LUNAR LANDSCAPE EVOLUTION AND SPACE WEATHERING. P. O'Brien[1], S. Byrne[1], and T. J. Zega[1], [1]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, 85721(pob@lpl.arizona.edu)

Introduction: Airless bodies like the Moon are continuously bombarded by micrometeorites, cosmic rays, and energic particles from the solar wind. These processes, collectively known as space weathering, dominate the chemical evolution of the surfaces of these bodies. The optical properties and microstructure of materials exposed to space weathering are altered by the deposition of nanometer-scale reduced metallic Fe particles (npFe) [1,2].

Space weathering is the dominant process modifying the lunar surface today, yet the rate at which this process occurs is uncertain. The amount of weathering that occurs in a given grain is a function of the amount of time that grain spends in the upper millimeter of the regolith, the approximate penetration depth of energetic particles. Surface residence time is in turn dependent on the macroscopic processes that excavate, transport, and bury material across the surface of airless bodies. Other factors like the flux and energy of the bombarding particles and composition of the target surface contribute to differences in weathering rates throughout the solar system.

Lab measurements of soil samples can quantify the magnitude of space weathering that has occurred using proxies like amorphous rim thickness or volume fraction of nanophase iron. The most commonly used metric of soil exposure is I_s/FeO, which measures the amount of nanophase iron in a bulk soil, normalized by the amount of FeO in the soil available to be reduced to npFe [3]. More weathered soils will have more npFe and therefore a higher value of I_s/FeO than soils from immature samples which have spent less time near the surface being weathered. I_s/FeO values have been measured for Apollo lunar soil samples and Luna 24 cores and compiled in [3]. Together these measurements of samples from different locations and depths constitute the distribution of space weathering states in the lunar mare. However, the surface residence time of each sample is unknown. Therefore, to determine the rate at which these samples were weathered it is necessary to estimate how long lunar soil particles typically spend within the upper millimeter of the surface.

Model: To investigate this problem we use a numerical landscape evolution model that simulates the macroscopic processes that overturn and bury regolith on airless bodies. We evolve synthetic landscapes under two main processes: relief-creation from impact cratering and relief-reduction from micrometeorite gardening, mass-wasting, and seismic shaking (Fig. 1).

Impacts are randomly sampled from the relevant impactor flux distributions of [4]. Each impact is converted to a final crater diameter using pi-group scaling relations [5] and the crater is added to the landscape as a parabolic bowl with raised rim [6]. We track impacts globally and include secondary craters from sufficiently large impacts outside the model domain [7,8].

The processes which erode topographic features and move material downhill can be modeled as diffusion [9,10]. Diffusivity is the only free parameter in our model and sets the overall surface roughness of the final landscape. Higher diffusivity causes topographic features to erode faster, producing smoother landscapes compared to the case of low diffusivity. To calibrate the model so that it produces landscapes that resemble a given location on a planetary body, we must find the diffusivity that produces synthetic surfaces that match the surface roughness of that area. For the case of the Moon, we measure the value of a surface roughness metric like RMS slope across the lunar mare and then determine the diffusivity that generates surfaces which, on average, have the same RMS slope.

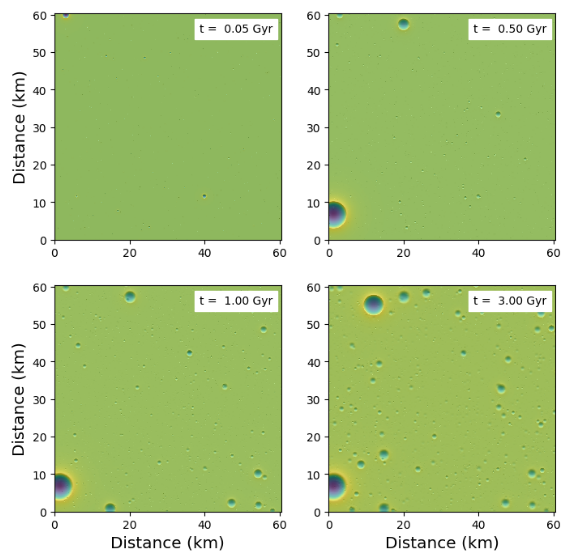

Figure 1. Evolution of a model surface over time from initially flat to a landscape that resembles a patch of the lunar mare

Tracer Particles: We seed the initial model with tracer particles and track their 3D position over time as the surface evolves. At each timestep we compute the effect of all impacts that occur using the Maxwell Z-model in which particles can be moved in the subsurface along flowlines during the crater excavation stage [11]. If any tracer particle flowline intersects the surface, the particle is ejected ballistically and transported across the surface. Particles in modeled grid cells, where diffusion leads to a net flux of material transported out of the cell, are shifted one cell in the steepest downhill direction.

At the conclusion of each model run we evaluate the distribution of surface residence times, i.e. the cumulative amount of time each particle spends at a depth of one millimeter or less. We then run the model in a Monte Carlo fashion using parameters relevant to the lunar mare to characterize the distribution of surface residence times of soil particles in mare regions.

