A Refreshed Model for the Mixing Rate of Lunar Regolith E. S. Costello[123], R. R. Ghent[34], and P. G. Lucey[1] [1]Hawaii Institute of Geophysics and Planetology, University of Hawaii, Honolulu, HI, USA , ecostello@higp.hawaii.edu; [2]Dept. of Geology and Geophysics, University of Hawaii, Honolulu, HI, USA; [3]University of Toronto Dept. of Earth Science, Toronto, ON, Canada; [4]PSI, Tucson, AZ, USA.

Introduction: Meteoritic impactors churn lunar regolith, the layer of heterogeneous grains that covers nearly the entire lunar surface to a depth of tens to hundreds of meters. Modeling impact driven overturn or mixing allows us to explore the physics controlling a wide array of lunar surface processes. The lifetime of rays, ejecta blankets, stratigraphic layering and the burial, exposure, and the break down of volatiles and rocks are all subject to the rate of mixing.

Gault et. al. 1974 presented a pioneering work in their Poisson probability based regolith evolution model [1]. This model continues to influence model builders as well as those seeking to explore the breadth of surface processes controlled by mixing. Distinguishing itself from Monte Carlo method models for mixing, Gault et. al.'s model presents a direct relationship between depth of overturn and time. With a focus on mixing rather than sedimentation, evolution of a site, or the depth history of a grain, Gault et. al.'s model is designed to inform trends among regolith exposure effects reaching to different depths.

To describe a turnover rate, Gault et. al. present the cumulative number of turnovers *n*, at a local depth, in a length of time *t*. Results for overturn rate are presented as contours which trace the cumulative number of times a certain point has been successfully turned over to 50 or 99 percent probability in a set amount of time. A point on the lunar surface is considered "turned over" if at any time it has been influenced by an impact event. Area of influence is controlled by scaling relationships between meteoroid mass and resulting crater size. The frequency of influence is controlled by meteoritic flux.

Informed by models and observations made since 1974, we revisit Gault et. al.'s model to constrain the rate of impact-driven mixing. In this work we refresh the model in three ways: 1) We rework the Poisson probability expression that is central to this unique approach to the mixing problem. 2) We update values for meteoritic flux using contemporary observational data. 3) We present a treatment of crater size and shape parameters that is novel to the Poisson based mixing model. As we continue to refine the model, our approach will enable the exploration of secondary cratering phenomena and provides a mechanism to quantitatively include the effects of grain on grain interactions on mixing.

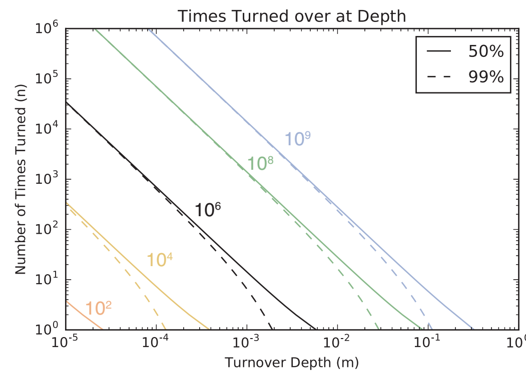

Figure 1: The contours of overturn rate. Material that is buried X deep has a 50% or 99% chance of being overturned Y times in the number of years indicated on the contour.

Poisson Expression: The Poisson probability expression, a key step in Gault et. al.'s model's mathematical process, describes the number of times a point has been influenced by an cumulative number of impact events in a certain amount of time.

Imagine a point *P* on the lunar surface. If the point is within the excavation radius *r* and area of effect πr^2 of an impact, it is defined to be successfully "overturned." Intuitively we know that any crater of excavation radius greater than *r* that impacts within the area of effect πr^2 will also successfully expose point *P*. Thus, to accurately represent the total number of impact events successfully exposing point *P*, we consider an integral distribution of crater radii. In documentation of the model, Gault et. al. present a differential form of the Poisson expression and account for only craters of radius *r*. We correct this by presenting the cumulative form and accounting for the influence of the integral distribution of crater radii *r* and greater.

