The flux of impact ejecta on the lunar surface from scaling considerations: Implications for operational hazards and geomorphic forcing

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Motivation:

- LROC and telescopic monitoring of new impact crater formation are a reminder that impact ejecta is frequently launched from the lunar surface [1-3] (Fig. 1).
- Future exploration missions and long-term infrastructure need to know the hazard posed by impact ejecta.
- Lunar geomorphology is also substantially affected by impact ejecta and secondary cratering.

Goal:

- **Quantify the flux of impact ejecta to an arbitrary point on the lunar surface, and determine the particle and mass flux as a function of velocity.**

Strategy:

- Specify the lunar impact rate over a wide range of sizes [4, 5] (see Fig. 2a).
- Apply the Housen and Holsapple 2011 ejecta model [6] that predicts the mass-velocity distribution of ejecta from a given impact (Fig. 2b).
- Solve the problem via Monte Carlo:
  a. Generate random craters with time.
  b. Handle the Moon's spherical geometry to deliver these random events (see Fig. 2c).
  c. Choose an arbitrary point and assess the incoming mass flux at a given velocity. Convert mass flux into a particle flux using the assumption that the ejecta matches the regolith's particle size distribution.

Considerations:

- More mass is re-delivered to the surface as ejecta than comes from primaries (~10^3× more ejecta mass than impactor mass).
- More energy is delivered to the surface by primaries, as required by conservation (~10^2× impactor kinetic energy than ejecta kinetic energy) [e.g. 7].
- Geomorphic work on the Moon appears to be dominated by secondaries [8]. But what size events matter? (Fig. 3)
- It is not *a priori* evident that a particular scale of primaries dominates the ejecta flux:

  Cumulative number of events: $N(D) \sim D^{-3.1}$ for craters D<100m [5].

  Total ejecta mass for a given event: $m(D) \sim D^3$.

Summary of Results:

- Average impact ejecta hazard is smaller than baselined pre-Apollo [9, 10] (Fig. 5).
- The vast majority of impact ejecta is delivered at relatively low velocities (<100 m/s) (Fig. 2-5).
- The median ejecta flux expected in a given time period is lower than the mean flux, due to the long tail of unlikely large events that contribute to the mean.
- Infrastructure or missions with longer stay times on the Moon will be exposed to larger events, though the hazard is still manageable.
- Appropriate engineering can be applied to mitigate the impact ejecta hazard.

New Impacts on the Moon:

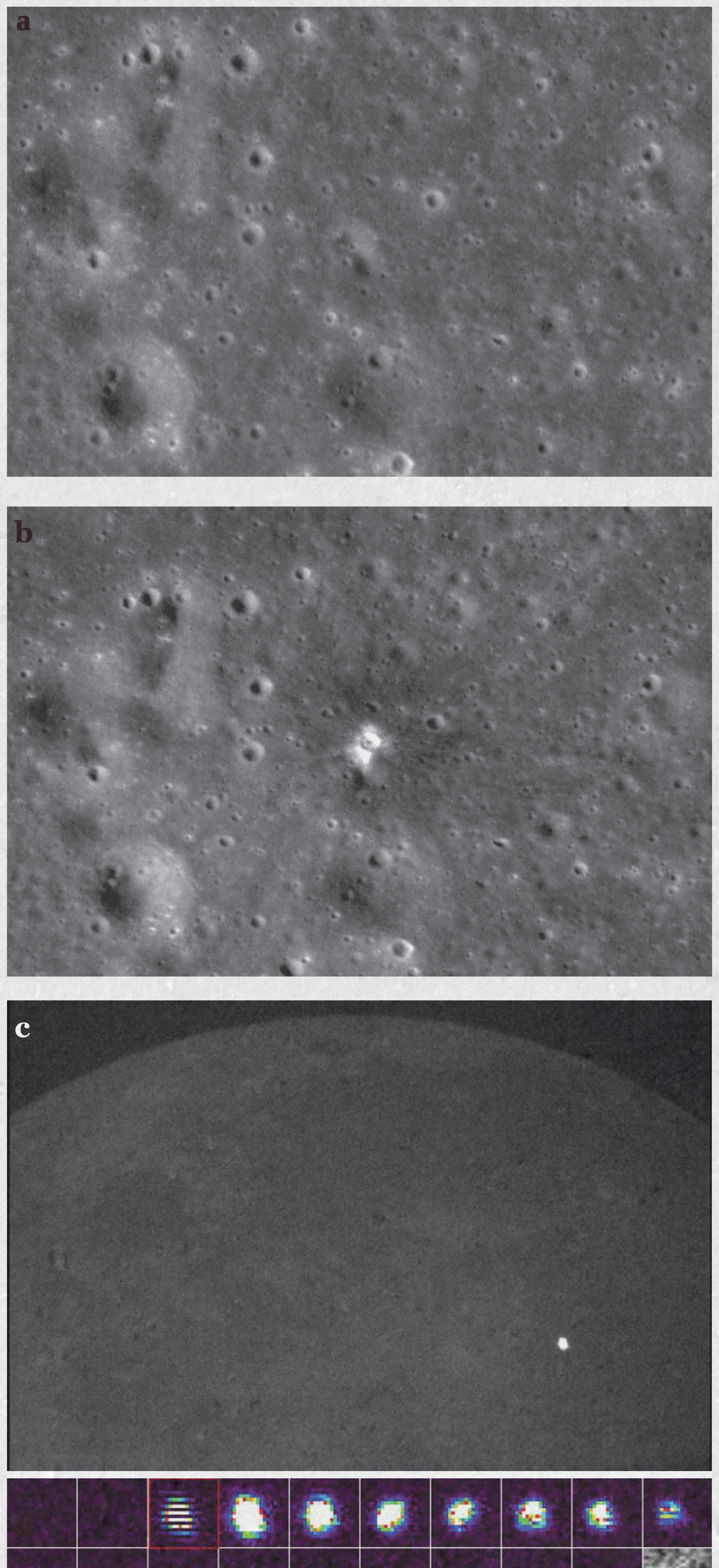

Figure 1. LROC (a) before and (b) after images of the March 17, 2013 impact. Ejecta from this 18-m crater resulted in surface changes kilometers from the impact. (c) Impact flash of this impact event; (d) Sequence of video frames (1/30th of a second spacing) during the event [1,2].

Method:

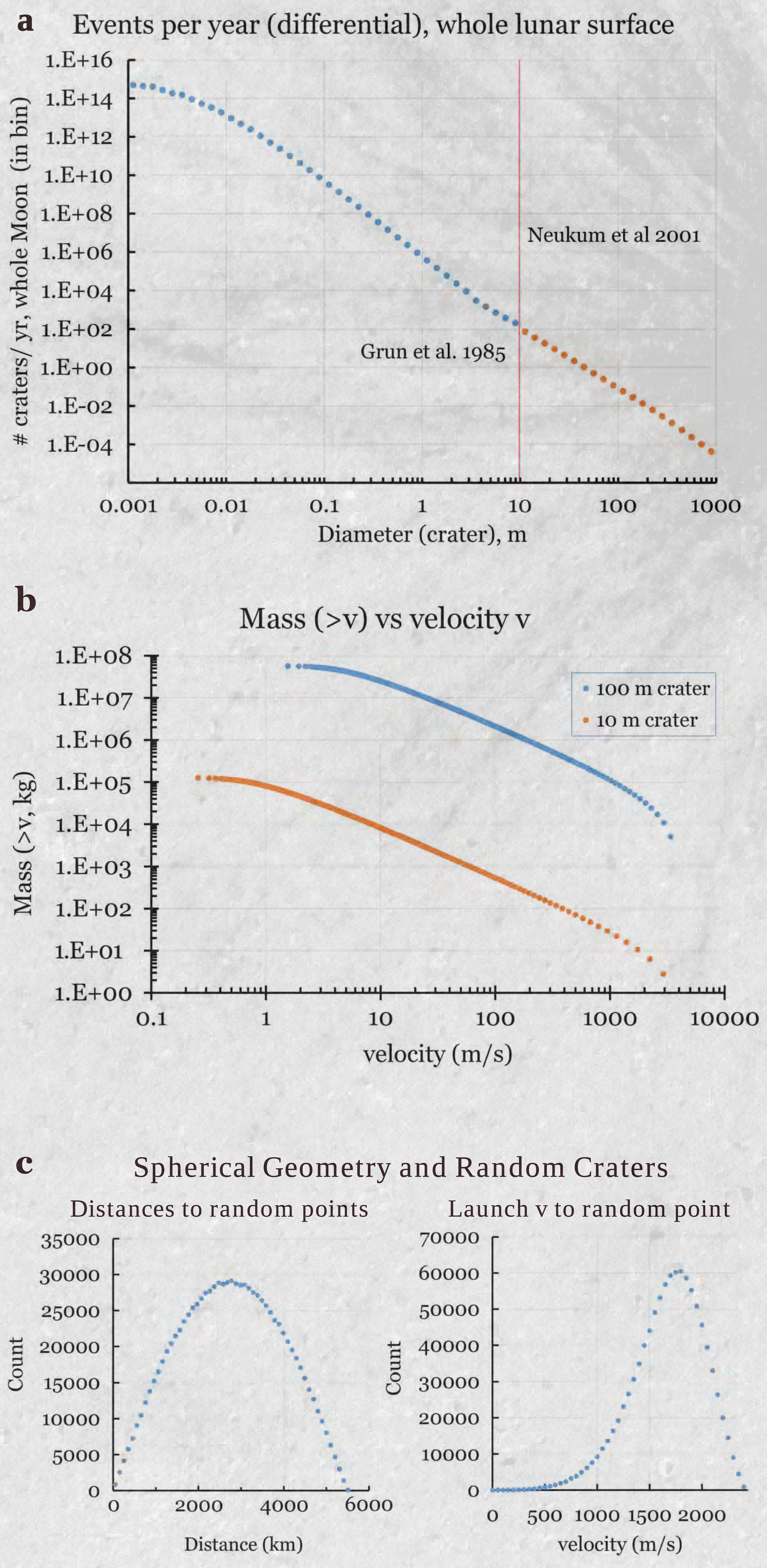

Figure 2. (a) Lunar crater production from Grun et al. [4] and Neukum et al. [5], used as the production function for the ejecta model. (b) Example of the Housen and Holsapple [6] ejecta-mass velocity distribution for 10m and 100m diameter craters. (c) Spherical geometry has a non-intuitive impact on the ejecta hazard. The distribution of distance of randomly produced points (& area) from a reference point on a sphere is:

$$n(\text{dist}) \sim \text{dist}(\pi R_{Moon} - \text{dist})$$

The peak number of points is ~90° away (0.5πR).

(a), (b), & (c) are combined in a Monte Carlo model to predict the ejecta flux.

What events are significant?

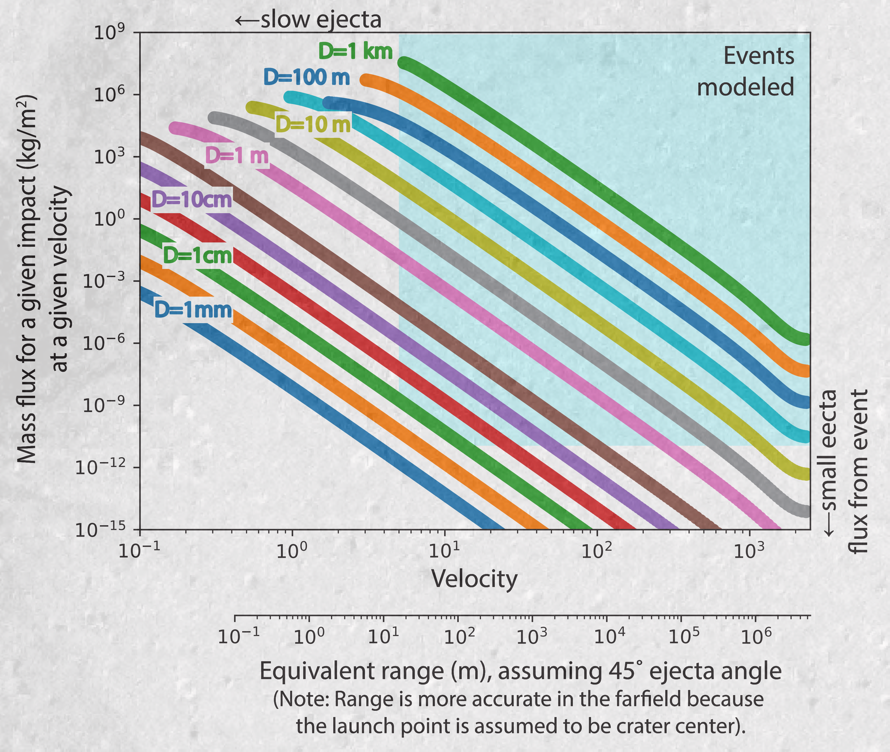

Figure 3. This plot recasts Fig. 2b to consider the relevance of individual primary events. It is intractable to model every small primary (Fig. 2a), since they are so common. Small events mostly redistribute particles in their immediate surroundings. Here, we limit analysis to craters ≥1 cm that contribute ejecta $>10^{-11}$ kg/m^2 at velocity >5 m/s.

