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Dark halos and rays of young lunar craters: A new insight into interpretation

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ABSTRACT

Images acquired by the Narrow Angle Camera of the Lunar Reconnaissance Orbiter allow phase-ratio imagery of young lunar craters surrounded by dark halos. Such imaging is a new optical remote-sensing technique that is sensitive to the degree of surface roughness. We apply the phase-ratio technique to LRO images of young dark-halo craters near the crater Denning and in the Balmer basin, in addition to craters created by the impacts of the Ranger-6 spacecraft and Saturn-5 sections of Apollo-13 and Apollo-17. We suggest an alternative explanation of the dark halos and rays seen near the craters at large phase angles. Phase-ratio imaging suggests that these features result from higher surface roughness. Thus, the interpretation of dark crater halos and rays as a composition/maturity variance should be used with caution. The composition and structure factors can be effectively discriminated only using images acquired in a wide range of phase angles including small angles.

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1. Introduction

Many young lunar craters have bright halos and rays that were formed by excavating subsurface materials at major and secondary impact locations (Oberbeck, 1971). Fresh material ejected from lunar craters is generally brighter than the surrounding region, since it consists of immature soils that are slowly altered by micrometeorite bombardment and solar wind, resulting in soil darkening over long time periods. Eventually, the reflectance of ejecta material may appear as that of the surrounding regolith. Although the excavated materials of fresh craters should be of high reflectance, dark-haloed and dark-rayed craters on the Moon have been observed, but their number is significantly lower than craters without such halos and rays (Salisbury et al., 1968). These features are considered to be deposits of low-albedo materials; however, there is no unique explanation of their origin.

Some of these features, like several small craters in the old crater Alphonsus (Fig. 1a), perhaps have a volcanic origin (Salisbury et al., 1968; Head and Wilson, 1979). They are often associated with rilles and lineaments and considered as a source of pyroclastic material forming the dark halos (shown with arrows in Fig. 1a). Accordingly, the craters probably represent sites of volcanic fountaining on the Moon.

A feasible origin proposed for the dark ray system of the Copernican-aged crater Dionysius (Fig. 1b) implies impact melt deposits and dark primary ejecta (e.g., Schultz and Spudis, 1979; Hawke et al., 1979). Later Giguere et al. (2006) concluded that dark rays of Dionysius are dominated by mare basalts, not glassy impact melts.

The crater Tycho is an example of a large crater with a dark halo of non-volcanic origin. The crater seen in Fig. 1c has a dark annulus that is considered to be caused by rock melted due to the extreme heat of impact and ejected throughout the area immediately surrounding the crater (Pieters et al., 1994; Morris et al., 2000). The dark halo of Tycho consists mostly of dark glassy materials that have pooled in the low spots surrounding the crater. There are no other large craters having such a prominent dark halo that is visible, probably because the crater Tycho is both young and large.

Another type of dark halo crater can be found where a brighter ejecta blanket covers an older and darker lava flow. If a more recent impact occurs, it can pierce the layer of the bright ejecta material and excavate the darker material beneath. Examples of such craters can be found in the Schiller–Schickard region, where the mare material has been unearthed from beneath the light-colored deposits emplaced there at the Mare Orientale formation (e.g., Antonenko et al., 1997; Antonenko, 2013). Fig. 1d presents the crater Inghirami W (pointed by an arrow), located in the Schiller–Schickard region. It reveals a dark halo of excavated material. This underlying mare-type lava is called cryptomare. In principle, this mechanism of dark-halo formation is valid for all crater sizes including even those of 1–10 m. In this case dark-material layers

