

IMPACT REMNANTS DETECTED BY THE CHANG'E-4 ROVER ON THE MOON. Y. Yang¹, S. Li², M. H. Zhu³, Y. Liu¹, B. Wu⁴, J. Du^{5, 1}, W. Fa⁵, and Y. Zou¹, ¹National Space Science Center, CAS, Beijing, China (yangyazhou at nssc.ac.cn); ²University of Hawaii, Honolulu, HI, USA; ³State Key Laboratory of Lunar and Planetary Sciences, Macau University of Science and Technology, Taipa, Macau, China; ⁴Department of Land Surveying and Geo-Informatics, the Hong Kong Polytechnic University, Hong Kong, China; ⁵School of Earth and Space Sciences, Peking University, Beijing, China.

Introduction: Asteroids and comets have been pummeling terrestrial planetary surfaces over billions of years, leaving numerous relics on their surface. Analysis of impactor relics can provide crucial insight into dynamical process that have affected the inner solar system [1]. The lunar surface regolith has recorded pristine marker of the impact processes which can be traced even after long-time surface evolution. The unprotected lunar surface may add ~2% wt.% carbonaceous chondritic materials after millions of year's exposure to space based on the geochemical analysis of typical meteoritic elements within returned lunar soil samples [1-3]. Understanding the types and the sources of these exogenous materials is important to better understand the early evolution of our solar system. The survived projectile fragments of impactors identified from the returned Apollo samples and lunar meteorites have provided critical clues on the temporal variations of the sources regions of impactors [1, 4]. However, those survived projectile fragments have been mostly mixed into bulk lunar regolith due to the continuing bombardment processes [1]. The mixing and overturn process of the lunar regolith can obscure the direct identification of impactor relics on the Moon.

Here we report *in situ* detection of possible undisturbed impactor relics within a fresh small crater along Chnag'E-4 rover's traverse.

Data & Method: As the original spectral features of any impactor relics within the lunar regolith may be strongly obscured by space weathering process, fresh craters are considered as the best candidates for a rover mission to search for possible impactor relics retained on the lunar surface. The Yutu-2 rover on board the Chang'E-4 mission has been exploring the lunar surface since landed at Von Kármán crater on the lunar far side in January 2019. The rover found a small fresh crater with a diameter of ~2 m on the ninth lunar day of the mission and conducted detailed observations around the crater [5]. There are some "glassy" materials in the crater center, which shows high reflection and distinct sintered structure in the images obtained by the panoramic camera (PCAM) on board the rover (Fig. 1a, 1c). The rover conducted detailed spectral measurements from the crate rim to the crater center along two different directions (Fig. 1b) using the visible and near-infrared imaging spectrometer (VNIS). The

VNIS consists of a complementary metal-oxide semiconductor (CMOS) imager (256×256 pixels, 450-945 nm) and a single pixel short-wavelength infrared (SWIR) detector (900-2395 nm) [6-7]. The CMOS imager has a field-of-view (FOV) of 8.5° and can capture an area of ~15 cm× 21 cm with a spatial resolution better than 1 mm/pixel, which provides unprecedented opportunity to study the composition of the "glassy" materials in details.

Results: Within in a fresh small crater, we found that the CMOS imager has captured part of the "glassy" materials at site N66. Figure 1a shows four CMOS images at wavelength 560 nm obtained at four typical sites (N66, N64, N63, N57) including the crater center and crater walls. The "glassy" material show much higher reflectance values compared to other rock fragments or regolith. Figure 1b shows the reflectance spectra of four different regions of interest (ROIs) from the four CMOS images (Fig. 2a). N57 and N63 represent spectra of rock fragments within the crater, N64 shows the spectrum of the background regolith, and N66 is the spectrum of the "glassy" material. In contrast to the reddened spectra of nearby lunar regolith and rock fragments, the spectra of the "glassy" material show distinct blue spectral slope.

Detailed geological studies have revealed that the materials in the Chang'E-4 landing area are mainly ejecta from the nearby Finsen crater and Alder crater [8-9]. The mineral abundances of derived from the VNIS spectral data of both the observed lunar regolith and a fresh rock indicate that plagioclase is the dominant mineral phase at the landing site [10-12]. These kinds of materials will not show blue spectral slope, and the subsequent space weathering process will further reddened the spectra. Because both glass and CC have a similar blue spectral slope in the CMOS wavelength, the observed "glassy" material may contain some glass and/or exogenic materials from impacts.