Meteorite Flux: Cumulative meteoritic flux can be represented by a power function of meteorite mass or diameter: Ax^B. Gault et. al. vary the values of *A* and *B* for certain size ranges of meteorite, generating characteristic flattening at shallow depth in resulting overturn contours.

The most extreme flattening in the integral mass distribution used by Gault et. al. occurs at shallow depths and for tiny meteoroids, m < 10^{-7}g. Gault et. al. flatten the mass distribution for tiny projectiles because observations and crater counts available at the time described a low flux of low mass meteorites [2]. Our contours do not share this flattening. We update the values for *A* and *B* in the power law expression using modern atmospheric observation data [3]. These observations indicate that the parameters of flux remain constant over a large size range.

Gault et. al. also flatten the distribution of tiny meteorites because grain on grain interactions do not generate the the simple bowl crater structure. In our treatment, we approach crater scaling such that we can quantitatively explore the effects of grain on grain interactions and energy partitioning with future iterations of the model.

Shape and Size of Craters: Craters are bowl-shaped depressions the size of which depend largely on the energy of their parent explosive event. For now, we are concerned only with the depth to diameter ratio of the crater and topological shape rather than resulting ejecta blankets or rays.

Gault et. al. approach crater scaling using hypervelocity crater experiments and a set of variables held constant for certain ranges of meteoroid mass, all of which inform a model representing craters as spherical caps. Updating crater shape, we use a parabolic geometry to describe the topography of a simple crater bowl [4, 5, 6, 7]. This update leads to a higher rate of overturn.

Our approach to the crater size problem begins with an expression for transient crater diameter as a function of impacting meteoroid diameter [8]. Solutions for this expression fall into two regimes: strength and gravity. Large meteoroids create gravity regime craters. Small meteoroids create strength regime craters.

In the strength regime, the ratio of effective target yield strength to the initial dynamic pressure is an order of magnitude greater than the ratio of the lithostatic pressure at a depth equivalent to the projectile radius and the initial dynamic pressure generated by the impact. In the gravity regime the pressure at depth ratio is an order of magnitude larger than the yield strength ratio. The expression for strength regime overturn includes room for fine tuning with regard to grain on grain impacts.

Results: Our model suggests that the top millimeter of regolith is exposed at least 10 times every million years. These results approximately agree with the 1 millimeter “Mixing Layer” reported by Gault et. al. The high rate of overturn for the top few millimeters is consistent with describing the fluffy and thoroughly reworked layer of regolith where we observe a low thermal inertia layer from LRO Diviner thermal radiometer data [9], interpreted to result from a low-density near-surface structure.

Discussion: At longer timescales, our results diverge slightly from those of [1]. Gault et. al. show the top 5cm are overturned at least 10 times every billion years whereas our model suggests a somewhat deeper top 8cm are overturned at least 10 times every billion years. Still, when translated into in situ exposure age, both Gault et. al.’s original and our refreshed rates are lower than that predicted by Arnold’s Monte Carlo model [10] or calculated by assessing Apollo lunar soil samples [11, 12]. The modest turnover our model predicts at long timescales is a consequence of using the low contemporary meteoroid flux rate. Clearly, the rate was much higher earlier in lunar history [13], producing much more intense turnover to greater depths. Accounting for changes in flux rate throughout lunar history is a natural next step in developing the model.

Additionally, compelling recent work suggests that our contours, even at short timescales, are underestimating the rate of overturn in the top few centimeters of regolith by several orders of magnitude [14]. In an effort to match this rate, the role of secondary impact cratering demands exploration in our regolith mixing models. The overturn rate, especially for the shallow end of turnover depth, will be drastically affected by including secondary cratering, well beyond the effects of differences in crater scaling and shape or refinement of impact flux. Ongoing refinements of the model include treatment of secondary impacts.

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