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 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 1a) 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...
et al., 1972], while others argued for a mixture of primary material and locally derived secondary and tertiary ejecta [Head and Hawke, 1975]. The debate intensified when Apollo 16 landed in the highlands at even greater distances from the Imbrium basin [Muehlberger et al., 1980]. Some proposed that primary Imbrium or Orientale ejecta composed the deposits at the site [Chao et al., 1973; Hodges et al., 1973; Eggleton and Schaber, 1972], while others emphasized the role of ballistic emplacement of Imbrium ejecta and the erosion of local material to produce the deposit [Morrison and Oberbeck, 1975; Head, 1974].

A major influence on the understanding of the emplacement...
of crater and basin ejecta came from the laboratory experimental works of Oberbeck, Gault, and Quaide. In particular, laboratory experiments were combined with lunar observations and modeling [Oberbeck, 1975] to show that ballistic erosion and sedimentation played a significant role in lunar geologic processes and history. This work provided a model which predicted the amount of local material derived from secondary cratering events as a function of crater size and radial range [Oberbeck et al., 1975; Morrison and Oberbeck, 1975; Oberbeck and Morrison, 1976; Oberbeck and Aggarwal, 1977; Morrison and Oberbeck, 1978].

In order to better understand the nature of crater rays and clarify the local versus foreign origin of ray material, the physical and chemical properties of a single lunar ray system for Copernicus crater have been studied in detail, and the results are presented here. This study uses a combination of data: spectral reflectance (for composition), radar (for physical properties), and images (for photogeologic context). The crater Copernicus was chosen because of its well-developed ray system, the crater's relative youth, and the compositional contrast, as described below, between the target material of Copernicus crater (predominantly highland) and the material on which many rays were emplaced (mare material). This compositional contrast permits the mixing of primary and local material to be assessed using earth-based near-infrared reflectance measurements.

The following questions concerning the nature of crater rays are addressed: Is the high albedo material forming a ray of local or primary origin? What is the distribution of primary target material as a function of range from Copernicus? What is the physical nature of material forming a crater ray? Are these data consistent with existing models for ejecta emplacement and the evolution of crater rays?

2. REGIONAL SETTING OF COPERNICUS CRATER

Copernicus is a large bright-rayed crater, 95 km in diameter, located in Oceanus Procellarum at 9.5°N, 20.0°W (Figure 1). One crater diameter to the north are the Carpathian mountains, which form the main topographic ring of the Imbrium basin [Wilhelms and McCauley, 1971]. Prior to the Copernicus impact, the lunar surface in this region consisted of a thin discontinuous layer of basaltic mare averaging less than a kilometer in thickness [DeHon, 1979; Horz, 1978; Head, 1982]. Locally, the abundant exposures of Fra Mauro Formation protruding through the mare [Schmitt et al., 1967] suggest thicknesses adjacent to Copernicus, of less than a few hundred meters. Estimations of the thickness of the Imbrium ejecta deposits underlying the mare at Copernicus target site, which depend on assumptions used for determining the diameter of the Imbrium cavity, range from 430 m to 3 km thick [McGetchin et al., 1973; Pike, 1974]. Other basin ejecta and floor materials from previous impacts are probably included in lesser amounts in the crustal materials below the Imbrium deposits [Wilhelms and McCauley, 1971]. Earlier, more poorly known basin-forming events such as Insularum, 600 km in diameter enclosing the Copernicus region, and Procellarum, perhaps 3200 km in diameter centered 450 km from Copernicus [Whitaker, 1981], would have excavated and redistributed crustal material in the Copernicus region and perhaps were responsible for the relatively thinner crust in Oceanus Procellarum [Wilhelms, 1985; Pieters and Wilhelms, 1985].

Copernicus is one of the most prominent fresh craters on the lunar nearside and has become a stratigraphic marker for lunar geology. Features associated with Copernicus were used to define the most recent major time period of lunar history [Shoemaker and Hackman, 1962; Wilhelms and McCauley, 1971]. The geology of the Copernicus region was first mapped by Schmitt et al. [1967] using earthbased telescopic photographs. Lunar Orbiter 4 and 5 images were subsequently used to map the crater itself in more detail [Howard, 1975]. Since none of the Apollo spacecraft overflew Copernicus, no new data have been obtained for the crater itself since 1967, except for measurements using earth-based instruments.
Continuous ejecta deposits occur up to a crater diameter away from the rim of Copernicus, while the ray system extends radially for more than 500 km (5 crater diameters). Associated with the rays are numerous secondary craters, many of which occur in chains or clusters that exhibit a characteristic V structure, or herringbone pattern [Guest and Murray, 1971]. This herringbone pattern is attributed to the near-simultaneous impact and subsequent interference of ejected materials excavated during the formation of secondary craters [Oberbeck et al., 1975]. Shown in Figure 2a is a portion of the...
northern ray system for Copernicus that is considered in the present study. Secondary craters 0.5 to 7.0 km in diameter are mapped in Figure 2b.

The age of the Copernicus impact has been estimated as $(800 \pm 40) \times 10^6$ years ago [Eberhardt et al., 1973]. This age was derived using the Ar$^{39}$/Ar$^{40}$ method from particular Apollo 12 soils (e.g., 12033) that contain a large amount of unusual KREEP-rich ropy glasses. The composition of these glasses distinguishes them from other Apollo 12 glasses and local soils [Marvin et al., 1971; Meyer et al., 1971] implying that they are of foreign origin. Since Apollo 12 lies near the end of a feathery ray from Copernicus (see Figure 1), these nonlocal glasses are usually thought to be associated with the Copernicus event. In addition to being KREEP rich, the bulk composition of the ropy glasses is less iron rich and more aluminum rich than the local basaltic material; Al and (Fe + Mg) are intermediate between noritic-anorthositic rocks and basaltic rocks. Most lithic fragments contained within the glass are from noritic rocks or their constituents.

The composition of surface materials in the Copernicus region has been examined using earth-based remote sensing techniques. Early in the development of reflection spectroscopy, when only silicon detectors were available, it was recognized that Copernicus had excavated predominantly highland, not mare, material [McCord et al., 1972a] and that the soils for most undisturbed areas in and around the crater had developed to a relatively mature state [McCord et al., 1972b]. The portion of Mare Imbrium to the north of Copernicus across the Carpathian mountains was recognized as being a low-titanium basalt, whereas the mare farther to the northwest includes more titanium-rich basalts with islands of the low-Ti basalt [Pieters, 1978]. The approximate boundary between these two mare basalt types is indicated in Figure 2b.