Results: We run the model many times for a model period of 3.5 Gyr corresponding to the age of a typical mare unit and find that a significant fraction of particles spend between 0.5-1.5 Gyr in the upper millimeter of the regolith (Fig. 2). This time period is consistent with observations that optically bright, pristine, crater-ray materials fade over timescales of ~1 Gyr [12] due to space weathering.

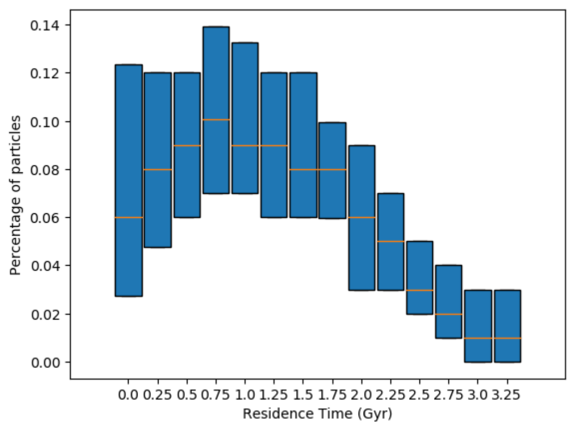

Figure 2. Results from ~50 model runs, showing the surface residence times of tracer particles. Orange lines show the median in each time bin and boxes show the interquartile range

We can now map our distribution of surface residence times to the distribution of space weathering states from [3] to determine how I_s/FeO increases in a grain as it undergoes space weathering on the lunar surface. This transformation uses the cumulative distribution functions, e.g. particles in the 90th percentile of surface residence time correspond to the 90th percentile of I_s/FeO values. The relation between I_s/FeO and surface residence time is well fit by an exponential dependence on time (Fig. 3). We assume unweathered soil should have no nanophase iron and so force the fit to predict an I_s/FeO value of 0 at t=0.

Discussion: Our preliminary results suggest that the growth of nanophase iron particles is initially rapid when soil grains are exposed and slows down as the grains remain in the upper millimeter of the lunar regolith. This implies that pristine, unweathered material exposed on the Moon will quickly darken and then asymptotically approach the optical properties of the dark, background material.

Using our model to simulate other airless bodies in the inner solar system like Mercury or the Martian moons we can estimate the relative rate of space weathering on those bodies as compared to the Moon.

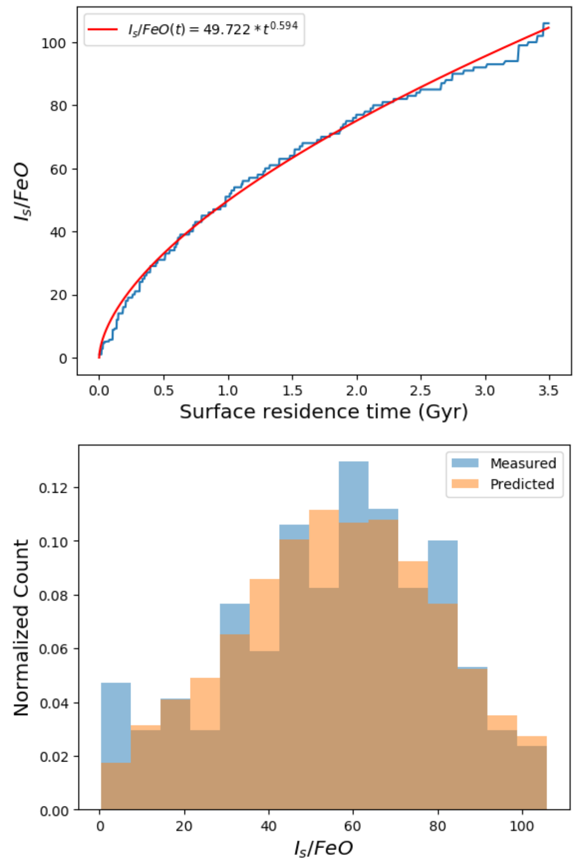

Figure 3. (top) Best fit curve for I_s/FeO vs. time **(bottom)** Histograms comparing measured lunar soil I_s/FeO values from [3] and those predicted for our modeled tracer particles using the above relation

References: [1] Hapke (2001) *JGR Planets*, 106, 10039-10073. [2] Pieters and Noble (2016), *JGR Planets*, 121, 1865-1884. [3] Morris (1978) *LPSC*, 9, 2287-2297.[4] Marchi et al. (2009) *Astr. Journal*, 137, 4936-4948. [5] Holsapple (1993) *Annu. Rev. Earth Planet. Sci.*, 21, 333-373. [6] Richardson (2009) *Icarus*, 204, 697-715. [7] McEwen and Bierhaus (2006) *Annu. Rev. Earth Planet. Sci.*, 34, 535-567. [8] Hirata and Nakamura (2006) *JGR Planets*, 111. [9] Soderblom (1970) *JGR*, 75, 2655-2661. [10] Fassett and Thompson (2014) *JGR Planets*, 119, 2255-2271. [11] Maxwell (1977) *Impact and Explosion Cratering*, 1003-1008. [12] Wilhelms (1987) *U.S. Geol. Surv. Prof. Pap.*, 1348, 302.