NEW LUNAR IMPACT SPLOTCHES: PRODUCED BY METEOROID STREAMS AND SECONDARY IMPACTS
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Introduction: Lunar Reconnaissance Orbiter Camera (LROC) Narrow Angle Camera (NAC) temporal ('before and after') image pairs have been used to detect 222 new impact craters and 47,000 new bright or dark spots called "splotches" over 6.6% of the Moon [1]. These impact events churn the surface regolith on a timescale of 81,000 years— more than a hundred times faster than previous models estimated from meteoritic impacts [2]. The global splotches have been interpreted as resulting from a mix of primary and secondary impacts, but mostly secondary impacts of regolith that churn the surface [1, 3]. Impact flash observations [4] provide a test of how many splotches may be produced by small meteoroids, and the answer appears to be that all of them could potentially be explained in this manner. The observations of splotches associated with new craters as secondaries suggest that they account for at least 10% of the total, so individual primary meteoroid impacts would account for the remaining splotches.

Impact Flashes: A monitoring program at NASA's Marshall Space Flight Center recorded over 300 visible flashes on the nightside of the Moon from 2006-2011 [4]. A selection of 126 flashes recorded during periods of photometric skies was analyzed by those authors to estimate kinetic energy and mass for each impactor. From the timing of these flashes, meteorid shower associations were determined for most of the events. From the published estimates for impactor mass, density, velocity, and kinetic energy [4], we used http://keith.aa.washington.edu/craterdata/scaling/index.htm [5] to estimate the sizes of craters such impacts should make in the lunar regolith. Figure 1 shows the resulting cumulative size-frequency distribution (SFD), and Figure 2 shows the SFD of the splotches. Best power-law fits to cumulative data ($Ncum/km^2/yr = a d^{-b}$) result in a=1E-14 and b=4.013 for the meteoroid craters and a=1.48E-11 and b=4.144 for the splotches. The similar exponents (b) may suggest that these are related populations, but secondary craters typically have b near 4 as well.

An estimated 1.09×10^5 splotches with diameters of >10 m form annually over the entire Moon [1]. If the majority are indeed unresolved craters, what diameter albedo change (splotch) would be produced by each unresolved new impact? For relatively recent impacts the reduced-resolution spot is ~5x larger [6]. However, for craters only a few years old this may be an underestimate. If we assume 5x larger, or that a 10 m splotch is produced by a 2 m diameter crater, then using the Suggs et al. derived impact rate, we get an estimated annual splotch formation rate of 2.6 x 10^4 per year over the entire Moon, equal to ~24% of the splotches. If the spot is 6 times wider than the crater, then the splotch formation rate estimate becomes 5.3 x 10^5 per year, ~5x that observed. Clearly the result is a very sensitive function of how large of an albedo spot is produced by each meteoroid impact, but the flashes can plausibly account for all of the splotches.

Secondary impacts: A cluster of 248 new splotches was observed to form around a new 18-m crater [3], at least 1000 splotches are associated with a new 43-m crater (the largest one found), and there are other linear patterns in the splotch map; some have been used to target and discover new larger craters. Many new splotches are seen in radial chains from new impacts on Mars [7], but at a maximum range of only ~10 km. Secondaries from the Moon will be more widespread than on Mars due to the ~2x higher primary impact velocity combined with a lower gravity. They are observed to extend at least 30 km from the new 18-m crater [3]. Could such secondaries be sufficient to produce globally distributed splotches (Figure 3)? Given 16 new craters >10 m [1], and if we assume that only craters of at least 10 m produce resolvable splotches and there are an average of 250 of them per crater, the total is 4,000 out of the 47,000 new splotches (applies to 6.6% of the lunar surface for both splotches and new resolved craters). For the entire lunar surface we would expect 16/0.066 = 242 new craters >10 m over the LROC observing period. If each distributes splotches over a 100 x 100 km area, then these secondary splotch clusters are contained within only 6.4% of the lunar surface, inconsistent (by themselves) with the observed distribution (Figure 3).

One hypothesis consistent with these estimates is that primary meteoroids produce 50-90% of the splotches while secondaries produce 10-50% of them concentrated over relatively small areas of the surface. There are local concentrations in the splotch map (Fig. 3), consistent with secondaries, although this will be more uniform when the distribution of repeat coverage is considered (Extended Data Figure 2 of [1]).

