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Investigation Recent Impacts with Temporal Image Pairs and Photometric Sequences

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Abstract

Temporal observations and follow-up photometric sequences by the Lunar Reconnaissance Orbiter Camera (LROC) enable the detection and analysis of newly formed impact craters. From the temporal pairs we can locate new craters and identify up to four distinct reflectance zones surrounding the impact site. Photometric sequences acquired after the impact reveal a higher backscatter signature associated with several of the reflectance zones.

1. Introduction

The Lunar Reconnaissance Orbiter (LRO) extended mission is enabling the discovery and investigation of recent surface changes. An initial investigation led to the discovery of over 200 newly formed impact craters and 47,000 secondary surface disturbances and unresolved primary impact craters [1]. Additional temporal observations have led to the discovery of over 200 more craters and 76,000 other changes. Photometric sequences acquired during the Cornerstone Mission (Sept 2016-present) are enabling us to further study these new surface features and provide insight into the cratering process.

2. Temporal Imaging

We can identify new surface features by comparing images that cover the same surface area with nearly identical lighting conditions. We compared WAC global mosaics captured between April 2012 and January 2016 to identify several primary impact craters ranging in size between 30 and 70 m in diameter. While these craters are smaller than a single WAC pixel, the disturbance around each crater extends several km in many cases allowing us to locate them and target NAC images to confirm the formation and gather crater size statistics.

Direct comparisons of NAC images to other NAC images with similar lighting conditions (incidence angle difference < 3°) enables us to identify hundreds of additional craters down to the resolution limit of the NAC (several meters). During the initial study [1], NAC temporal image pairs had an average time difference between observations of 1.3 years. Due to the progression of the orbit and the illumination environment, LROC started collecting temporal pairs in November of 2017 with a baseline of 7.3 years. The longer baseline increases the odds of a surface change occurring over the imaged terrain and improves our coverage statistics. Additional long baseline temporal observations between 7 and 10 years will continue to be acquired during the third year of the Cornerstone Mission and the next Extended Mission.

Temporal ratio images created by dividing the after image by the before image are used to identify changes to the surface reflectance. Because the lighting and viewing geometries are similar and the images are spatially registered, the values in the temporal ratio image are close to one except in cases where a reflectance change has occurred on the surface, such as a ray forming from a new impact.

3. Photometric Sequences

Once a prominent new surface feature is discovered, we can target follow-up observations. For a select number of the larger, newly formed impact craters (> 30 m), we are targeting photometric sequences and geometric stereo pairs. Each month LROC can observe the newly formed crater under a different illumination environment. By comparing reflectance measurements from images acquired over many months, we can evaluate the phase curve of small regions of the surface around the site. To reduce the effects of varying incidence angle, we can also target photometric sequences where images of the site are acquired on consecutive orbits (phase and emission angles vary, incidence angle remains nearly constant). In addition, sometimes as part of the same sequence, a NAC geometric stereo pair is collected. These stereo observations allow us to create digital terrain models (DTMs) to examine the topography of the site [2]. The DTMs can also be used to calculate the incidence and emission angles relative to local topography, thus allowing the effects of topography to be remove when applying a photometric correction. With the sum of these observations, we can account for the dependence of reflectance on the observational geometry (incidence, emission, and phase) and investigate how the physical properties of the regolith (such as grain size, roughness, and porosity) affect the way light is reflected [e.g., 3].

4. Newly Formed Impact Craters

To date, we have discovered over 400 newly formed craters using LROC temporal imaging. Temporal image ratios of the before and after images reveal up to 4 reflectance zones around the new impact craters [1, 4]:

- Proximal high reflectance zone (PHRZ)
- Proximal low reflectance zone (PLRZ)
- Distal high reflectance zone (DHRZ)
- Distal low reflectance zone (DLRZ)

These changes in the surface reflectance are caused by exposure of immature regolith as well as changes in the regolith properties. In addition, phase ratio images, which are collected as part of a photometric sequence, are created by taking the ratio of a low phase image over the high phase image with similar incidence angle (i.e., $p(g_1)/p(g_2)$; where $g_1<g_2$ and $i_1\approx i_2$) [5]. These phase ratio images allow one to assess the slope of the phase function and compare it to the surrounding, undisturbed regolith.

Figure 1 shows an example of a temporal ratio image and phase ratio image of a new 26 m crater whose impact flash was observed on Earth on 11 September 2013 [6]. In the temporal ratio, a PHRZ and PLRZ is visible immediately adjacent to the crater. Both proximal regions in the phase ratio image appear brighter than the background, indicating a steeper phase function between 31° and 64°. In addition, there is no clear differentiation in the phase ratio image between the two distinct proximal zones visible in the temporal ratio image. The PHRZ and PLRZ are interpreted to be the immature and mature material (respectively) of the continuous ejecta blanket [1]. The steeper phase function indicates increased backscattering that could be caused by increased surface roughness. Additional bright rays in the phase ratio image extend several km from the impact site indicating increased backscatter and roughening of the regolith or an increase in the local porosity. Some of these rays correspond to the DLRZ in the temporal image pair that Speyerer et al. [1] interpret to be caused by sparse ballistic sedimentation or impact induced jetting from the primary impact event.

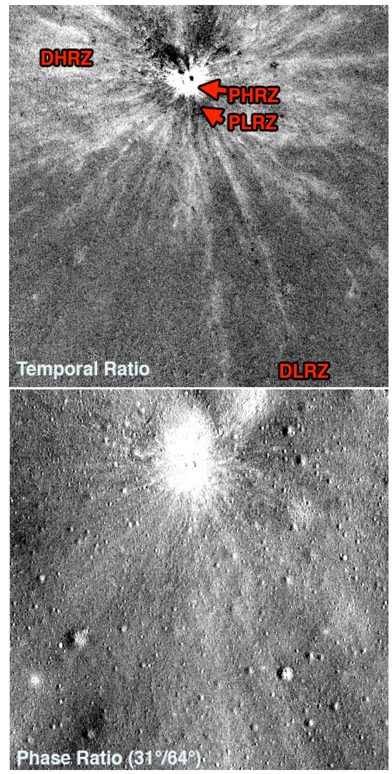

Figure 1: (Top) Temporal ratio image created by taking the ratio of M1149637354LR (2014-075) and M1119014742LR (2013-086) of a new 26 m crater. (Bottom) Phase ratio image created by taking the ratio of M1151986536LR (i=46°, e=17°, g=31°) with M1152000776LR (i=44°, e=21°, g=64°). Each image is 1300 m across.

5. References

[1] Speyerer et al. (2016) *Nature*, 258, 215-218. [2] Henriksen et al. (2017) *Icarus*, 283, 122-137. [3] Hapke (2012) *Theory of Reflectance and Emittance Spectroscopy*. [4] Robinson et al. (2015) *Icarus*, 252, 229–235. [5] Kaydash (2011) *Icarus*, 211, 89-96. [6] Madiedo et al. (2014) Mon. Not. R. Astron. Soc. 439, 2364–2369.