THE FLUX OF IMPACT EJECTA ON THE LUNAR SURFACE FROM SCALING CONSIDERATIONS: IMPLICATIONS FOR OPERATIONAL HAZARDS AND GEOMORPHIC FORCING.

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Introduction: The impact cratering process has been critical to the evolution of the Moon's surface over its geologic history and remains an important ongoing process today [1]. Impact events have a major local effect, but also excavate ejecta particles that re-impact the lunar surface over a wide area. Quantifying the flux of ejecta to a given point on the Moon is the subject of this work. We also estimate how this flux is partitioned into different particle sizes and different ejecta velocities.

Motivation: There are two main factors motivating this work. First, and most critically, is the assessment of the hazard posed by impact ejecta for future surface exploration (i.e., to infrastructure, spacesuits, etc.). LROC observations of new craters have led to the re-emphasized need to consider this hazard [2]. In fact, a hazard assessment of this type was made prior to Apollo [3], although some of the underlying assumptions of that work are now clearly obsolete (see [4]). We also now know much more about the impactor flux [e.g., 5,6], scaling of impact events [7], and scaling of ejecta [8] than was known in the 1960s, so revisiting this hazard assessment is appropriate. We note that [4] also have recently revisited the earlier hazard estimates and independently revised them downward using an entirely different analytical approach.

The second motivation is that several recent papers [1, 9, 10] have argued that the flux of distal ejecta is the controlling factor in how fast the lunar surface evolves. For this reason, improving understanding of the ejecta mass flux and how the flux translates into geomorphic work is of interest. To be clear, it is obvious that the ejecta mass flux is much larger than the primary impactor mass flux – indeed, this is self-evident because the craters excavated by hypervelocity impacts are much larger than their impactors. On the other hand, the energy delivered by a given primary to the surface is larger than the sum of the energy delivered by all its associated ejecta, as required by conservation, aggravated by the fact that not all of an impactor's kinetic energy is partitioned into ejecta excavation. If distal ejecta and secondaries control lunar geomorphic evolution, this suggests that re-impacting ejecta must more efficiently translate their energy into geomorphic work than primaries (see also [11], §2.2.3). It is also easy to imagine the relative efficiency of primary and secondary impacts to do geomorphic work varying with the size of the primary. Considering the details of this process is thus of significant interest for lunar geomorphology.

Impactor Flux and Ejecta Scaling: Primary impact events occur at a very wide range of impactor sizes or masses, following a size-frequency distribution (SFD) that is fairly well-characterized [5, 6]. The cumulative frequency of small events ($D<\sim1$ km) is close to a power law with index of -3 ($N\sim D^{-3}$), though the power law index varies with size and there is some structure in the impactor SFD (Fig. 1). Small events are thus radically more probable than large events. However, the total excavated mass goes as $M\sim D^3$. No single event scale that dominates the excavated ejecta mass, and we need to consider carefully both the details of the impactor flux (or crater production function) and the ejecta mass-velocity scaling [8] to understand either hazards or surface forcing.

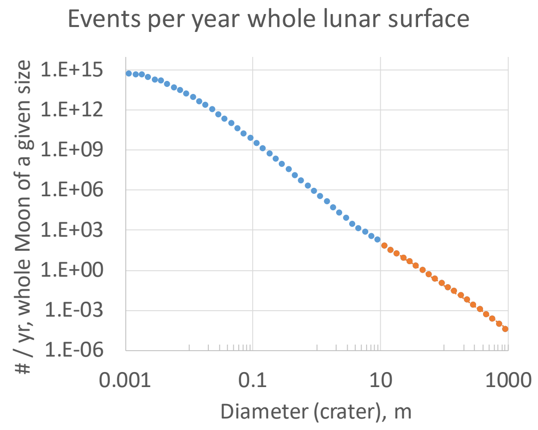

Figure 1. Impact flux from [5] (blue) and [6] (orange), expressed here as the number of craters in a given size bin per year on the whole Moon.

Method: To assess the ejecta flux, we have developed a Monte Carlo model for the cratering and ejecta excavation process in python. The model generates craters from the production function at random locations on the Moon, correctly accounting for spherical geometry (but not anisotropy in the primary flux, which is important for small primaries). We then apply the ejecta scaling model developed by [8], which gives the ejecta mass delivered as a function of velocity for a given impact size with a few empirically calibrated scaling parameters (e.g., Fig. 2). This ejecta velocity-mass distribution in Fig. 2 is consistent with a (primary) ejecta thickness decay in the form of a power-law with an exponent close to -3, in agreement with common analytical expressions (e.g., [12]).