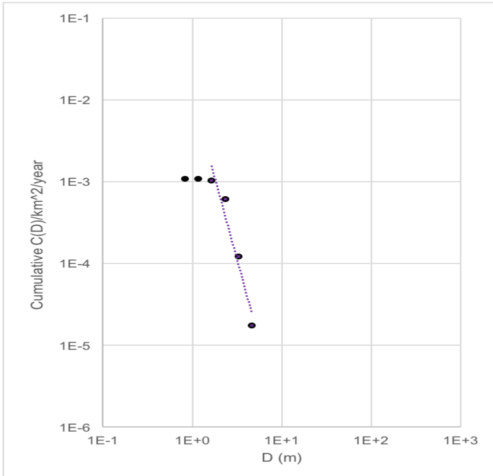

Figure 1. Cumulative SFD of craters expected from impact flashes [4], due mainly to meteoroid streams. Dotted line is a linear fit to the largest 4 bins, which appear complete: $C(D)=1E\text{-}14D^{-4.013}$.

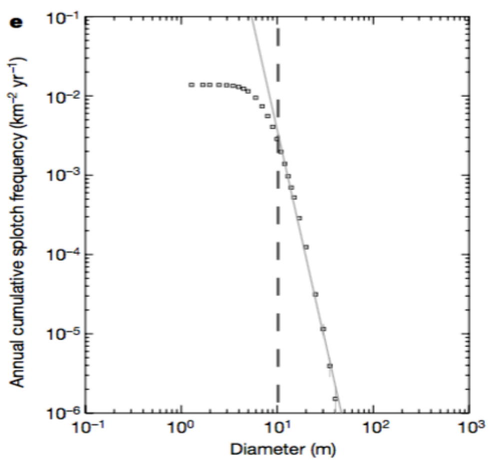

Figure 2: SFD of new lunar splotches [1]. Thin black line is a linear fit to diameters larger than the completeness limit (vertical dashed line): $C(D)=1.48E\text{-}11D^{-4.144}$

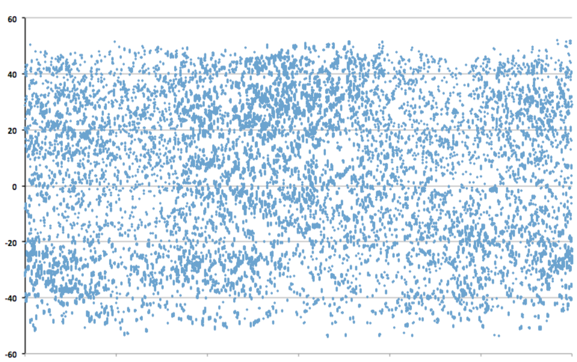

Figure 3: Map of new splotches.

Implications for crater chronology: A fit to the 15 of the 16 new craters larger than 10 m has a surprisingly "steep" slope (*b ~4*), steeper than expected for asteroid impacts [1], and steeper than observed at Mars [7]. In fact, the exponent appears similar to that of the expected meteoroid craters from impact flashes, so the summed population would also have about the same slope. If this is the correct slope down to 1-m scale craters, then all of the splotches can be explained as due to new primary impacts, consistent with the lunar flashes. The main effect of the meteoroids (not considered by published production functions) would be to increase the total impact rate by ~25% at these diameters. However, the data is sparse for new craters >10 m diameter, so the SFD slope is poorly constrained and this question should be reconsidered when better statistics are available. Evidence from meter-scale bolides striking Earth shows that a very small fraction are from meteor streams and the asteroid SFD becomes shallower for larger objects and resulting craters [8]. Meteoroid streams likely do not change the SFD for craters larger than ~10 m.

The idea that secondary impacts could produce a globally distributed and random-appearing set of splotches (Fig. 3) in just a few years, initially seemed to support the idea that distant secondary craters can be treated like the primary flux when counting craters to date surfaces [9]. Our re-analysis suggests that the splotches from secondary impacts are spatially clustered while meteoroids produce the more uniform coverage observed globally.

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