# DISTANT SECONDARY CRATERS FROM LYOT CRATER, MARS, AND IMPLICATIONS FOR AGES OF PLANETARY BODIES.

S. J. Robbins[1,2] and B. M. Hynek[2,3], [1]APS Department, UCB 391, University of Colorado, Boulder, CO 80309, [2]LASP, UCB 392, University of Colorado, Boulder, CO 80309, [3]Geological Sciences Department, UCB 399, University of Colorado, Boulder, CO 80309.

**Introduction:** Crater counting is the only way to estimate absolute ages on solid surfaces without returned samples. A basic assumption of crater age-dating is that crater formation is a stochastic process. However, half a century ago, [1] identified the issue of secondary craters - craters that form from the ejecta of a larger primary impact event and are necessarily smaller than the primary. The subject of secondary craters was generally ignored in the literature until [2] identified 10s of thousands of secondary craters that contaminate crater statistics on Jupiter's moon Europa, and [3] identified similar numbers of secondaries around the fresh crater Zunil on Mars. Understanding the role secondary craters have on local and global crater statistics is important, especially because the crater population with diameters $D < 1$ km on Mars may be significantly contaminated by secondary craters [4].

We identified thousands of secondary craters originating from the largest relatively pristine crater on Mars: Lyot crater is a ~222-km-diameter peak-ring crater located at 50.5°N, 29.3°E (Fig. 1), and it has been dated to an age of ~3.3 Ga [5]. The craters we identified are up to 25% of the way across the planet, and there could be countless more that we could not link to Lyot due to degradation, resurfacing, resolution limitations, or lack of clear, tight clusters.

**Identification of Craters and Secondary Clusters:** In our work creating a global Mars crater database complete to $D = 1$ km [6], we have identified ~500,000 craters across Mars' surface. While identifying craters and looking at the small crater distribution, we observed numerous clusters that appeared to trend radially from Lyot at distances up to ~5200 km. Determining whether these clusters likely originated from Lyot was not aided by observable rays nor a nearly crater-free landscape as is the case with Zunil [3, 8]. Instead, we traced great circle arcs between the potential clusters and Lyot to determine if the cluster was elongated along the great circle. To trace a great circle arc, an iterative approach from [9] was used.

Every crater in [6] was analyzed for its distance to all other craters within 2° of it. If the 5$^{th}$-nearest crater was within 10 crater diameters, then it was considered to be in a cluster. Candidate clusters were visually inspected in THEMIS mosaics [7] to validate the cluster and better determine, based upon morphology, if the cluster was likely to be secondaries. If they were, great circle arcs were drawn (*e.g.*, Fig. 2) to test orientation. This method only identifies clusters of craters, and we frequently observed fields of smaller craters that were also likely from Lyot but not included in this study. We differentiate these with "fields" meaning regions of craters that show an over-density from the background that appear to be secondaries, whereas "clusters" are closely packed craters with rims often touching.

Our search identified 143 distinct clusters of $N \approx 10$-300 craters each, where craters have diameters $D >$ ~800 m from our database [6]. 5341 craters from our global database were extracted as members of these distant secondaries, similar in magnitude to the number identified in mosaics on Europa [2]. The closest far-field cluster is ~700 km away (~6 crater radii) and the farthest is ~5200 km away (~46 crater radii). We distinguish "far-field" from close secondaries because there is an annulus of morphologically classical secondaries [1, 10, 11] that is spatially correlated with Lyot (Fig. 1) ("near") while clusters that are not as clearly linked to Lyot are considered "far."

**Nearby Secondary Field:** Secondary craters are generally much easier to identify close to their primary crater since they are entrained in its ejecta and show an over-density as an annulus around the primary; Lyot follows this pattern. Most near secondary craters we identified are embedded in long troughs emanating radially from Lyot and are superimposed on the continuous ejecta (Fig. 1). We extracted 1590 of these nearby secondary craters and display their size-frequency distribution (SFD) in Fig. 3. The diameter range fitted (3.0-6.9 km) has a power-law slope of -4.0±0.2. This is significantly steeper than a typical crater population with a slope between -2 and -3, but it is typical for secondary crater populations [4].

**Distant Secondary Craters:** All 5341 craters in our far-field clusters were combined into one SFD (Fig. 3); $D > 2.5$ km craters are likely contamination by primaries and only comprise 0.3% of those identified. The power-law slope is -3.9±0.1 for $1.0 < D < 2.5$ km. To verify this was representative, we created SFDs of all 26 individual clusters with $N \geq 50$ craters and fit slopes over approximately the same diameter range; the power-law exponent ranged between -1.1 and -8.5 with $\mu$=-3.9 and median -3.5. The five largest ($N > 120$) averaged -4.1 with a range of -3.1 to -5.9. Given the somewhat small numbers involved, we consider these to be consistent (and closely match [4]) but emphasize there can be a spread in slope.

**Discussion and Conclusions:** We have identified ~150 secondary crater clusters up to 1500 km farther from their primary than Zunil. They are mainly located southeast of Lyot; we found six clusters southwest, and four east and northeast. We also mapped the continuous ejecta blanket (Fig. 1) and it has a preferential direction towards east-northeast. The ejecta distribution would seem to conflict with the secondary clusters, but it can be explained by modification and burial towards the south, an interpretation supported by Mars geologic mapping [12]. From the secondary clusters, we infer an impactor hitting Mars obliquely from the northwest. The impact produced deep radial troughs filled with secondary craters within ~1-2 crater radii from the rim - very different from Zunil which produced very few secondaries within 16 crater radii [8]. Lyot also produced on the order of $10^4$ far-field secondary craters $D$ > ~800 m in clusters we were able to identify.