The development of new near-infrared instruments [e.g., McCord et al., 1981] allowed major advances in the identification of surface mineralogy. Data acquired for Copernicus show a complex array of mineral assemblages associated with the crustal stratigraphy in this region [Pieters, 1982; Pieters and Wilhelms, 1985]. Shown in Figure 3 are reflectance spectra for representative small (~5 km in diameter) areas within Copernicus (see Figure 1b for the geographic positions of these areas): (Left) Reflectance scaled to unity at 1.02 \( \mu \)m, (Right) residual absorption after continuum removal (division by tangent at 0.73 and 1.6 \( \mu \)m). Spectra are offset vertically. The major mafic component for Wall 3 and Floor 2 areas is a low-calcium pyroxene, whereas for Peak 3 it is olivine. Floor 1 area exhibits additional mineral/glass components and is an area of extensive impact melt.
local Apollo 12 basalts [Marvin et al., 1971], nevertheless trends toward a basaltic composition and thus indicates basaltic material was also incorporated into the melt during the impact event. Although the actual thickness of the basalt at the target site is not known, it must have been sufficiently thin to allow melting and mixing of basalt and norite before ballistic ejection of the fragment-laden, KREEP-rich melt toward the Apollo 12 site. Additional minor components in 12033 that may have originated at the Copernicus target site include an apparently unique fragment of troctolite. This fragment exhibits melted and quenched grain boundaries that can best be explained by excavation of plutonic material during a major impact event [Marvin and Walker, 1985].

The mineralogy derived from both the near-infrared spectra of Copernicus and the Apollo 12 lunar samples suggests the following stratigraphy at the Copernicus target site: thin layer of basalt overlying an extensive noritic layer above a zone of troctolite. Which, if any, of these stratigraphically distinct compositions are directly associated with the KREEP component is unknown.

3. SPECTRAL AND PHYSICAL PROPERTIES OF A COPERNICUS RAY

A sequence of small areas (each about 5 km in diameter) along Copernicus's northern ray system was chosen for detailed study (see Figure 1b). These areas (E5 to R5) were chosen to be in locations that were homogeneous at the scale of telescopic observations. For this sequence, areas were selected for study because they specifically did not contain large secondary craters. The spectral and physical properties of each studied area are discussed separately below. Two representative areas were also chosen within the low-Ti basalt substrate in Mare Imbrium, one to represent mature mare soils (M1; Figure 1b) and the other to represent fresh, more crystalline basaltic material (CM; Figure 1b). Two additional areas (R6 and R7) were also selected because of their presumed heterogeneity. Area R6 exhibits a very high surface roughness (at the 10-cm scale) based on radar backscatter measurements, while area R7 is centered on a prominent group of secondary craters. The areas associated with the ray itself are discussed in sequence below in order of increasing radial distance from the rim of Copernicus.

Near-infrared reflectance spectra have been obtained for these areas along the ray and neighboring mare (Figure 4). The diameter of each area observed telescopically was approximately 5 km, although it is estimated that repeated observations increased the effective spot size to about 10 km. For some areas (R5, M1), measurements were repeated for four independent observing runs to check for observational errors and phase effects. To complement these spectral measurements, albedo information was derived from Pohn and Wildey [1970]. Earth-based photography, Lunar Orbiter images and a few oblique Apollo photographs (Figure 5) of this Copernicus region were studied in detail to document surface mor-
Fig. 5. Oblique Apollo 17 photograph taken approximately 300 km north of the crater Copernicus, looking south along the main ray system investigated here. Copernicus is the large crater on the horizon, while the specific areas studied in detail are indicated with labeled arrows. The large impact crater in the bottom righthand corner of this view is the 20-km-diameter crater Pytheas. Apollo frame number AS17 2442.

Measured Properties of Ray Areas

Mare 1 (M1). This area was chosen because it appears from albedo and radar backscatter data to be relatively free of ray material and should thus be representative of the local mature mare substrate. The area is just to the east of the main ray system, discussed below, although high-albedo material also lies 8 km to the north. There are no secondary craters within the spot; the closest such crater larger than 1 km diameter is ~20 km to the west or ~50 km to the south, so that it is unlikely that tertiary ejecta covers this area. The radar backscatter for this general area is moderately low, typical for the surrounding apparently undisturbed mare, although this backscatter is not as low as that from an apparent ring of material around Pytheas, the 30-km crater located 100 km to the west. The spectral reflectance characteristics for M1 are comparable to other low-titanium basalt soils [Pieters et al., 1980]. It exhibits a steeper continuum slope than most highland soils (including those Copernicus soils presented in Figure 3). The pyroxene band strengths are stronger than for highland soils and centered at longer wavelengths. The band center near 1.0 μm for M1 is due to Fe- and Ca-rich clinopyroxenes [Adams, 1974], the major mafic mineral in this basalt.

Mare Crater (CM). This area is centered on the post-Copernicus primary impact crater Draper C (U. S. Geological Survey Map I-462), which has a subdued ejecta blanket pre-
served. Draper C is about 9 km in diameter, has a small flat floor, but lacks terraces. The crater exhibits a strong radar backscatter from its floor and walls, which is typical of fresh blocky mare craters [Thompson et al., 1981], while a moderate amount of backscatter from the ejecta blanket is observed out to about one crater radius beyond the rim. Although the thickness of the mare is only approximately known in this area, the spectral reflectance properties for the CM area (observed essentially within the crater cavity) are characteristic of fresh mare basalt [Pieters et al., 1980; Pieters, 1983]. The band strength is more than a factor of 2 stronger than for mare soils, while the band center (near 1.01 μm) is still controlled by the Ca-rich clinopyroxenes of the basalt. One of the primary differences between fresh mare material and mature
mare soils is the strength of the mafic absorption bands. Weakening of soil pyroxene bands with surface exposure is the normal process of soil maturation and is associated with the development of soil agglutinates [Adams and McCord, 1973]. Freshly exposed mare basalt, such as fragmental debris at craters, is not only brighter than mature mare soils but also always exhibits stronger absorption bands.

Ejecta 5 (E5). This area is within 10 km of the northern rim of Copernicus. It is located on a very hummocky unit that could contain a component of impact melt in the overturned flap [Howard and Wilshire, 1975]. This spot is located about 10 km to the east of the line between the E3–R2–R5 ray system and the center of Copernicus. It is well within the band of high radar backscatter which characterizes both the floor of Copernicus and a bright region of the ejecta blanket extending 15 to 20 km beyond the rim. The reflectance spectrum for E5 exhibits the weakest absorption bands for any area associated with Copernicus. The band center near 0.91 μm nevertheless is characteristic of the highland low-calcium pyroxene feldspathic composition observed in the crater interior.

Ejecta 3 (E3). The morphology of this area is dominated by the extensive covering of ejecta from Copernicus that blankets this area. Except to the east, it is at about this radial distance from Copernicus that the continuous ejecta blanket fragments into discontinuous deposits. At this E3 locality, however, the ejecta blanket is apparently still continuous.

