SESQUINARY CRATERS ON THE MOON CAN FORM CLUSTERS.

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Introduction: Sesquinary ("1.5-ary") impact craters [1,2] on the Moon are created by projectiles previously ejected from the Moon into geocentric orbits by larger impacts. In a sense, they are transitional between primary and secondary craters. Here I extend the classic analysis [3] of lunar impact ejecta dynamics to assess sesquinary crater significance, show that the sesquinaries can form clusters and present examples of possible clusters of sesquinaries on the Moon.

Global sesquinary impact inventory: I performed massive calculations of trajectories of projectiles launched from different places on the Moon in different directions using MERCURY code [4]. The calculations traced massless projectiles in the gravitational field of the Earth, the Moon, and the Sun on their present-day orbits until the projectiles hit the Earth or escape from the Earth-Moon system or hit the Moon to produce sesquinaries. The projectiles were launched from 1212 points uniformly distributed over the entire Moon. For each launch point, 24192 projectiles were launched at: {7 zenith angles form 30° to 60°} × {72 azimuths in all directions} × {48 initial velocities from 2.40 km/s (just above the escape velocity of $v_{esc} = 2.38$ km/s) to 4.75 km/s (above which no sesquinary impacts can occur)}. The launch date was the same for all projectiles and chosen arbitrary. Limited test runs showed that the fate of many individual projectiles depended on the launch date, while the global statistics of sesquinary impacts do not.

The effect of the launch zenith angle on launch-azimuth-integrated number of sesquinary impacts is minor. Sesquinary production depends strongly on location of the primary impact (=launch point), as discussed in detail in [3]. Primaries within ~60° around the lunar apex (the center part of the western hemisphere) produced almost no sesquinaries, in particular, large young craters Jackson, Ohm, and Glushko. The highest sesquinary production efficiency is for impacts in a wide band at ~40°-80° distance from the antapex. In particular, Giordano Bruno, the youngest crater of its size, has a high sesquinary production potential.

The majority of sesquinaries are produced soon after the primary impact; more than a half of them are produced during the first year with prominent production peaks at about 1, 2, 3, 4, 5, and 6 lunar orbital periods; over a third of all sesquinaries are produced within these peaks (see discussion in the next section). Only ~11% of all sesquinaries are formed more than a year after the primary impact; in my calculations, the last sesquinary impacts occurred a few thousands of years after the primary, and no projectiles left in the geocentric orbits after ~10^4 years.

The majority of sesquinaries are formed by projectiles ejected just above v_{esc} [3], about a half of sesquinaries in my calculations were produced by projectiles launched at 2.40 and 2.45 km/s. Among all projectiles launched at these velocities, only 3.0% hit the Moon, significantly less than in limited and therefore less accurate calculations in [3]. Almost all (98%) of traced projectiles that hit the Moon were slower than 3.00 km/s at their launch.

To calculate the average sesquinary formation efficiency I applied a power-law distribution of ejection velocity according to [5]: I assumed the mass ejected faster than v to be proportional to $v^{-4/3}$. Variations of the power law exponent in its reasonable range [5] does not change the result significantly. I also assumed that the primary impacts and their ejection efficiency are distributed uniformly over the entire Moon. Under these assumptions, the mass of material that re-hit the Moon is <u>0.50%</u> of the total mass ejected from the Moon above v_{esc}. Application of scaling laws from [5] to a silicate primary impactor yields ~0.6 of the impactor mass to be ejected above v_{esc}. Dedicated hydrocode modeling [6] for realistic typical impact conditions gives 2 – 4 impactor masses, therefore the total mass of sesquinary impactors is 1% – 2% of the total mass of primary impactors. An unknown part of this mass is finely fragmented and does not produce observable craters. Sesquinary impact velocities are in a narrow range of 2.38 - ~3 km/s, much slower than typical primary impacts. As a result, the total number of sesquinaries is much less than 1% of the total number of primaries larger than a given size. Thus, <u>the bulk contribution of sesquinaries into the cratering record is negligibly small</u>.

The largest primary impacts, however, may have a noticeable effect. For example, for crater Tycho, the youngest crater of its size, the sesquinary production efficiency is 0.08%. Typical recognizable distal Tycho's secondaries are hundreds of meters in diameter. Assuming typical Tycho-forming impact conditions, the total sesquinary impactor mass is sufficient to make ~4×10^6 craters 200 m each, a factor of 3 greater than the total number of primaries greater than 200 m formed since the Tycho impact (108 Ma ago) according to the "standard" Neukum production function. This crude estimate indicates that the proportion of sesquinaries form the largest young impacts in the youngest subpopulations of subkilometer-size craters could be noticeable.

Clustering of sesquinary craters: The majority of the sesquinary-forming projectiles are launched with velocities just above v_{esc}, therefore their apogees are close to the initial launch location, where a high concentration of projectiles is produced. In an oversimplified case with no lunar and solar gravity, all projectiles launched from some point will return to the same point in space after an integer number of orbital periods, which produces focusing. Lunar and solar gravity significantly complicates this picture, however, some focusing will still occur. If the projectile orbital period is commensurable with the lunar orbital period, the impacts would occur early, before the perigee drifts off the initial point and focusing is still possible. This explains the monthly spikes in sesquinary impacts for the first 6 months after the primary impact, when the Moon returns to the same (approximately) place in space, where the primary impact occurred.

