, and lattice binding energies for olivine were taken from [11]. For each incident ion energy, SRIM tabulates the number of vacancies (i.e., the number of times an incident ion dislodged a crystalline atom) as a function of depth in the material, which is then normalized to number of vacancies per incident ion. We then calculated the vacancy production rates in lunar soil by convolving the SRIM simulation results with the mean differential ion flux at the Moon observed by ARTEMIS for protons (summed over plasma environments) and estimated for alphas (Figure 1).

The vacancy production rates can be inverted to establish the weathering timescale of exposed lunar soil for grain compositions for which the amorphization fluence has been experimentally measured. [12] have measured a critical charged-particle amorphization fluence of between 1 and 5×10^{16} He^+ ions/cm^2/s for ultra-thin olivine sections exposed to 4 keV He^+ ions (i.e., typical solar wind alpha energies). Along with the concurrent flux of protons expected in the solar wind, this fluence is achieved at the Moon between 20 and 100 years. Taking this timescale as representative of the formation time of a ≈10-20 nm thick rim (i.e., a thickness equivalent to that generated by only 1 keV solar wind protons and 4 keV solar wind alphas), we can "calibrate" the ARTEMIS+SRIM derived relative timescales. Figure 2 shows the charged-particle weathering timescale determined via this method compared to the inferred rim width-age data of [12], predicting that, for example, 100 nm thick amorphous rims should develop in olivine grains in approximately 50,000 years and 400 nm amorphous rims should develop in just under ≈3 Myr. Formation times for rims with thicknesses less than ≈100 nm qualitatively agree with those presented in [13] while the buildup of >100 nm rims extends to periods beyond those considered in [13]. We also suggest that the shape of the amorphous formation timescale for olivine presented here may also, at least qualitatively, explain the rim width-age relationship seen in anorthite grains as reported by [9], despite the lack of an experimentally measured critical amorphization fluence for anorthite.

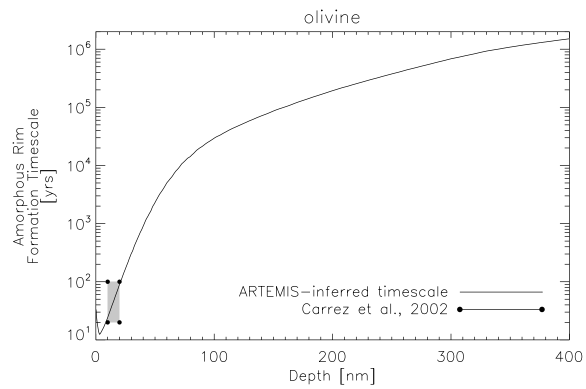

Figure 2: The formation timescale of amorphous rims on olivinic grains as determined from the combination of ARTEMIS observations, SRIM simulations, and the measurements of [12].

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