In addition, the spot is located on a heavily mantled crater chain (that nevertheless still has prominent V structures) which extends northward to join the R2–R5 ray. At E3 the subdued secondaries in this chain are about 3–5 km in diameter. The radar backscatter characteristics of this area are diffusely bright, with no prominent features. E3 is located just at the edge of the bright ejecta region of Copernicus which extends somewhat farther from the crater at this point than at any other location around the crater. The spectrum of E3 exhibits a more prominent absorption band than E5. The band center occurs at a longer wavelength, near 0.96 μm, indicating an average pyroxene composition that also includes a somewhat more calcium-rich component. This mafic component is more likely to be a 2-pyroxene mixture where the band shift is the combined result of a low-calcium orthopyroxene and a clinopyroxene [Singer, 1981]. Models for mixing systematics are discussed in detail in section 4.

Ejecta 4 (E4). This area, located just south of the Carpathian mountains, borders on a large secondary crater cluster, the largest crater of which is about 3 km in diameter. All the secondaries have a mantled appearance, and they all possess V structures. To the north and west (within 10 km), comparable size and larger secondaries are fresher looking (some possess well-preserved rims) and have V structures up to 12 km in length. Secondaries exist within 2 km of E4 in the uprange direction. Area E4 and the general region north to the Carpathian mountains are moderately high in radar backscatter, but only about half the echo strength of the continuous ejecta blanket to the south. Several of the larger secondaries are apparent on the radar image, but there is no localized feature at or close to the E4 spot. One of the locally radar-bright areas is the 6-km diameter crater located 10 km to the west. The spectral characteristics of E4 are similar to those for E3, implying a similar low and high-calcium pyroxene mixture, although the absorption band appears slightly weaker.

Ray 2 (R2). This area is located 60 km north of the Carpathian mountains in Mare Imbrium on the main ray system that extends from area E3 to area R7. Northward, from the Carpathian mountains the ray can be readily distinguished on the mare by its higher albedo. Area R2 is just north (within 5 km of the rim) of the Carpathian mountains. It is located along the edge of the bright ejecta region of Copernicus which extends several tens of kilometers toward the east. The radar backscatter characteristics of this area are diffuse and low, with no prominent secondary V structures. The spectrum of R2 exhibits a more pronounced absorption band than E4, with a band center near 0.96 μm, indicating a more mafic pyroxene composition. The band weakens with increasing distance from the crater, but the area is still dominated by mafic absorption bands. The albedo in this area is generally lower than in the surrounding ejecta.

TABLE 1. Summary of Observed Morphology of Areas Associated With Ray Material in Copernicus Region

<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>E5†</td>
<td>10.5</td>
<td>Yes</td>
<td>Yes</td>
<td>Heavily mantled, ~3.5 km diameter</td>
<td>Yes</td>
<td>~2</td>
</tr>
<tr>
<td>E3</td>
<td>12.1</td>
<td>Yes</td>
<td>Yes</td>
<td>Mantled, ~3.0 km diameter</td>
<td>Yes</td>
<td>~2</td>
</tr>
<tr>
<td>E4</td>
<td>13.1</td>
<td>Yes</td>
<td>Yes</td>
<td>Mantled, ~0.5 km diameter</td>
<td>Yes</td>
<td>~2 (Large, 2.5 x 5.5 km)</td>
</tr>
<tr>
<td>R2</td>
<td>13.8</td>
<td>Yes</td>
<td>Yes</td>
<td>Mantled, ~0.7 km diameter</td>
<td>Yes</td>
<td>~3</td>
</tr>
<tr>
<td>R5</td>
<td>14.5</td>
<td>Yes</td>
<td>Yes</td>
<td>Mantled, ~2.7 km diameter</td>
<td>Yes</td>
<td>~5</td>
</tr>
<tr>
<td>M1</td>
<td>15.3</td>
<td>No</td>
<td>No</td>
<td>Fresh</td>
<td>No</td>
<td>~135</td>
</tr>
<tr>
<td>R7</td>
<td>16.1</td>
<td>Yes</td>
<td>No</td>
<td>Fresh, ~2.4 km diameter</td>
<td>No</td>
<td>~1</td>
</tr>
<tr>
<td>R6</td>
<td>17.0</td>
<td>Yes</td>
<td>No</td>
<td>Fresh, ~2.2 km diameter</td>
<td>No</td>
<td>~21</td>
</tr>
<tr>
<td>CM</td>
<td>18.2</td>
<td>No</td>
<td>No</td>
<td>Fresh</td>
<td>No</td>
<td>~27</td>
</tr>
</tbody>
</table>

*Distance is measured from the center of Copernicus. Crater radius along the heading of the ray element investigated here is 44 km.
†Located on Rim of Copernicus: continuous ejecta blanket.

TABLE 2. Measured Properties of Areas Associated With Ray Material in Copernicus Region

<table>
<thead>
<tr>
<th>Area</th>
<th>Visible Albedo P&amp;W</th>
<th>Band Center, μm</th>
<th>Band Strength, %</th>
<th>Radar Backscatter Character</th>
</tr>
</thead>
<tbody>
<tr>
<td>E5</td>
<td>13.8</td>
<td>0.91</td>
<td>2</td>
<td>High</td>
</tr>
<tr>
<td>E3</td>
<td>12.7</td>
<td>0.96</td>
<td>4</td>
<td>Medium high</td>
</tr>
<tr>
<td>E4</td>
<td>12.1</td>
<td>0.96</td>
<td>5</td>
<td>Medium high</td>
</tr>
<tr>
<td>R2</td>
<td>10.5</td>
<td>0.96</td>
<td>5</td>
<td>Diffuse medium</td>
</tr>
<tr>
<td>R5</td>
<td>10.5</td>
<td>0.975</td>
<td>8</td>
<td>Diffuse medium</td>
</tr>
<tr>
<td>M1</td>
<td>9.3</td>
<td>1.00</td>
<td>10</td>
<td>Low</td>
</tr>
<tr>
<td>R7</td>
<td>9.9</td>
<td>0.99</td>
<td>11</td>
<td>High</td>
</tr>
<tr>
<td>R6</td>
<td>10.5</td>
<td>0.995</td>
<td>12</td>
<td>High</td>
</tr>
<tr>
<td>CM</td>
<td>9.9</td>
<td>1.01</td>
<td>24</td>
<td>High</td>
</tr>
</tbody>
</table>
km) of a major secondary cluster. This cluster is dominated by two elongate craters that are \( \sim 2.5 \times 5.5 \) km in size. V structures from these secondaries extend all across the area covered by the spectral measurements. These secondaries are well preserved with crisp southern rims and deep shadows (and presumably have experienced little infilling). The R2 area just to the north of these secondaries exhibits a textured or disturbed surface on the scale of 100 m. Neither area R2 nor the secondaries to the south exhibit exceptionally strong radar backscatter, even though a larger secondary cluster 10 km to the northwest does. The R2 area is nevertheless moderately bright in radar backscatter, about 10 to 15% of the echo strength of the Copernicus ejecta blanket. There is a minor amount of structure in the radar image, but generally the spot is typical of the diffuse radar characteristics of the ray in this area. The spectral reflectance properties of area R2 follow an apparent progression from the areas closer to Copernicus: The continuum is slightly steeper, the band strength, slightly deeper (but still less than for the mature mare), and a band center, slightly longer, near 0.965 \( \mu \)m, implying a little more of a clinopyroxene component in a two-pyroxene mixture for the mafic component of R2.

