THE ORIGIN OF LUNAR CRATER RAYS. B.R. Hawke[1], D.T. Blewett[2], J.J. Gillis[1], P.G. Lucey[1], C.A. Peterson[1], G.A. Smith[1], J.F. Bell III[3], B. A. Campbell[4], L.R. Gaddis[5], and M.S. Robinson[6], [1]Hawaii Institute of Geophysics and Planetology, University of Hawaii, 2525 Correa Rd., Honolulu, HI 96822, [2]NovaSol, 1100 Alakea Street, Honolulu, HI 96813, [3]Center for Radiophysics and Space Research, Cornell University, Ithaca, NY 14853, [4]Center for Earth and Planetary Studies, National Air and Space Museum, Washington, D.C. 20560, [5]U.S. Geological Survey, Astrogeology Program, Flagstaff, AZ 86001, [6]Center for Planetary Sciences, Northwestern University, Evanston, IL 60208.

Introduction: Lunar rays are filamentous, high-albedo deposits occurring radial or subradial to impact craters. The nature and origin of lunar crater rays has long been the source of major controversies. Some workers have proposed that rays are dominated by primary crater ejecta, while others have emphasized the role of secondary craters in producing rays [e.g., 1,2,3]. Pieters *et al.* [2] presented the results of a remote sensing study of a portion of the ray system north of Copernicus. They provided evidence that the present brightness of the Copernicus rays in this sector is due largely to the presence of a component of highland ejecta intimately mixed with local mare basalt and that an increasing component of local material is observed in the rays at progressively greater radial distances from the parent crater. These results have been questioned, and the origin of lunar rays is still uncertain [e.g., 4]. In an effort to better understand the processes responsible for the formation of lunar rays, we have utilized a variety of remote sensing data to study selected rays associated with Tycho, Olbers A, Lichtenberg, and the Messier crater complex. The data include near-IR reflectance spectra (0.6-2.5 µm) and 3.8- and 70-cm radar maps. In addition, Clementine UV-VIS images were utilized to produce high-resolution FeO, TiO_2, and optical maturity maps for the various rays using the methods presented by Lucey and co-workers [e.g., 5,6].

Results and Discussion:

Messier Crater Complex. Messier (14 km in long dimension) and Messier A (diameter = 11 km) are located near 2° S, 47° E in Mare Fecunditatis. Major rays extend north and south from Messier and west from Messier A. Spectra were obtained for portions of the rays west and south of the crater complex, as well as for Messier and nearby mature mare regions.

The spectrum obtained for the interior of Messier crater exhibits an extremely deep (29%) ferrous iron absorption band centered at 0.98µm, and a fresh mare composition is indicated. Both the near-IR spectrum and the FeO image clearly demonstrate that Messier did not penetrate the Fecunditatis mare fill. In addition, Messier and Messier A crater exhibit strong returns on both the 3.8- and 70-cm depolarized radar images [7,8]. The spectrum collected for the ray west of Messier A has a 15% absorption feature centered at 0.99 µm. The ray has slightly enhanced values in the depolarized 3.8-cm radar image, but no enhancement is apparent in the 70-cm data set. The mature mare unit adjacent to this ray has a spectrum with a shallower band depth (12%) and a similar band center. The FeO image indicates that the west ray exhibits FeO values similar to adjacent mare deposits. The brightness of the ray west of Messier A is due to the presence of large amounts of fresh mare basalt. Near-IR spectra as well as the FeO, TiO_2, and optical maturity maps indicate that the ray south of the Messier complex is also dominated by fresh mare material.

Lichtenberg Crater Rays. Lichtenberg crater (diameter = 20 km) is located in Oceanus Procellarum (31.8° N, 67.7° W). This impact structure displays a relatively high-albedo ejecta blanket and ray system to the north and northwest. However, Lichtenberg ejecta is embayed by mare basalt south and southeast of the crater. The FeO map produced for the Lichtenberg region indicates that the ejecta and rays north and northwest of the crater exhibit relatively low FeO abundances. These deposits appear to be dominated by low-FeO highlands debris. The optical maturity image demonstrates that these highlands-rich ejecta deposits and rays are fully mature. Hence, the Lichtenberg rays exhibit a relatively high albedo because of their composition. These mature highlands-rich rays appear bright in comparison to the adjacent mature mare surfaces. These "compositional" rays stand in stark contrast to the immaturity rays associated with the Messier crater complex.

