JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 90, NO. B14, PAGES 12,393–12,413, DECEMBER 10, 1985

The Nature of Crater Rays: The Copernicus Example

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Crater rays are formed during a cratering event as target material is ballistically ejected to distances of many crater radii forming narrow, generally high albedo, approximately linear features extending outward from the crater. The nature of crater rays was examined for the lunar crater Copernicus using new information on the composition of surface material (from near-IR reflectance measurements), surface roughness (from radar backscatter measurements), and photogeologic data (from available images). Part of the data analysis included use of mixing models to quantify the mixing systematics observed between primary ejecta and local substrate of the ray on the basis of compositional parameters from reflectance spectra. Primary material from Copernicus can be detected in the surface material of rays in decreasing amounts with increasing radial distance (e.g., 20–25% primary ejecta at six crater radii). For distances greater than three crater radii the proportion of local material to primary ejecta observed from these compositional reflectance data is approximately equal to that predicted by previous laboratory and ballistic studies of craters. Within three crater radii the compositional data indicate a higher proportion of primary ejecta than predicted. For extended areas along the ray that do not contain large secondary craters the primary ejecta is intimately mixed on the granular scale with local material throughout the regolith. The relatively high albedo of the rays of Copernicus is due to the feldspathic composition (highland) of the primary ejecta in rays emplaced on a mare substrate. Immature local substrate is only observed in Copernicus's ray at large unmantled secondary craters or other areas with sufficient topographic slope to prevent the accumulation of mature soils.

1. INTRODUCTION

Crater rays are filamentous, generally high-albedo features that emanate nearly radially from young impact structures. Rays are narrow in relation to the crater radius, extend distally for many crater radii, and constitute a distinctive albedo feature around some of the largest and freshest lunar craters visible from earth. Synoptic views of ray systems (Figure 1*a*) give the strong impression that the rays comprise bright material that has been excavated from the crater cavity and been emplaced beyond the continuous ejecta deposit. If this visual impression is correct, then the process that forms crater rays represents a significant mechanism for the lateral transport of primary material to great distances from its point of origin and, particularly for craters larger than a few tens of kilometers in diameter, constitutes a fundamental process for the regional mixing of crustal materials.

Earth-based telescopic images of the moon allowed the first studies and descriptions of rays and ray systems. *Shoemaker* [1962] described the arcuate and loop-shaped streaks of the Copernicus ray systems and showed that these patterns could be locally resolved into individual en echelon feather-shaped elements 15–20 km in length, with their long axes oriented approximately radially to the crater. He noted the presence of elongate depressions or gouges in the ray system, ranking in diameter from 8 km down to the limits of resolution and generally located at the proximal ends of the individual ray elements. Shoemaker observed that some of the gouges were not oriented radially to the crater. Although a commonly accepted view at this time was that rays had no discernible topography, Shoemaker indicated that low sun angle images showed roughness along rays, and he attributed this at least in part to the gouges and their surrounding rims. *Shoemaker* [1962] interpreted rays as "thin layers of ejecta from the crater about which they are distributed" and pointed out that this interpretation dated back to at least the 19th century. Gouges were interpreted as secondary impact craters formed by individual large fragments (or clusters) ejected from the parent crater Copernicus. Specific ray elements were believed to be "splashes of crushed rock derived chiefly from the impact of individual large fragments or clusters of fragments."

The acquisition of higher-resolution photographic data for the lunar surface from the Ranger, Surveyor, and Lunar Orbiter missions in the 1960's provided additional clues as to the nature of lunar rays. On the basis of these data there was general agreement that rays represented deposition of material from both the main crater and secondary craters [*Shoemaker*, 1966; *Shoemaker et al.*, 1969; *Schmitt et al.*, 1967; *Trask and Rowan*, 1967], but neither the detailed mechanisms nor the relative significance of each component was known. *Oberbeck* [1971] studied high-resolution Lunar Orbiter images of a ray element southeast of Copernicus and showed that in addition to several large secondary clusters there was an abundance of small bright-haloed craters in the element relative to the surrounding mare. He interpreted these as small secondary or tertiary impact craters and suggested that the general high albedo of the ray elements was due more to the excavation of local blocky material than to either the emplacement of bright material from the primary crater or local material excavated by the larger secondary clusters.

On a larger scale, the Apollo missions provided information concerning the nature of ejecta deposits from basins. The Apollo 14 mission was targeted to the distal portion of the Fra Mauro Formation and the textured ejecta deposit surrounding the Imbrium basin. The ejecta emplacement process was a major question in terms of understanding the provenance of the Apollo 14 samples, with some favoring an origin as primary Imbrium ejecta [*Wilshire and Jackson*, 1972; *Chao*

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Paper number 4B5253.
0148-0227/85/004B-5253$5.00