Ray 5 (R5). This area is located on the main ray system that extends from spot E3 to spot R7. Area R5 is situated about 25 km west of the mature mare area M1 and lies entirely within the high-albedo ray element, which measures \( \sim 21 \) km in east/west extent at this point. The spot is centered near a cluster of small (<1 km), subdued secondaries which appear mantled by subsequent ejecta. This gives the region a textured appearance on the scale of 100 m. Within 5 km to the south, there are several 1- to 2-km diameter less mantled secondaries. The radar backscatter properties for R5 are relatively undistinguished. The backscatter of the secondary craters to the south and north is somewhat higher than for R5, but the latter nevertheless stands out in relation to the darker maria to the east and especially to the west, the backscatter for material surrounding the crater Pytheas. As with area R2, the reflectance properties for area R5 show an apparent progression away from Copernicus: The continuum is slightly steeper, the band strength is slightly stronger, and the band center is at a slightly longer wavelength. R5 is at approximately the same radial distance from Copernicus as the mare area M1, but its spectral reflectance characteristics are sufficiently distinct from the mare (higher albedo, weaker band, steeper, the band strength is slightly stronger, and the band center is at a slightly longer wavelength) to preclude the possibility that local mare material dominates the surface soil composition. (See Tables 1 and 2.)

Ray 7 (R7). This is an area chosen to represent the properties of secondary craters larger than 1 km in diameter. R7 is located at greater radial distance along the large ray that includes areas R5, R2, and E3. Area R7 is located in the middle of the ray and is centered on an elongated cluster of large secondary craters 10-4 km in extent plus several additional secondaries larger than 1 km in diameter. Details of this surface morphology can be seen in Figure 7. V structures and sharp rims are frequently associated with these secondaries. Other large (7-2 km) secondaries lie immediately to the south (within 15 km). Area R7 exhibits a notably high radar backscatter, about 25-30% greater than that for the Copernicus ejecta blanket. This high backscatter appears to be typical for such ray areas with large relatively unmantled secondaries, although R7 is the only ray area included in this study with such characteristics. The spectral reflectance properties of R7 are distinct from those of all areas previously discussed: The continuum slope is similar to that of R5, but the strength of the pyroxene absorption band is almost 50% stronger than R5 and even 15% stronger than that for mature mare M1. The band center for R7 is almost 1.0 \( \mu \)m. These characteristics indicate not only that the surface material at R7 is primarily basaltic in composition, but also that a mature soil has not fully developed at that site.

Ray 6 (R6). This area was included in the study because it exhibits one of the highest radar backscatter characteristics for any extended region within the northern ray system of Copernicus. R6 is located in the middle of the ray system to the north and east of the main E3-R7 ray. There are no secondary craters larger than \( \sim 0.5 \) km diameter within the measured area, although there are many near-circular subkilometer craters at this point (Figure 8). While these small craters seem to be associated with the ray, they do not have the morphological appearance of most secondary craters [Oberbeck and Morrison, 1973]. The radar image shows a profusion of bright, diffuse features, often (but not always) with circular symmetry, superimposed on a mottled but generally radar-bright background (25-30% of the ejecta backscatter returns of Copernicus). Within 8 km to the east of R6 is a small cluster of <1-km diameter secondaries with subdued V structures, while a cluster of many subdued secondary craters 0.5-1.5 km in diameter is located \( \sim 15 \) km to the northwest of R6. There are no large secondaries within 60 km to the south of the spot, indicating that no tertiary ejecta from other secondary impacts is likely to be found in this area. The spectral reflectance characteristics of R6 are similar to those for R7 but with the absorption band near 1.0 \( \mu \)m slightly stronger. The R6 area thus also exhibits a component of relatively immature mare basalt characteristics.

Discussion

From the above presentation of the data it can be seen that there is no unique way to characterize the Copernicus ray under consideration. It is heterogeneous; different chemical and physical properties are associated with different areas of the ray, and these properties appear to be influenced by the number and size of secondary craters and their deposits at any given site. The complementary information provided in the form of decimeter-scale roughness detected by the radar, the compositional parameters derived from the spectra, and the surface morphology inferred from photographic images does, however, enable many of the properties of the ray to be intercompared and interpreted. Although crater rays are complex and there are no simple rules that describe their properties, there is sufficient information to discern a few systematic trends which govern the nature of this ray system.

For example, a highland component within the rays of Copernicus ray is evident in the reflectance characteristics of areas E5 through R5, the locations of which increase in radial distance from Copernicus along a single continuous ray. For these areas the albedo is seen to be higher, continuum slopes are flatter, and absorption bands are weaker and centered at shorter wavelengths than the local mature mare. All these characteristics indicate a feldspathic component in the soils that includes a low Ca-pyroxene. For areas R2 and R5 in Mare Imbrium this highland component must clearly be of nonlocal origin. On the basis of the spectral data and inferred ejecta ballistics, the origin for the highland component would thus be Copernicus itself. It is also clear from the reflectance data, however, that the second major component at R2 and R5 is the local mare basalt soil, and the amount of this local
component appears to increase with radial distance from Copernicus. From the inferred age of Copernicus [Eberhardt et al., 1973] and previous spectral studies [McCord et al., 1972a, b] the surface soils are all relatively mature except for areas with sufficient topographic slope to prevent the normal accumulation of agglutinates since the Copernicus event. Numerical estimates for the mixture of these components are discussed in the following section.

For lunar bright-rayed craters there are two phenomena that affect the visibility of the ray system: the age and the
composition of the rays. When a crater first forms, the rays are composed of freshly exposed material that is inherently brighter than the undisturbed substrate if the two are of the same composition. At visible (photographic) wavelengths, immature soils from the Apollo collection are distinctly brighter than mature soils of the same approximate composition [Adams and McCord, 1971, 1973]. For fresh bright-rayed craters in the maria or highlands, crater rays are visible largely because new immature material is either deposited or excavated along the rays. As the surface material ages it becomes darker owing to the alteration processes that occur during soil formation [Adams and McCord, 1973]. If the substrate is the same composition as the ejecta forming the ray, the feathery visible parts of the ray will gradually disappear, leaving only the larger secondary craters to mark the ray's location. Copernicus is not, however, a very young crater and has been shown to exhibit mature soils for areas that have not been subsequently disturbed [McCord et al., 1972a, b].

