CAN SMALL IMPACTS EXPLAIN THE MOON'S SMOOTH SURFACE? P. O'Brien[1] and S. Byrne[1], [1]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721 (pob@lpl.arizona.edu)

Introduction: The lunar surface is degraded by a variety of physical processes that shape the topography over time. Micrometeorite bombardment [1], ballistic sedimentation [2], seismic shaking [3], and thermal cycling [4] erode existing surface features and, in concert with the impact rate, set the overall roughness of the landscape. Understanding these processes is therefore critical to interpreting the present-day surface of the Moon. However, the relative contribution of the various erosive mechanisms to the overall degradation of the lunar surface is presently unknown. Here, we aim to quantify the rate of landscape degradation from small impacts using a first principles numerical model of mass transport on sloped surfaces.

Soderblom [1] demonstrated that preferential downslope transport of ejecta from many small impacts gives rise to topographic diffusion. The diffusive model of micrometeorite erosion has subsequently been applied to studies of age dating [5-7] and crater saturation/equilibrium [8,9]. The key parameter in any such model of small impact erosion is the rate of diffusion, or diffusivity. We build upon the seminal model of [1] with updated measurements of crater morphology and the lunar impact rate to derive a novel estimate of the lunar landscape diffusivity. Based on analysis of topographic profiles of degraded craters, the diffusion rate on the lunar maria from all surface processes has previously been estimated at 5.5 m^2/Myr [10]. This empirical value serves as a point of comparison for our model and can help elucidate the role small impacts play in eroding surface features on the Moon.

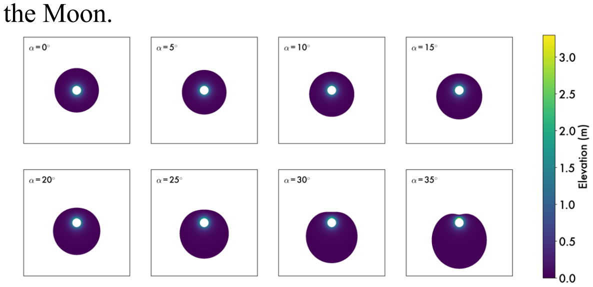

Figure 1. Ejecta thickness profiles for craters on sloped surfaces. On steep slopes, the ejecta blanket becomes increasingly elongated in the downslope direction (towards the bottom of each panel).

Mass transport model: Impacts occurring on sloped surfaces eject a cone of material at a fixed angle relative to the local gradient. As a result of the asymmetry in ballistic trajectories, material launched in the downslope direction travels further than material launched in the upslope direction. We develop an expression for the proximal ejecta blanket thickness profile produced by a crater forming on a sloped surface (Figure 1) by solving the ballistic range equations and incorporating measurements of lunar crater morphometery, e.g., rim height [11].

Next, we model the emplacement of asymmetric ejecta blankets on slopes and determine the net flux of material transported downslope by impacts. The mass of ejecta crossing a plane perpendicular to the downhill direction at some arbitrary coordinate is calculated as a function of crater position uphill or downhill relative to the plane (Figure 2). Ejecta mass is integrated over all impact positions upslope and downslope of the plane to obtain the net mass flux from all craters of that size on a given slope. This calculation is then repeated for a range of crater diameters and slopes.

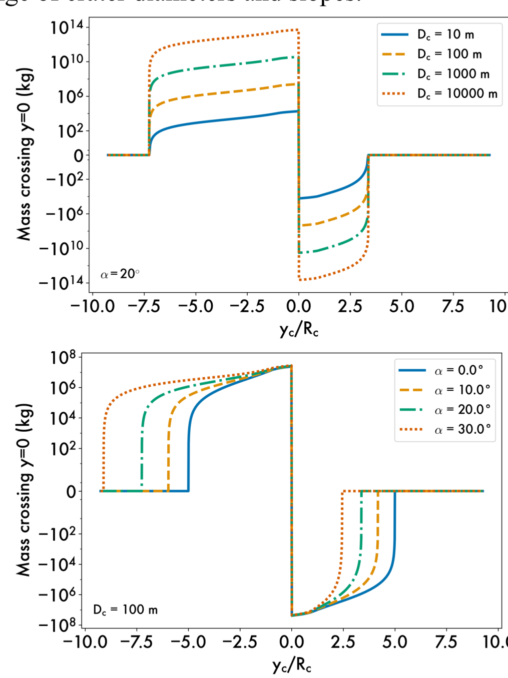

Figure 2. Ejecta mass crossing a plane at y=0 as a function of crater position in the along slope direction, y_c, for craters of varying size (top) and on varying slopes (bottom).

Impact flux: To incorporate the number of craters forming on the lunar surface, the flux of both primary and secondary craters is included in the model. The production rate of lunar primaries is given by the dynamical model of [12], and the number of secondaries generated by this primary population is determined according to the method outlined in [13]. The flux of small secondaries on the Moon is not well-constrained by observations, so we test the sensitivity of the diffusion rate to variations in the total cratering flux.