Among projectiles launched from the center of crater Tycho, a large number of projectiles goes into orbits with 3:5 commensurability with the Moon; these projectiles would hit mostly the central lunar farside on the 81st day after their launch. **Fig. 1** illustrates that in addition to the general focusing toward central farside, some additional caustic-like focusing occurs (note overlapping lines or overlapping dots on each line in Fig.1). Particles ejected by large impacts are known to cluster, as evident from secondary clusters. Such clusters would spread widely during a few months travel on geocentric orbits, however the caustic-like focusing can bring them back together. This means that <u>sesquinary craters can be concentrated into dense clusters</u>. Calculations shown in Fig.1 cannot be used to predict exact location of Tycho's sesquinary clusters, because the caustic configuration depends on the primary impact date. Moreover, when Tycho impact occurred, the Moon had somewhat different orbit than now, which also affects the results. In addition, Tycho impact itself caused significant libration of the Moon, which distorted the impact positions. However, it is probable that cluster(s) of sesquinaries form Tycho and possibly from other large young craters do exist on the Moon.

Candidate sesquinary clusters: At the northeastern limb of the Moon to the south from crater Hayn there are 5 unusually dense linear narrow clusters of 10s and 100s m size craters [7]. Fig. 2 shows one of them; note that only hectometer-scale craters are resolved on this image; overabundant decameter-scale craters are not seen here, but are apparent in higher-resolution images. There are no hints of an endogenic origin of these craters in their morphology and settings; they are impact craters. Neither do they show morphologies suggestive of low-velocity or oblique impact, like typical secondaries. The prominent roughness signature [7] of these clusters suggests a geologically young (Copernican) age. One of these clusters is superposed over proximal ejecta of Hayn, a large Copernican-age crater (older than Tycho), and hence postdates the Hayn impact. In high-resolution images (LROC NAC) the cluster-forming craters look softened; they obviously underwent significant regolith gardening and are not extremely recent. Great circles fitted to these linear clusters do not extend to the vicinity of any large (>20 km) young crater. All these features suggest that these clusters are not clusters of secondaries. It seems probable that these clusters are made of sesquinary craters from Tycho or other large young impact.

References: [1] Zahnle K. et al. (2008) Icarus 194, 660-674. [2] Alvarellos J. et al. (2005) Icarus 178, 104-123. [3] Gladman B. et al. (1995) Icarus 118, 302 – 321. [4] Chambers J. (1999) Mon. Not. Royal Astron. Soc. 304, 793-799 [5] Housen K. & Holsapple K. (2011) Icarus 211, 856-875. [6] Artemieva N. & Shuvalov V. (2008) Solar System Res. 42, 329-334. [7] Kreslavsky M. et al. (2013) Icarus 226, 52-66.

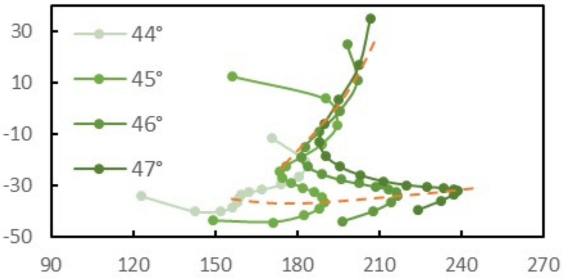

Fig. 1. Map of the central lunar farside with locations for sesquinaries that would be launched from Tycho center on Jan. 1, 2012 with 2.40 km/s velocity toward the E – ENE, and impacted the Moon on Mar. 22. Four curves correspond to 4 launch zenith angles; dots on the curves correspond to 1° steps in the launch azimuth. Dash lines mark caustics.

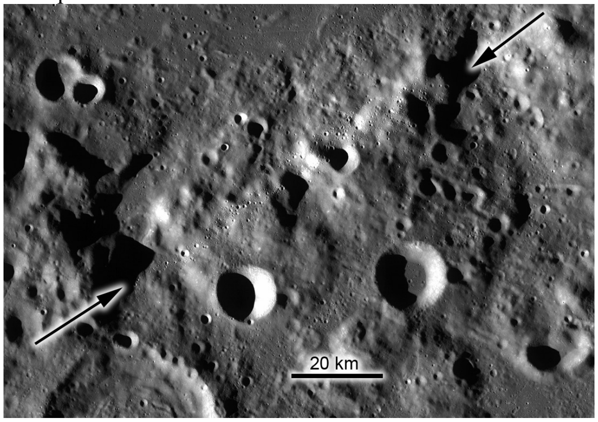

Fig. 2. Dense elongated cluster of relatively sharp craters (between long arrows). The scene is centered at 52.5°N 84.5°E; a portion of LROC WAC global mosaic.