To verify the composition of the observed "glassy" material, we performed spectral unmixing analysis using the Hapke model following the method used in [13]. Considering the distinct blueing spectral slope of the observed "glassy" material at N66, except the typical lunar type silicate minerals (i.e. olivine, pyroxene, plagioclase, ilmenite) and lunar glasses, we

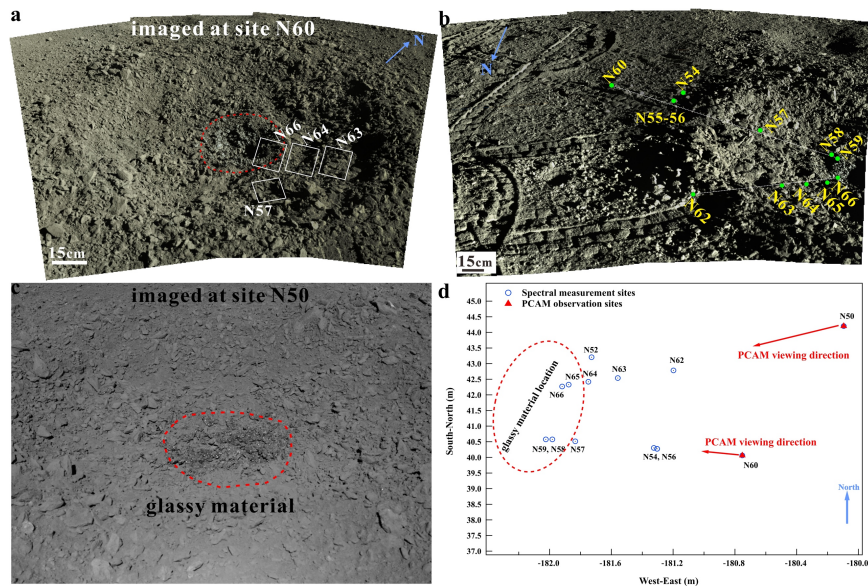


Fig. 1. Images obtained by the PCAM around the crater and the corresponding locations of spectral measurement sites. (a) A PCAM mosaics of the detected crater consisted of images obtained at site N60. The white boxes represent the imaged areas of the CMOS detector. The blue arrow indicates the azimuth of the north direction. (b) A PCAM image mosaic of the crater with all the VNIS measurement sites along the crater center to crater wall marked out with green dots. (c) A PCAM image of the crater center observed from another direction on the 8th lunar day at site N50. (d) The relative locations of the observed “glassy” material and the sites of VNIS and PCAM observations under the rover-lander coordinate system.

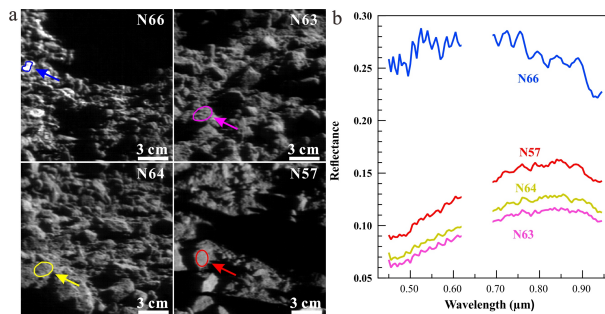


Fig. 2. (a) Images at wavelength 560 nm obtained by the CMOS detector at four typical sites at the crater center and the crater wall (N66, N64, N63, and N57, see Fig. 1b). The color circles are the regions of interest (ROI) used for spectral analysis. (b) The average CMOS spectra extracted from the ROIs shown in (a). The ROIs represent typical “glassy” material for N66, rock fragments for N57 and N63, regolith for N64, respectively. The bands between 0.62 and 0.69 μm due to potential artificial absorption here [5].

also added a spectrum of carbonaceous chondrite (CC) that has similar blue spectral slope to our endmember library. The unmixing results show that the “glassy” material is dominated by glasses and also reveals high abundance of CC remnants.

With the high resolution PCAM stereo images, we constructed a digital elevation model (DEM) for the detected small crater using photogrammetric methods (Fig. 3). The glassy materials are located in the crater center, and there is a pit within it. This fresh crater has a diameter to depth ratio of $\sim 5:1$ with central pit and $10:1$ without the central pit, which is much higher than the average ratio ($17:1$) of secondary craters at the landing site [14]. Impact cratering simulation using the iSALE

shock physics code indicates that the observed crater structure can be produced by a 15-cm diameter porous impactor hitting the lunar surface with a typical velocity of 15 km/s. The facts above seem to support a primary impact. However, a secondary impact cannot be ruled out as a diameter to depth ratio of $5:1$ to $10:1$ can be produced by low-velocity impact experiments in the lab [15]. As the mission continues, the rover may encounter more similar craters, this will help us to further verify the crater observed on the 9th day is primary or secondary.

Summary: The Yutu-2 rover may have detected the remnants from CC impact within the center of a fresh 2-m diameter crater. The identification has important implication on the origin of water on the Moon and improves our understanding on how the impact delivered materials alter the lunar surface.

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