Results: Diffusivity is a scale-dependent process and care must be taken to specify the spatial scale at which a diffusion rate is applicable. For a given scale, diffusive degradation is driven by craters whose effects can be meaningfully averaged over the landscape at that scale. A common rule-of-thumb for the largest crater contributing to diffusion, D_{max}, is that surface features are diffusively eroded by the formation of craters smaller than ~10% of the size of the feature [14]. Craters smaller than ~1 cm approach the size of individual lunar regolith grains and we assume they do not contribute significantly to the total downslope flux of regolith. Here, we set D_{max} to 100 m (applicable to the degradation of kilometer-scale features) to facilitate comparison with the diffusivity from [10].

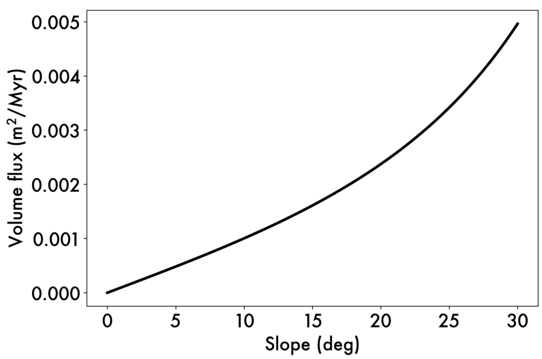

Figure 3. Net volume flux of regolith driven by small impacts is nonlinear with respect to surface slope.

Figure 3 shows the net flux of material transported downslope by craters between 1 cm and 100 m under the lunar impact rate. Unlike previous studies, we do not assume *a priori* that mass transport from small impacts is linearly dependent on surface slope, and in fact we find that net flux varies nonlinearly with slope. This leads to nonlinear diffusion akin to terrestrial hillslope evolution. Nonlinear flux, q, can be parametrized using equations of the following form [15],

$$q(\alpha) = \frac{\kappa_0 tan(\alpha)}{1 - (|tan(\alpha)|/S_c)^n}$$

where α is slope, S_c is the critical slope, n is an exponent between 1 and 2, and κ_0 is diffusivity when slopes are vanishingly small. A best fit curve to our results in Figure 3 yields S_c = 45.61°, n=1.74, and $\kappa_0 = 5.43 \times 10^{-3}$ m²/Myr.

Discussion: Our best fit value for the kilometer-scale diffusivity from small impacts is roughly three orders of magnitude smaller than that obtained by [10]. This discrepancy warrants further investigation. The number of new impacts observed during the Lunar Reconnaissance Orbiter mission lifetime suggest that the slope of the size-frequency distribution of small lunar primaries is potentially steeper than previously thought. Additionally, the discovery of tens of thousands of "splotches" point to the significant role secondary craters play in shaping the landscape at the smallest scales [16]. However, the relationship between splotch size and the diameter of an equivalent crater is currently unknown, making it difficult to conclusively establish the size-frequency distribution of secondaries below ~10 m in diameter on the Moon. Nevertheless, an enhancement in the production rate of lunar craters would lead to increased mass transport and a higher diffusion rate in our model. We tested the flux necessary to reproduce the observed lunar diffusivity [10] and found that the secondary production rate would need to be higher than our preferred value by a factor of roughly 3000. Similarly, if both the primary and secondary fluxes are scaled by the same factor, an enhancement of ~1000 brings our small impact diffusivity into alignment with the observed value.

Given current best estimates of the lunar impact flux, the diffusivity from small impacts appears to be insufficient to explain the observed degradation of kilometer-scale lunar craters without significantly enhanced small crater production rates. One possible explanation is that the steep walls of these craters have experienced significant degradation from non-diffusive processes such as landsliding, and therefore the diffusivity obtained from matching their degraded profiles is not representative of the overall landscape diffusion rate. Alternatively, small impacts might not be the dominant erosive mechanism on the Moon. Other processes, such as deposition of distal ejecta concentrated in crater rays [2] could contribute significantly to the degradation of lunar landscapes.

References: [1] Soderblom, L. A. (1970) *JGR*, 75, 2655–2561. [2] Minton, D. A. et al. (2019) *Icarus*, 326, 63–87. [3] Richardson, J. E. (2009) *Icarus*, 204, 697–715. [4] Molaro, J. L. & Byrne, S. (2012) *JGR: Planets*, 117, E10011. [5] Soderblom, L. A. & Lebofsky, L. A. (1972) *JGR*, 77, 279–296. [6] Craddock, R. A. & Howard, A. D. (2000) *JGR: Planets*, 105, 20387–20401. [7] Xie, M. et al. (2017) *GRL*, 44, 10171–10179. [8] Minton, D. A., Richardson, J. E., & Fassett, C. I. (2015) *Icarus*, 247, 172–190. [9] Hirabayashi, M., Minton, D. A., & Fassett, C. I. (2017) Icarus, 289, 134–143. [10] Fassett, C. I. & Thomson, B. J. (2014) *JGR: Planets*, 119, 2255–2271. [11] Stopar, J. D. et al. (2017) *Icarus*, 298, 34–48. [12] Marchi, S. et al. (2009) *AJ*, 137, 4936. [13] O'Brien, P. & Byrne, S. (2021) *JGR: Planets*, 126, e2020JE006634. [14] Minton, D. A. & Fassett, C. I. (2016) *LPSC*, 2623. [15] Roering, J. J., Kirchner, J. W., & Dietrich, W. E. (1999) *Water Res. Res.*, 35, 853–870. [16] Speyerer, E. J. et al. (2016) Nature, 538, 215–218.