The albedo contrast between many of the rays of Copernicus and the surrounding mare is thus now largely a compositional difference and not one of surface maturity. Even though Copernicus is one of the most prominent bright-rayed craters on the moon, it is by no means typical. The albedo distinction of Copernicus's rays allows their spatial characteristics to be readily studied, but it should be noted that the rays are not representative of freshly emplaced crater rays. The
rays of Copernicus are relatively bright because they contain a component of feldspathic foreign material that, with time, has produced mature soils with a higher albedo than soils from the local basalt.

Additional evidence for the compositional distinction between Copernicus ray material and local substrate comes from a number of post-Copernicus craters that can be identified which have excavated mare material and deposited it on the surface of the ray. Some of these crater ejecta deposits appear as dark-haloed craters superimposed on Copernicus ejecta or rays. The dark deposits from Draper C (crater CM) are one example (Figure 1b). Other dark-haloed craters such as Copernicus H can be identified [Hawke and Bell, 1981; Bell and Hawke, 1984] and are indicated with arrows in Figure 1a.

Many, if not most, small post-Copernicus craters are relatively young and are surrounded by the normal bright zone of immature freshly excavated material. Such craters appear as small bright spots both within the ray and in the mare of Figure 5. A much larger and prominent dark-haloed crater can also be seen within the eastern ray of this image (indicated with an arrow on the left). Two conditions must be met for an impact crater of any size on a ray of Copernicus to develop a dark halo: (1) the crater must be large enough to excavate basaltic material from beneath the ray and form deposits that
contain a proportion of basalt greater than that inherent in the highland-mare mixture of the ray itself, and (2) the material excavated must have been exposed long enough to produce a mature surface soil, which is then darker than soils from the ray. The observed number of dark-haloed craters associated with rays of Copernicus is thus also affected by both the age and the composition of the ejecta, the latter of which is controlled by the size of the impact crater and the degree to which it penetrates to the basaltic substrate.

The vertical thickness of the mixed zone of highland-mare components forming the ray can be estimated from the size of the smallest dark-haloed crater which has excavated basalt from beneath the ray. Unfortunately, appropriate high-resolution images do not exist for a thorough examination of the sizes and distribution of post-Copernican dark-haloed craters; very few such craters were found in the available images for Copernicus's rays. The smallest dark-haloed crater observed was approximately 360 m in diameter in a diffuse sec-

Fig. 8. Morphology of the surface at area R6. The center position of the area for which reflectance measurements were made is marked with a cross. On the eastern (right) side of this image, no secondary craters larger than about 200 m can be seen, although other kilometer-sized craters are present. The R6 spot is located on the eastern edge of a "disturbed" area which contains many subdued kilometer-sized secondary craters with associated V structures. These secondaries probably contribute to the higher than usual radar backscatter that is associated with this ray element. This image is part of Apollo 17 rectified pan frame 3065; illumination is from the right.
tion of a ray at about six crater radii from Copernicus (frame AS17-2290). Using a conservative excavation depth/diameter of 1/10 and requiring the boundary between the ray and mare substrate to be at least one third the excavation depth, the ray thickness would be of the order of 10–15 m. Thinner rays would allow smaller dark-haloed craters to be produced. These observations imply that the vertical mixing zone of primary ejecta with local substrate that forms the ray could extend throughout most of the regolith where the ray is locally extensive. It also implies that much of the current extent of Copernicus's ray system will remain as a visible feature on the lunar nearside for at least another aeon of lunar history, since this compositionally different ray material is apparently an integral part of the regolith.

Data for areas R6 and R7 are more difficult to interpret than those for the proximal areas on the continuous ray because in this case both R6 and R7 possess an immature soil component and have a high radar backscatter, and yet the two areas have very different surface morphologies. Area R6 contains no craters with morphologies that indicate a secondary origin; all the craters are roughly circular and lack the characteristic V structures and braided or mantled texture. Conversely, area R7 contains several well-preserved secondary craters larger than 3 km in diameter and has many smaller, mantled, secondary craters and a prominent set of herring-bone dunes.

The most likely explanation for the occurrence of immature soils at both R6 and R7, on the assumption that each area is indeed the age of Copernicus (about 800 million years [Eberhardt et al., 1973]), would be that at both areas an additional physical property has prevented the surface soils from reaching maturity by normal soil formation processes. Steeper local slopes occur within the interiors of the larger secondary craters of R7 than on the exterior deposits (Figure 7) and would cause downslope movement of material during soil-reworking processes, thus preventing normal soil accumulation.

Images of area R6 (Figure 8), however, show an absence of craters larger than a few hundred meters in diameter. Although a different reason for the lack of soil formation may thus be required for R6, the high backscatter of the radar data for both areas puts general constraints on the possible causes. These data show that both area R6 and area R7 are unusually rough (i.e., bright) at the 3.8-cm radar wavelength. Such roughness may be due either to a higher than average number of blocks at the surface (or buried within a few radar wavelengths of the surface) or to local topographic undulations at a scale of a few tens of centimeters [Zisk et al., 1974; Thompson et al., 1981]. Since neither of these physical features are readily observed at R6 within the available image resolution, it is difficult to account for the high radar backscatter and associated immature soil. Most surface boulders should have been removed by maturation processes acting over the history of the ray element [Arvidson et al., 1975]. Unusually rough small-scale topography, unobserved directly, may be more likely to account for the observations, but the direct cause for this roughness is not defined. R6 does lie near the end of a mare ridge system, although no unusual morphology is observed.

4. Quantitative Models

Most of the questions relating to the nature of crater rays require an understanding of how ejecta from the primary crater interacts with local surrounding material. Models derived from the ballistics of ejecta emplacement developed by Oberbeck and coworkers [Oberbeck, 1975; Oberbeck et al., 1975] were summarized in the introduction. The compositional measurements for the Copernicus ray described in the previous section are new data directly relevant to the details of this interaction. Since these compositional data are a completely independent source of information about ray materials, it will be useful to compare quantitative results for models of mixing systematics based on ballistic data with recent models of reflectance properties of compositional mixtures. A first-order approximation suggests that there are four types of surface material associated with Copernicus's ray system: mature and immature noritic material derived from the primary crater and mature and immature basaltic material derived from the local mare substrate.