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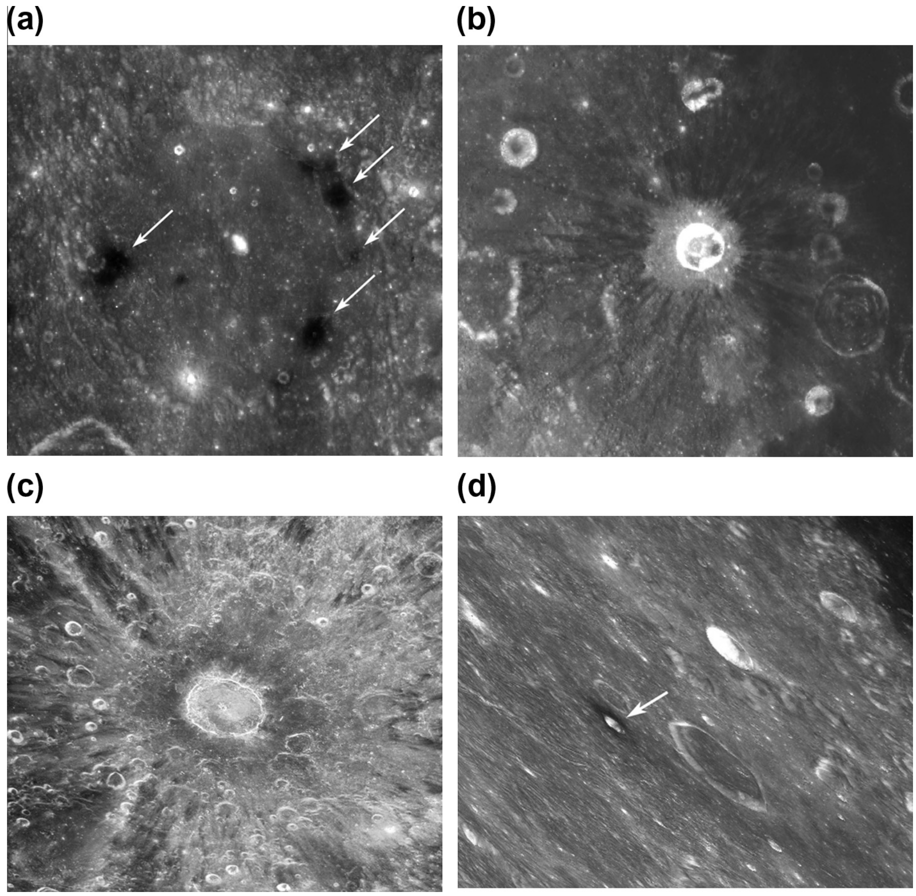

Fig. 1. Different dark-haloed craters. (a) The 120-km crater Alphonsus, (b) the 18-km crater Dionysius, (c) the 82-km crater Tycho, (d) a part of the Schiller–Schickard region. The LROC WAC mosaic (643 nm) produced by NASA/GSFC/Arizona State University and available at the http://lroc.sese.asu.edu/data/pr/tiff/lrocwac643nmnearside.tif is used.

can be brought to light when the thin younger layer composed of brighter materials has been pierced.

In this paper we suggest an alternative mechanism that may produce dark halos (rays) around craters, which is based on the difference of brightness phase curves of halos (rays) and their surrounding surfaces. We consider here several examples of dark halo craters whose darkness relates to the phase-angle effect. Three examples are shown of craters formed by the impacts of the Apollo 13 and Apollo 17 Saturn IVB boosters and the Ranger 6 spacecraft. The fourth and fifth we present are of young natural craters located near the old crater Denning and in the Balmer basin.

2. New mechanism and research method

Each location on the lunar surface can be characterized by the dependence of its brightness (or reflectance, or apparent albedo A, or radiance factor) on phase angle α (e.g., Shkuratov et al., 2011; Hapke, 2012). At different locations this dependence is different. The brightness decreases with increasing α and the rate of this decrease can be characterized by the phase function slope. Surface roughness affects the phase function, since the shadowing effect increases with increasing roughness (e.g., Hapke, 2012).

Fig. 2 shows two phase curves of absolute reflectance. One of them shows what may be considered a typical mare surface; whereas, the other one corresponds to what may be considered a typical highland surface. The data are taken from the absolute photometry of the Moon (Velikodsky et al., 2011) for small areas in Mare Tranquillitatis and near the highland crater Gylden close to the center of the nearside. As can be seen, the phase curves cross each other. This can occur for crater halos (rays) and their surroundings. That is, at small phase angles, the halos can be brighter than their surroundings; whereas, at larger phase angles an inversion may be observed. An illustration of such an inversion is

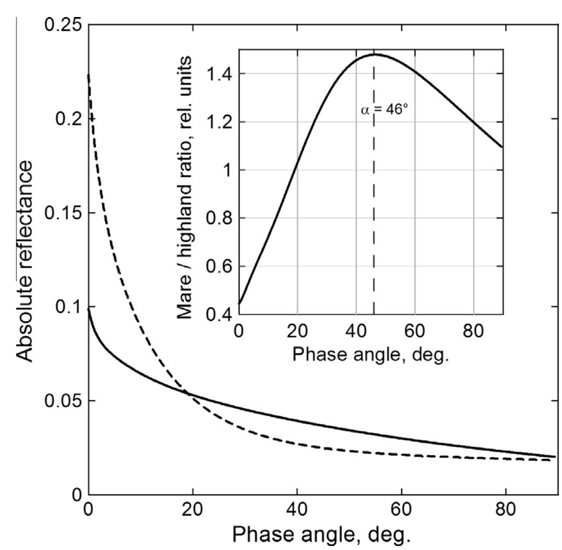

Fig. 2. Phase curves of absolute lunar reflectance. Data are taken from Velikodsky et al. (2011). Solid and dash curves correspond to typical mare and highland surfaces, respectively. The ratio of mare phase curve to highland one is in inset.