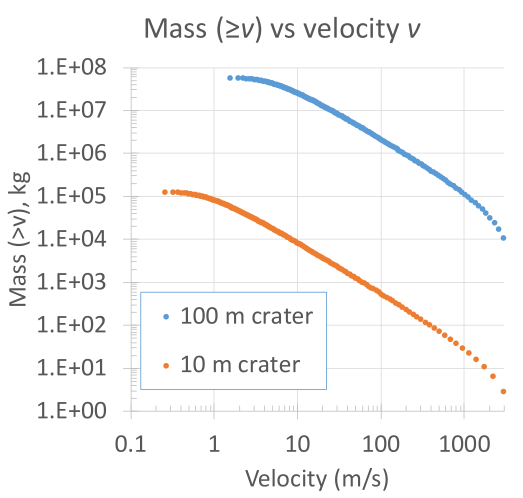

Figure 2. Example of mass (≥velocity) versus ejecta velocity of the ejecta for two sizes of lunar craters

From this, we can directly calculate the mass flux and the velocity distribution of the delivered mass to an arbitrary point on the Moon from accumulating random impacts by combining Fig. 1 and Fig. 2 in the Monte Carlo model.

Translating this mass flux into a number flux requires specifying an ejecta particle size distribution (PSD). Currently, we assume that the ejecta PSD follows the PSD of typical lunar regolith [13], which is likely a very good assumption for small impacts (*D*<30-50m). For larger impacts that form craters >100m, the ejecta PSD should include larger ejecta blocks [e.g., 14, 15], excavated from depth. Handling this complication is left for future work.

Hazards and Ejecta Particle Flux: Figure 3 shows the median particle flux of delivered ejecta particles of different mass (shown in cumulative frequency), in two different velocity bins, <1 km/s, and from 1 km/s to escape velocity. As expected, we find more than an order of magnitude higher flux of ejecta particles than what is delivered by primary impactors in this size range. Most ejecta is delivered at slow velocities (shown in Fig. 3 as <1000 m/s, though note that most of the flux in this bin is contributed by velocities <100 m/s, see Fig. 2). This is a consequence of the vast majority of ejecta mass being emplaced into craters' near-fields, which outweighs the commonality of distant rather than nearby craters.

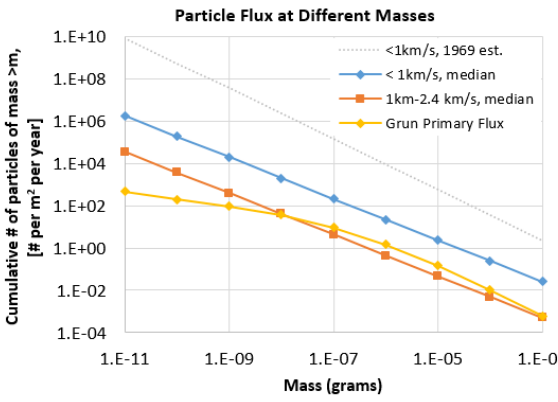

Figure 3. The median ejecta mass flux derived in different velocity bins. The dotted line is from [3] and the orange primary impactor rate is from [5].

Our estimate of the median ejecta flux (Fig. 3) is much lower (by a factor of ~10^2-10^3) than was determined in the pre-Apollo estimate [3]. Independently, [4] have corrected this earlier estimate of the ejecta flux downward as well; rather reassuringly, our results agree with this corrected mass flux from [4] within a factor of 2-5, despite different methods. Ejecta, though common, should be a manageable hazard during future lunar exploration with appropriate engineering.

Geomorphic Considerations: Applying this scaling-based approach for ejecta flux to lunar geomorphology applications remains a work in progress. Because of the number of events, numerical modeling that explicitly treats secondary events may be generally unfeasible, especially if small primaries are included. Thus, treating the geomorphic role of these impacts with an analytical or heuristic approach [e.g., 10] remains attractive. The scaling-based approach for the ejecta flux here could be used to justify such a rule if we can better account for spatial inhomogeneity of ejecta deposition (rays) [e.g. 10, 16], and improve the model for how ejecta delivered to the surface does geomorphic work [e.g., 11].

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