As described in the previous section, the reflectance spectra of the areas on the ray extending out from Copernicus to area R5 increase regularly in slope and in the depth of the pyroxene band. Additionally, the pyroxene band minimum shifts from 0.91 μm toward 1.00 μm, which is consistent with a change from orthopyroxene-bearing anorthosite-norite rocks to clinopyroxene-bearing basalts [Adams, 1974]. This change of lithology along the ray is interpreted as an expression of the mixing of differing proportions of Copernicus ejecta with the mare basalt substrate. The kind of mixing and the relative proportions of the rock/soil types warrant further examination as a means of better understanding the process of ray emplacement.

Two models are used here to describe the spectral reflectance changes that occur when different materials are mixed. One model applies where patches of one material are interspersed with patches of another so that any small packet of reflected radiation has interacted with one material only. This is the so-called "checkerboard" or linear model where the spectral reflectance contribution from each material is weighted linearly by the areal extent of the material [Singer and McCord, 1979]. For the lunar rocks/soils being considered, the scale of mixing may range from centimeters to kilometers or larger and cannot be specified using the reflectance data.

The second model describes reflectance from mixed materials when small packets of radiation have passed through each material present. The model applies to lunar soils which contain rock, mineral, and glass particles typically on the scales of millimeters to microns in diameter. The spectral reflectance contributions of the individual soil components do not add in a linear fashion but instead are weighted by such factors as the optical extinction coefficients of the particles. The nonlinear mixing of intimate mixture of minerals in soil spectra is described by Johnson et al. [1983] and involves the calculation of single-scattering albedos from individual components. The method is also sensitive to particle-size effects on reflectance spectra.

The telescopic reflectance data for all areas associated with Copernicus's ray were examined with both mixing models. Many areas along the ray were measured more than once. We have included some of these multiple measurements to indicate the range of data variations due to observational parameters. Principal component analyses (PCA) were used to describe the systematic variations of the reflectance data in terms of mixing lines between a variety of compositional endmembers. Separate PCA analyses were made to test the linear checkerboard and the nonlinear intimate mix models.

Procedures

The telescopic reflectance spectra for the Copernicus ray areas were filtered using a five-point running mean to suppress random instrumental errors. Thirty wavelengths between 0.7
and 1.8 μm were used to define each telescopic spectrum. Wavelengths near the telluric water bands were not sampled for this analysis (reducing the random residual errors in the PCA analysis to 0.5% reflectance). Since direct albedo information was not obtained from the telescopic data, all spectra were normalized by dividing each reflectance value by the sum of the reflectances at the 30 wavelengths.

Principal component analyses were performed on these modified spectra to describe the variation in the reflectance data and to test the types of mixing systematics that may account for the variations. A more detailed description of these procedures and strategy can be found in works by Smith et al. [1984] and Johnson et al. [1984]. Since PCA procedures are essentially linear transformations of the data, the linear mixing model can be readily applied to results from PCA of the normalized reflectance data. The nonlinear mixing model for intimate mixtures, however, first requires conversion of the reflectance measurements to single-scattering albedos (SSA) before initiation of PCA analysis. The normal albedo data of Pohn and Wildey [1970] were used to scale the telescopic spectra to the appropriate albedo value which then allows conversion to single-scattering albedo using the equations described by Hapke [1981]. This conversion is the major difference between how the data were treated for the linear checkerboard model and the nonlinear intimate mixture model. In order to allow the results of the two PCA analyses to be compared in the mixing models, the single scattering albedo spectra were renormalized (a linear function), thus removing albedo as a variable component before application of PCA.

The first few principal components of variation in the reflectance data describe most of the variation between spectra and allow the data to be examined for possible mixing systematics between end-member spectra. After choosing appropriate end-members to represent the data, the PCA variations in all spectra can be described as a proportional mixture of these end-members. To test how well the two mixing models describe each data set, intermediate spectra are calculated from PCA end-member spectra using the proportions from the appropriate PCA. The calculated mixture spectra from the two models are compared to the real spectra, and the total residual error (RMS) of their difference is examined. This error should be minimized if the model describes the mixing systematics well.

### Results

The PCA that utilized the nonlinear transformation to single-scattering albedos (for the intimate mixture model) contained a greater proportion of the variance within fewer orthogonal components. A comparison of the variance for the two PCA’s performed on the telescopic data is shown in Table 3. Even before applying the mixing model analyses it is apparent that the nonlinear transformation PCA describes the variations of the data better than the linear PCA.

Results of the PCA analysis of the telescopic spectra after the single-scattering albedo conversion are shown in Figure 9. The first principal component of variation (axis 1) is largely sensitive to the overall slope of the reflectance spectra, while the second principal component (axis 2) is more sensitive to the absorption band depths near 1 μm. Note that if normalized spectra were not used in the PCA, the primary axis would be albedo.

The spectra represented in Figure 9 can be considered as mixtures of three end-members: mature highland soil at Copernicus crater (E5, F3, W3), mature soil on rayed mare (M1), and fresh mare crater ejecta (CM). It is reasonable to select E5, M1, and CM as spectral end-members for the purpose of analyzing mixing, as was previously inferred from inspection of the reflectance spectra and from measurement of the wavelength of the pyroxene absorption band near 1 μm. Figure 9 shows that all of the telescopic spectra for Copernicus’s ray, except R6 and R7, can be considered to lie approximately along a mixing line between E5 and M1. Areas R6 and R7 appear to require a component of fresh mare material (CM), again in keeping with the conclusions drawn earlier based on the depths and wavelengths of the pyroxene bands.

The Copernicus data are consistent with compositional trends defined by a similar analysis of the spectra of about 500 lunar samples [Smith et al., 1985; Johnson et al., 1985]. The relationship between the telescopic and the laboratory data sets is illustrated in Figure 10. Samples presented in Figure 10 were selected to represent known major compositional and spectral classes identified from the lunar sample collection: noritic rocks (77017), mature anorthositic soils (61241), mare basalts (12063), and mature basaltic soils (12070). Apollo 12 basalt and soil were chosen because they may reasonably represent the low-Ti mare materials near Copernicus. All spectra in Figure 10 were filtered, recalculated as single-scattering albedos, renormalized, and rotated to the PCA vectors defined by the above four lunar samples. The telescopic spectra (Figure 10) thus plot in slightly different positions in relation to one another when the PCA is defined by the lunar samples.

When referenced to lunar samples, the Copernicus crater materials W3, F3, and E5 (Figure 1b) plot close to mature Apollo 16 soil (sample number 61241). Outer ejecta-blanket areas E3 and E4 and inner ray, sites R2 and R3 lie along a broad potential mixing line between the mature highland soil and mature mare soil (Sample number 12070). Mare material, M1, plots close to 12070. The spectra of R6 and R7, the most cratered of ray areas measured, fall below and to the right of M1 along a mixing line with CM. The M1-CM mixing line lies close to and parallel to the 12070-12063 mixing line. The more extensive collection of lunar sample spectra, therefore, provides a consistent and reasonable framework for interpretation of the telescopic spectra for Copernicus rays.

