SIGNIFICANCE OF NEW IMPACT EVENTS ON THE LUNAR SURFACE.

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Introduction: Random impacts by cometary and asteroidal materials shape and alter the surfaces of all solid Solar System bodies. These impacts form craters and cause surface disturbances many crater diameters away from the primary impact point. Temporal observations (before and after images) acquired by the Lunar Reconnaissance Orbiter Camera (LROC) provide our first detailed look at new impact craters and secondary disturbances from small impactors since the start of the mission. These temporal pairs reveal that the lunar regolith is rapidly reworked by secondary impacts that churn the upper few centimeters of the regolith.

Temporal Imaging: LROC has acquired over a million Narrow Angle Camera (NAC) images of illuminated terrain. From this collection, over 20,000 images are of regions of the Moon where previous NAC observations with similar lighting geometry exist (i.e. incidence angle difference <3°, incidence angle < 50°, and nadir pointing). These temporal pairs enable the search for a range of surface changes, including new impact craters, secondary disturbances, and mass wasting events that formed between the time the first and second images were acquired.

Impact Craters: Temporal imaging has so far revealed over 200 new impact craters ranging in size from 73 m down to the detection limit of the NAC. In addition, impact flashes observed using Earth-based telescopes also helped locate two new craters that formed on 17 March 2013 and 11 September 2013 [1-3]. Robinson et al. [1] documented the 17 March impact site and located an 18 m crater surrounded by four distinct reflectance zones (Proximal High Reflectance Zone (PHRZ), Proximal Low Reflectance Zones (PLRZ), Distal High Reflectance Zone (DHRZ), Distal Low Reflectance Zones (DLRZ)) that were propose to be the result of ballistic and jetted material modifying surface properties and altering surface reflectance. Further observations of other new impact sites reveal that the proximal zones fall within several crater diameters from the crater center and are most likely the result of ballistically emplaced ejecta, while the distal zones grow exponentially as a function of crater diameter [4].

We interpret the vast distal zones to be the result of jetting that occurs early in the crater-formation process when a mixture of melted and vaporized material is ejected at low angles and at extremely high speeds by a rapidly expanding gas [5]. Robinson et al. [1] proposed that jetted vapor may smooth and redistribute surface grains, a process similar to blast zones around landing sites. This process is thought to modify the highly porous (up to 90%) structure in the upper few cm of regolith and form the DHRZ. Furthermore, we propose that jetting could also cause numerous, small secondary impacts downrange from jetted melt and/or fine-grained regolith carried by the jetted vapor; As this jetted material expands and impacts the surface it churns the upper several mm of regolith and thus increases surface roughness resulting in the DLRZ.

Secondary Surface Changes: In addition to the primary impact crater, Robinson et al. [1] identified 248 *splotches,* which refers to surface reflectance changes (either an increase or decrease) that lack a visible crater rim or other morphologic signature. These splotches range in size from 2 to 22 m, extend away from the impact site to at least 30 km, and are not present in images acquired in the region just before the impact event [1]. Additionally, some of the splotches are asymmetric in shape and point back to the 18 m primary crater. Systematic scanning of other temporal pairs has led to the identification of over 47,000 other splotches that have formed since the start of the mission. Localized groups of splotches are observed around new impact craters, which is consistent with the interpretation that a majority of the splotches are the result of secondary impacts [4].

From the splotch size frequency distribution, we estimate that splotches >1 m cover 99% of the Moon in 8.1×10^4 yr. By assuming a conservative splotch churning depth of 1:50 we estimate that the top 2 cm of regolith is reworked and gardened from secondary splotches during this period [4]. This surficial gardening rate is >100 times faster than the previous models predicted from primary impacts alone (10^7 yr) [6].

Conclusions: Temporal imaging reveals that the lunar surface is more rapidly modified by primary and secondary impacts than previously thought [4]. The distal reflectance zones, which we interpret to be the result of a change in porosity and/or surface roughness, span out over 200 crater diameters in some cases. Additionally, the quantity of secondary splotches reveals a new mechanism for rapid churning of the upper few cm of regolith. Continued temporal observations will aid in improving our understanding of the formation process and help refine the current impact and regolith gardening rates.

References: [1] Robinson M. S. et al. 2015. *Icarus* **252,** 229–235. [2] Suggs R. M. et al. 2014. *Icarus* **238,** 23–36. [3] Madiedo J. M. et al. 2014. *Monthly Notices of the Royal Astronomical Society* **439,** 2364–2369. [4] Speyerer E. J. et al. 2016 *Nature*, in revision. [5] Johnson B. C. et al. 2014. *Icarus* **238,** 13–22. [6] Gault D. E. et al. 1974. *Lunar Science Confence*, 2365–2386.