The implications for using craters to age-date surfaces are significant. First, in agreement with previous work, secondary crater contamination needs to be taken into account and can significantly affect crater size-frequency distributions. Near large craters, it is an important factor at multi-kilometer scales (Fig. 2) and relying on a 1 km secondary-primary transition diameter [4] will yield erroneous results. Isolated secondary clusters have steep SFDs and if one were to include these craters when age-dating a larger surface, it will result in an inaccurate older surface. Second, our study shows that one cannot rely upon a nearby primary crater to use as a criterion for determining if a cluster is secondary in nature -- something that is still a point of contention in the community. Further case studies of secondary craters, especially far from their primary, on Mars and other bodies are needed because the two studied on Mars to-date show significant differences. A more robust model and understanding of secondary cratering is needed to better constrain planetary surface ages and its implications for the overall history of the solar system.

**References:** [1] Shoemaker, E.M. (1965), JPL Tech. Report No. 32-700. [2] Bierhaus, E.B. et al. (2005), *Nature*, *437*, 1125-1127, doi:10.1038/nature04069. [3] McEwen, A.S. et al. (2005), *Icarus*, *176*, 351-381, doi: 10.1016/j.icarus. 2005.02.009. [4] McEwen, A.S. & E.B. Bierhaus (2006), *Annu. Rev. Earth Planet. Sci.*, *34*, 535-567, doi: 10.1146/ annurev.earth.34.031405.125018. [5] Dickson, J.L. et al. (2009), *GRL*, *36*, L08201, doi:10.1029/2009GL037472. [6] Robbins, S.J., and B.M. Hynek (2010), LPSC XLI, #2257. [7] Christensen, P.R. et al. (2004), *Space Sci. Rev.*, *110:1*, 85-130, doi: 10.1023/B:SPAC.0000021008.16305.94. [8] Preblich, B.S. et al. (2007), *JGR*, *112*:E05006, 1-18, doi:10.1029/ 2006JE002817. [9] Vincenty, T. (1975), *Survey Rev.*, *XXIII*(176), 88-93. [10] Oberbeck, V.R. and R.H. Morrison (1974), *Moon*, *9*, 415-455, doi: 10.1007/BF00562581. [11] Shoemaker, E.M. (1962), *In Physics and Astronomy of the Moon*, pp. 283-359. [12] Greeley, R. & J.E. Guest, (1987), USGS Misc. Invest. Map, I-1802-B.

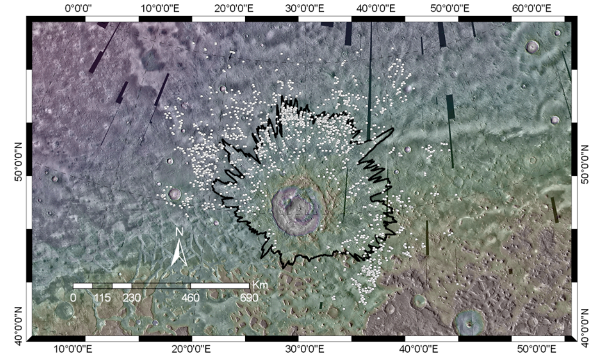


**Figure 1:** THEMIS Daytime IR mosaic showing the region around Lyot crater in a local stereographic projection. The continuous ejecta blanket of Lyot is outlined in black, and the identified near-field secondaries are shown as white circles.

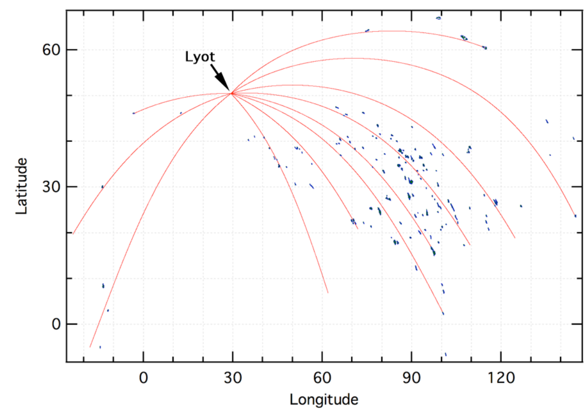


**Figure 2:** Map showing distribution of clusters of identified secondary craters from Lyot. Arcs are representative examples of great circles between Lyot and distal secondary craters.

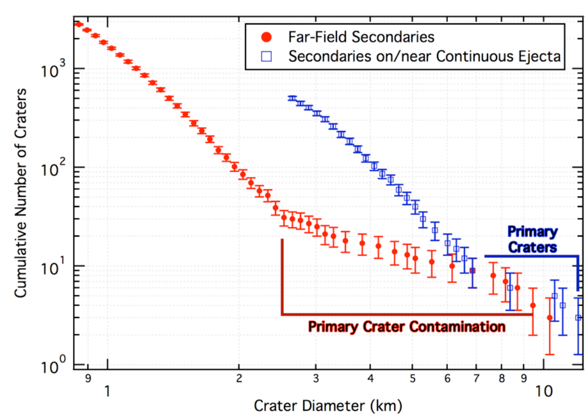


**Figure 3:** Lyot's nearby secondary crater size-frequency distribution (SFD) and the overall SFD of far-field secondaries. The slope for the nearby secondaries is -4.0±0.2, the slope for far-field secondaries is -3.9±0.1. These are significantly different from the typical SFD slope of -2 but in good agreement with other secondary crater studies [4].