Since PCA is essentially a linear analysis of data variation, the position of any data measurement relative to a hypothetical mixing line between end-members describes the proportion of each member contributing to the measurement. As an example of mixing systematics that can be calculated from PCA results for Copernicus areas E5, M1A, and CM we chose as end-members from the data presented in Figure 9. Listed in Table 4 are the calculated proportions of each end-member for the spectra along Copernicus’s ray. Since area M1 was measured many times, the choice of M1A as an end-member to represent the M1 area allows the uncertainty of these proportions to be estimated as 5%.

The calculated fractions of these three end-members for

### Table 3. Principal Component Analysis for Telescopic Reflectance Data

<table>
<thead>
<tr>
<th>PCA Axis Number</th>
<th>Normalized Data (for Linear Model)</th>
<th>SSA Transformed Data (for Nonlinear Model)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Variance</td>
<td>% of Total</td>
</tr>
<tr>
<td>1</td>
<td>2.93e-5</td>
<td>81.34</td>
</tr>
<tr>
<td>2</td>
<td>6.12e-6</td>
<td>16.96</td>
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<tr>
<td>3</td>
<td>4.53e-7</td>
<td>1.25</td>
</tr>
<tr>
<td>4</td>
<td>6.07e-8</td>
<td>0.17</td>
</tr>
</tbody>
</table>
Fig. 9. First two principal components of variation for the telescopic spectra of the Copernicus region. Spectra were filtered, recalculated as single-scattering albedos, renormalized, and sampled at 30 wavelengths between 0.7 μm and 1.8 μm. Axis 1 (93.5% of variance) is sensitive to curve slope. Axis 2 (6.0% of variance) is most sensitive to the depth of the absorption band near 1 μm. Spectra can be modeled as mixtures of E5, M1, and CM. Vertical and horizontal scales are in percent for approximate scaling of proportions of spectral end-members.

Fig. 10. First two principal components of telescopic spectra of Figure 9 rotated into PCA variation space defined by four lunar samples. Lined zones with arrows indicate inferred changes in spectra with maturation from lunar rocks to soils. Stippled zone indicates mixing trend between mature soils in the Copernicus region. The spectral variation observed among lunar samples provides a consistent framework for variation in telescopic spectra of the Copernicus area.

Discussion

Two kinds of information can be derived from the above results on the assumption that the end-member spectra are representative of distinct surface units. Proportions of local substrate and primary crater material for each area along the
The linear model describes checkerboard or patchy areal mixing. The nonlinear model describes intimate mixing at the granular level.

The residual errors (rms) of the difference between the measured reflectance spectrum and a calculated spectrum based on the first two principal components of PCA that defined the proportion of end-members E5, M1A, and CM are shown in Table 5.

TABLE 4. Calculated Proportion of End-Member Components at Measured Areas Along Copernicus Ray

<table>
<thead>
<tr>
<th>Area</th>
<th>E5</th>
<th>M1A</th>
<th>CM</th>
</tr>
</thead>
<tbody>
<tr>
<td>E5</td>
<td>1.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>W3</td>
<td>1.01</td>
<td>-0.04</td>
<td>0.03</td>
</tr>
<tr>
<td>F3</td>
<td>1.00</td>
<td>-0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>E3</td>
<td>0.74</td>
<td>0.23</td>
<td>0.02</td>
</tr>
<tr>
<td>E4</td>
<td>0.65</td>
<td>0.40</td>
<td>-0.05</td>
</tr>
<tr>
<td>R2A</td>
<td>0.42</td>
<td>0.62</td>
<td>-0.03</td>
</tr>
<tr>
<td>R2C</td>
<td>0.36</td>
<td>0.69</td>
<td>-0.05</td>
</tr>
<tr>
<td>R5X</td>
<td>0.27</td>
<td>0.72</td>
<td>-0.01</td>
</tr>
<tr>
<td>R5C</td>
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<tr>
<td>R5D</td>
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<td>0.79</td>
<td>0.02</td>
</tr>
<tr>
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<td>0.79</td>
<td>0.03</td>
</tr>
<tr>
<td>M1A</td>
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<td>0.00</td>
</tr>
<tr>
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<tr>
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<tr>
<td>M1D</td>
<td>-0.04</td>
<td>1.01</td>
<td>0.03</td>
</tr>
<tr>
<td>R7</td>
<td>0.04</td>
<td>0.84</td>
<td>0.12</td>
</tr>
<tr>
<td>R6</td>
<td>0.02</td>
<td>0.81</td>
<td>0.17</td>
</tr>
<tr>
<td>CM</td>
<td>0.00</td>
<td>0.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>

TABLE 5. Residual Errors (rms) of the Difference Between the Measured Reflectance Spectrum and a Calculated Spectrum Based on the First Two Principal Components of PCA That Defined the Proportion of End-Members E5, M1A, and CM.

<table>
<thead>
<tr>
<th>Area</th>
<th>Linear Model</th>
<th>Nonlinear Model</th>
<th>Ratio</th>
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<tr>
<td>E3</td>
<td>1.26e-3</td>
<td>0.674e-3</td>
<td>1.87</td>
</tr>
<tr>
<td>E4</td>
<td>1.33</td>
<td>0.723</td>
<td>1.84</td>
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<td>R2A</td>
<td>1.17</td>
<td>0.657</td>
<td>1.78</td>
</tr>
<tr>
<td>R2C</td>
<td>1.68</td>
<td>0.966</td>
<td>1.74</td>
</tr>
<tr>
<td>R5X</td>
<td>1.15</td>
<td>0.625</td>
<td>1.84</td>
</tr>
<tr>
<td>R5C</td>
<td>1.77</td>
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<tr>
<td>R5D</td>
<td>1.41</td>
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</tr>
<tr>
<td>R5A</td>
<td>1.51</td>
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</tr>
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<td>R7</td>
<td>1.05</td>
<td>0.680</td>
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<tr>
<td>R6</td>
<td>0.965</td>
<td>0.675</td>
<td>1.43</td>
</tr>
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</table>

The linear model describes checkerboard or patchy areal mixing. The nonlinear model describes intimate mixing at the granular level.
served dark-haloed craters), the compositional measurements of the Carpathian Mountains is basaltic (consistent with the ob-

summarized in Table 4.