Lichtenberg has been mapped as a Copernican-aged crater [e.g., 9]. However, the ejecta deposits of Lichtenberg are embayed by mare basalt flows that have recently been estimated to have an age of 1.68 Ga [10]. Hence, Lichtenberg crater is older than 1.68 Ga, perhaps much older. Lichtenberg has an age greater than the commonly accepted date (1.1 Ga) for the Copernican-Eratosthenian boundary [9].

Tycho Ray in Mare Nectaris. A major ray from Tycho crater crosses much of Mare Nectaris. Spectra were obtained for Rosse crater (diameter = 12 km), mature mare units, and two small areas on the Tycho ray northeast of Rosse. Both of the spots on the ray are located near a Tycho secondary crater cluster. The spectrum collected for a mature mare area east of Rosse exhibits an 8.5% absorption feature centered at 0.98 µm. Both ray spectra have 11.6% bands centered at ~0.99 µm. It appears that the ray in the areas for which spectra were collected are dominated by fresh mare debris. These results are in agreement with those presented by Campbell *et al.* [11]. These workers noted that the Tycho secondary craters in the cluster are easily seen in high-resolution 3.0-cm radar images, and a radar-bright area extends 10-15 km downrange of Tycho from the approximate center of the cluster. In addition, they noted that the radar-bright region exhibited a deeper "1-µm" feature in multispectral ratio images and suggested that fragmental material was emplaced well downrange of the visible secondaries, perhaps by a secondary debris surge. The FeO, TiO_2, and optical maturity images support this interpretation.

In summary, analyses of near-IR reflectance spectra, multispectral imagery, and a variety of radar data suggest that the Tycho ray in Mare Nectaris is dominated by fresh local material excavated and emplaced by secondary craters. While some highlands material from Tycho is undoubtedly present in the ray, the major factor that produces the brightness of the ray is the immature mare basalt.

Tycho Ray Southwest of Nectaris. We also investigated a continuation of the Tycho ray discussed above in the highlands southwest of Mare Nectaris. The FeO and TiO_2 values associated with this ray segment are very similar to those exhibited by the adjacent highlands terrain. The maturity map shows that the brighter portions of this ray segment are composed of immature material. In summary, this ray is composed of relatively fresh highlands debris.

Olbers A Ray. This Copernican-aged impact crater (diameter = 43 km) is located in the highlands on the Moon's western limb (8.1° N, 77.6° W) and exhibits an extensive ray system. Eight near-IR reflectance spectra were obtained for a prominent ray that extends northeast of Olbers A across Oceanus Procellarum. Spectra were also obtained for Olbers A crater as well as both mature mare and fresh craters near the ray. All spectra were analyzed and spectral mixing model studies were conducted using the techniques described by Blewett *et al.* [12]. Three component mixing studies were performed using mature mare, fresh mare, and highland material as endmembers. The spectra obtained for most areas along the ray are dominated by mare material. However, highland debris is quite abundant (contributing 29-60% of the flux to the spectra). FeO and TiO_2 maps produced from Clementine UV-VIS images indicate that the ray contains a significant amount of highlands debris.

Conclusions:

It was found that lunar rays are bright because of compositional contrast with the surrounding terrain, the presence of immature material, or some combination of the two. Mature "compositional" rays such as those exhibited by Lichtenberg crater, are due entirely to the contrast in albedo between ray material containing highlands-rich primary ejecta and the adjacent dark mare surfaces. "Immaturity" rays are bright due to the presence of fresh, high-albedo material. This fresh debris was produced by one or more of the following: 1) the emplacement of immature primary ejecta, 2) the deposition of immature local material from secondary craters, 3) the action of debris surges downrange of secondary clusters, and 4) the presence of immature interior walls of secondary impact craters. Both composition and state-of-maturity play a role in producing a third, "combination", class of lunar rays. Compositional rays can persist far longer than 1.1 Ga, the currently accepted age of the Copernican-Eratosthenian boundary. Hence, the mere presence of rays is not a reliable indication of crater age. The optical maturity parameter could be used to define the Copernican-Eratosthenian boundary. The time required for an immature surface to reach the optical maturity index saturation point could be defined as the Copernican Period.

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