Results (1):

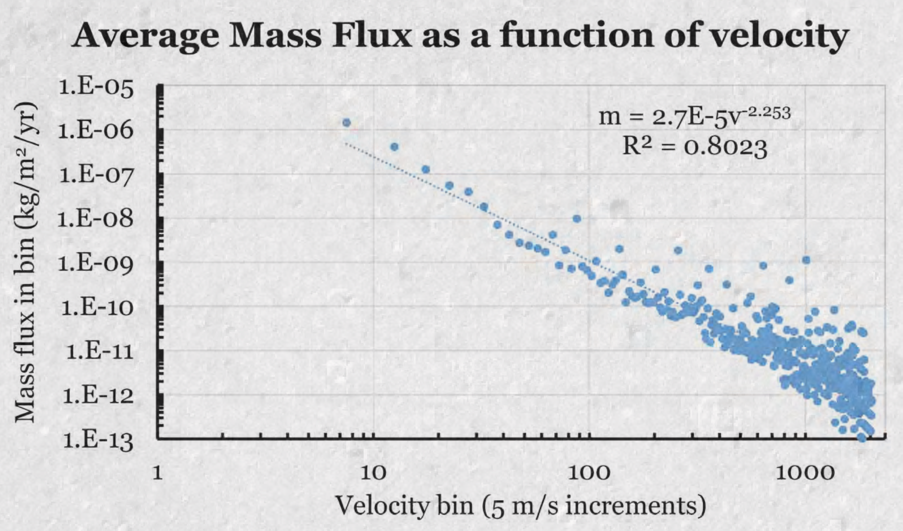

Figure 4. The average annual ejecta mass flux on the lunar surface in a given velocity bin using the thresholds from Fig. 3.

Results (2):

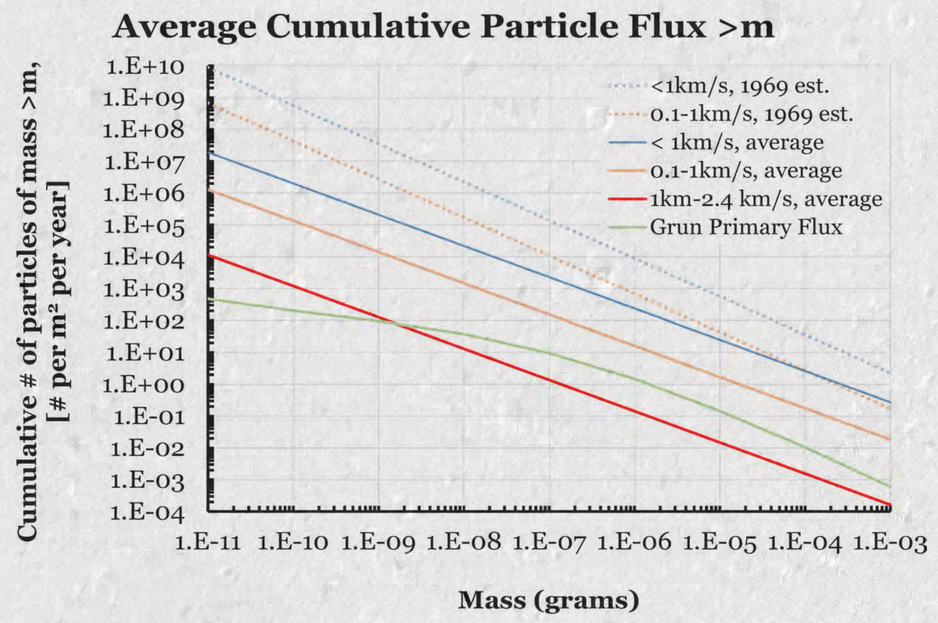

Figure 5. This plot puts Fig. 4 in terms of particle flux on the lunar surface assuming ejecta matches the regolith PSD. Note that most of the ejecta in the <1 km/s bin is actually delivered at <<100 m/s (Fig. 4). This plot is also very conservative because it may overestimate the contribution of small, 1-10 cm craters to the ejecta flux. Regardless, the 1969 estimate of the average ejecta hazard [9] was overstated, a conclusion supported by [10].

Geomorphic Forcing, Ejecta Flux, Splotches, and Rays

- Speyerer et al.[3] estimate splotch formation rates:
  - >10 m splotches: n=109,000 global/yr, 0.0029/km^2/yr.
  - 18 m-primary (Fig. 1) made >250 splotches [3].
  - Implies that primaries D>~5 m make most >10m splotches. If much smaller primaries were involved, >10m splotches would be more common than observed.
- Zone of proximal optical disturbance around newly formed craters implies minimum (local) ejecta mass flux to cause a splotch of >~1.8×10^{-3} kg/m^2.
- If ray length L is controlled only by an ejecta mass threshold (no ray widening), expect simple crater $L \sim D^{1.3}$, close to $L \sim D^{1.2}$ found by Elliott et al. [11].

Acknowledgments: I thank Anthony DeStefano, Mike Zanetti, Rob Suggs, Danielle Moser, Bill Cooke, and Megan Bruck Syal for discussion and collaboration that enhanced this work. Any errors are my own.

References:

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