The two ray areas (R7 and R6) that do not follow the mixing systematics for mature soils from E5 to M1 provide additional insight into localized processes associated with ray materials. As discussed in the previous section, these two areas have a different morphology than the other ray areas studied and exhibit properties that indicate a component of fresh or immature mare basalt for the area measured. This immature basalt component is evident in the maturation trends shown in Figure 10. It is proposed that the apparent spectral immaturity of R6 and R7 is caused by the exposure of relatively fresh subsurface material on the steep inner walls of craters or perhaps on large blocks of rock. This interpretation is supported by the high radar backscatter for areas R6 and R7. Within the telescope aperture the steep inner walls of craters would appear as local areas (patches) of less mature soil. From a spectral mixing viewpoint these immature patches should model as a linear (checkerboard) mixture with the surrounding more mature material. Areas R6 and R7 then should show the poorest fit to the nonlinear model in comparison with the other ray areas measured.

A test of this hypothesis was made by examining the rms errors for the ray spectra for the two mixing models (Table 5). Figure 11 shows the ratio of the rms errors for the linear versus the nonlinear models plotted against distance from Copernicus. Areas R6 and R7 have the lowest linear/nonlinear error ratios, which is consistent with the concept that they are expressing relatively more patchy (linear) spectral mixing. The patchy material component is interpreted to be fresher mare basalt. Although the rms ratio systematics for other ray areas in Figure 11 are not tightly constrained, there may be a general trend from granular (nonlinear) to patchy (linear) mixing with increasing distance from Copernicus. Since the reflectance measurements integrate over a few-kilometer area, increasing irregular patches with distance would not be surprising at this scale.

It should be noted again that the primary/local mixing ratio derived from these models uses the simplified description that the primary material is of highland composition and the local material is basaltic. A thicker mare at Copernicus would dilute the "highland" component in the primary ejecta. The proportion of primary material in the distal rays would thus be underestimated in this study, since only the highland component was used as a marker. If the mare basalt thickness for the Copernicus target area was more than the nominal several hundred meters estimated from Schmitt et al. [1967], a potential conflict would arise between these observations of a component of highland primary material at the distal regions of Copernicus ray and the results of experimental and field data concerning the depth of origin of ejecta. From both experimental investigations [Stoffler et al., 1975] and field observations of terrestrial craters [Horz and Bahnholzer, 1980] it has been hypothesized that the material that now forms the distal portion of the ejecta pattern around any lunar crater would

positional end-members have been chosen and that the mixing systematics used to estimate proportions are valid. Determination of values for \( \mu \), on the other hand, is based on entirely different observations. The basic interaction of ejecta with substrate material has been studied in the laboratory using carefully controlled materials, with the results requiring scaling to planetary parameters. The values of \( \mu \) given in Figure 12 were obtained using earth-based and lunar orbital images of secondary craters around Copernicus (Oberbeck et al., 1975).

It is remarkable indeed that both approaches to understanding the relation of crater ejecta to local substrate provide the roughly similar projections displayed in Figure 12. Both show that the larger the radial distance from a major impact crater, the smaller the amount of primary ejecta that is incorporated within the ray, in relatively predictable proportions. For large craters such as Copernicus, however, there is still sufficient primary material within the area extent of a ray to be detected on the surface hundreds of kilometers distant from the crater. For example, in the case of area R5, which is about six crater radii from the rim of Copernicus, measurable amounts (~20-25%) of primary ejecta of highland composition can be identified from the mixing model calculations summarized in Table 4.

There is a notable discrepancy, however, between the two approaches in descriptions of the proportion of primary material emplaced within three crater radii (>150 km). Assuming that the substrate for ejecta deposits between Copernicus and the Carpathian Mountains is basaltic (consistent with the observed dark-haloed craters), the compositional measurements of the surface deposits within three crater radii of Copernicus, E3 and E4, show a much higher proportion of primary materi-

al (highland) than that predicted by Oberbeck et al. [1975] (Figure 12). A possible interpretation of this relates to the type of mixing that may occur in areas of thicker ejecta deposits nearer the crater. In a thicker, more continuous curtain of ejecta being emplaced near the crater, early ejecta would mix with the basalt substrate, but subsequently following ejecta would interact with this just-emplaced mixture. The last primary ejecta would interact with a substrate already highly contaminated with primary material, and thus the resulting surface material would give a spectral signature not representative of the average for the entire mixture.
come from the uppermost near-surface strata within the target. For Copernicus, this would include the layer of mare basalt. The fact that some component of highland material is still seen in the distal ray lends support to the suggestion that the mare basalt at Copernicus was thin.

5. SUMMARY AND CONCLUSIONS

From the data and discussions presented in the previous sections a number of new specific pieces of information about the nature of crater rays and Copernicus in particular can be highlighted.

1. Observable amounts of primary crater ejecta are measured in the laterally extensive rays of Copernicus. This ejected material occurs mixed with local material of the substrate.

2. Since most soils associated with Copernicus crater and rays are now mature, the present brightness of Copernicus rays is due largely to the component of highland primary ejecta intimately mixed with local substrate (mare basalt soil) and not to brightness associated solely with immature soils excavated by secondary and tertiary impacts.

3. On the basis of the rare occurrence of small dark-haloed craters in areally extensive filamentary rays, the vertical thickness of the mixed zone of primary and local materials composing the ray probably extends to depths including most of the regolith.

4. The proportion of local to foreign material (or mare substrate to primary highland ejecta) described by the mixing systematics of the reflectance data is similar to that predicted by ballistic studies of impact craters and their ejecta [Oberbeck et al., 1975]. An increasing component of local material is observed at progressively greater radial distances. The new compositional data indicate that the amount of material transported to significant lateral distances as impact crater ejecta is approximately equal to the amount predicted by the ballistic studies.

5. The proportion of primary crater ejecta from subsurface horizons that is emplaced upon the surrounding terrain out to distances of three crater radii is observed to be notably higher on the basis of the compositional data than the value predicted by laboratory cratering models and terrestrial field data. This may indicate that in areas of continuous ejecta deposit the uppermost parts of the deposit are not as influenced by basal substrate mixing.

6. Mixing model systematics for reflectance data indicate that primary ejecta is intimately mixed at the granular scale with local material for areas along a ray that do not contain many secondary craters greater than 100 m in diameter. With increasing distance from the primary crater the ray material may occur in more patchy distributions (across a few-kilometer area along the ray).

7. Mixing model systematics indicate that local material occurs in patches that have not reached the same soil maturity as the rest of the ray for areas of a ray that contain many observable secondary craters. Such immature soils are only observed in association with large and morphologically fresh secondary craters or areas that otherwise indicate sufficient topographic roughness to prevent the accumulation of mature soils.

Overall, the ray system for Copernicus is distinctly heterogeneous in composition and maturity as well as morphology. Parts of the ray behave in a regular and systematic manner (for example, the increasing proportion of local material in ray deposits with greater radial distance from the primary). Other features occur only randomly or infrequently, perhaps controlled by differences in grain size and cohesion of impacting secondary projectiles [Schultz and Gault, 1985] (for example, the presence or absence of fine, possibly primary, material mantling secondary craters at similar radial distances).

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