THE ORIGIN OF COPERNICUS RAYS: IMPLICATIONS FOR THE CALIBRATION OF THE LUNAR STRATIGRAPHIC COLUMN.

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Introduction: The nature and origin of lunar rays have long been the subjects of major controversies. We have been investigating the origin of lunar crater rays in support of the new Lunar Geologic Mapping Program. 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. Clementine UV-VIS images were used to produce high-resolution FeO, TiO_2, and optical maturity (OMAT) maps for the various rays utilizing the methods presented by Lucey et al. [1, 2]. Near-IR spectra and 3.8- and 70-cm radar maps were also utilized [3, 4]. Our preliminary finding resulted in a model for lunar ray formation [5, 6]. It was found that lunar rays are bright because of compositional contrast with the surrounding terrain, the presence of immature debris, or some combination of the two. The purpose of this report is to present the results of studies of Copernicus rays, to assess the implications for the calibration of the lunar stratigraphic column, and to reevaluate the ages of large craters in Mare Imbrium.

The Origin of Copernicus Rays in Mare Imbrium: Copernicus is a large bright-rayed crater, 93 km in diameter, located at 9.5º N, 20.0º W on the lunar nearside, and has long been used as a stratigraphic marker for lunar geology [7, 8, 9]. Continuous ejecta deposits occur up to a crater diameter away from the rim crest of Copernicus, while the ray system extends radially for more than 500 km [9]. We have investigated the Copernicus rays that extend north across the surface of Mare Imbrium with particular emphasis on four major rays. Two of these rays (Rays 1 and 2) extend north of Copernicus, and two (Rays 3 and 4) extend to the northeast. The albedo of the rays varies from moderate to high, and all exhibit numerous secondary craters which range in diameter from 200 m to 7.0 km.

The rays north of Copernicus (Rays 1 and 2) exhibit moderate to strong returns in the 3.8-cm depolarized radar image mosaic. The highest values are associated with secondary crater clusters. These areas have greater abundances of 1- to 40-cm-sized fragments in the upper 0.5 m of the regolith. Portions of Rays 1 and 2 exhibit slightly enhanced backscatter in the depolarized 70-cm radar image. The strongest enhancements are associated with secondary crater clusters. These enhancements have an excess of meter-sized blocks within 5-10 m of the surface.

The Copernicus rays in Mare Imbrium exhibit lower FeO and TiO_2 values than do the adjacent mare deposits. The background mare flows have FeO values that range between 17 and 19 wt.% and TiO_2 concentrations that range between 4 and 6 wt.%. The rays north of Copernicus have FeO abundances that vary from 12 to 16 wt.% and TiO_2 values that range from 2 to 4 wt.%. The FeO and TiO_2 concentrations generally show a negative correlation with the albedo values exhibited by the ray surfaces. FeO abundances generally increase along a given ray as a function of distance from Copernicus. The measured FeO value (8.0 wt.%) for the Copernicus ejecta blanket can be used to calculate the amount of highland-rich primary ejecta in the rays north of Copernicus. The calculated abundances of primary ejecta range from 20% to 60%.

The optical maturity (OMAT) images of the Copernicus rays indicate that relatively high OMAT values are associated with secondary crater chains and clusters. The highest values are exhibited by steep slopes on the crater interiors. Apparently, downslope movement on the interior crater walls constantly adds fresh material to the regolith. Ray surfaces away from the interiors of secondary craters display much lower OMAT values. These OMAT values are slightly higher than those exhibited by fully mature background mare surfaces near the rays. The rays of Copernicus in Mare Imbrium have not reached full optical maturity.

In summary, the Copernicus rays in Mare Imbrium display relatively low FeO and TiO_2 values because of the presence of variable amounts of highland-rich primary ejecta. The rays exhibit relatively low OMAT values except for areas with secondary crater clusters. Still, the rays are not fully mature. The Copernicus rays are bright largely due to contrast in albedo between the ray material containing highland-rich primary ejecta and the adjacent dark mare surfaces.

Implications for the Copernican-Eratosthenian Boundary: The working distinction between the Eratosthenian (E) and Copernican (C) Systems is that Copernican craters have visible rays whereas Eratosthenian-aged craters do not [7, 11, 12]. Since compositional rays can persist for 3 Ga or more, the mere presence of bright rays is not a reliable indicator that a crater was formed during the C Period [6, 9, 13, 14, 15]. It is clear that a new method is required to distinguish C- from E-aged craters. It has been suggested that the OMAT parameter be used to define the C-E boundary [6, 14, 15]. With increasing age, the OMAT values for ejecta and rays decrease and eventually become indistinguishable from the background value, which is the optical maturity index saturation point [2, 15]. The time required for a fresh surface to reach the optical maturity index saturation point could be defined as the Copernican Period. Surfaces that have reached full optical maturity would then be of Eratosthenian (or greater) age. Grier and co-workers [14, 15] noted that if the ejecta of Copernicus were slightly more mature, it would be indistinguishable from the background in an OMAT image. Our results for the Copernicus rays in Mare Imbrium are consistent with these findings. Hence, the saturation of the optical maturity index may occur at about 0.8 Ga, which is the commonly accepted age of Copernicus [16, 17, 18].

A Reevaluation of Lunar Crater Ages: Because of the new definition of the C-E boundary, we have investigated the ejecta and rays associated with a number of large craters in Mare Imbrium. Our purposes were to determine the compositions and maturity states of the rays and to assess the ages of the parent craters in light of the new criteria.

Aristillus, Autolycus, and Theaetetus are located north of the Apollo 15 site. They have been mapped as Copernican craters based on the presence of rays [8, 10, 12]. The high-albedo rays of Aristillus, Autolycus, and Theaetetus contain highland material and are bright because of compositional contrast with the surrounding mare terrain. The rays and ejecta of these craters have reached full optical maturity. Hence, Aristillus, Autolycus, and Theaetetus are older than Copernicus and should be mapped as Eratosthenian-aged craters.

Timocharis (D=34km) and Euler (D=28 km) were mapped as Copernican-aged craters by Carr [19] and Wilhelms and McCauley [8] because they exhibit bright ejecta and rays. However, Wilhelms [20] recommended that they be assigned an Eratosthenian age. Portions of the ejecta deposits of Euler and Timocharis are bright because they contain FeO-poor highlands material. The OMAT data indicate that the ejecta and rays of both craters have reached full optical maturity. Hence, Euler and Timocharis should be mapped as Eratosthenian-aged craters. Unlike Euler and Timocharis, Lambert (D=30 km) excavated only FeO-rich mare material and does not exhibit bright rays. The OMAT image shows that Lambert ejecta is fully mature. Lambert was correctly mapped as an Eratosthenian crater by previous workers [8,19,20,21].

Pytheas (D=20 km) has been mapped as a Copernican-aged crater [8,19,20] because it exhibits bright ejecta deposits. FeO and TiO_2 maps indicate that the high-albedo portions of the Pytheas ejecta blanket contain abundant highland material. The OMAT data indicate that these highlands-rich deposits are fully mature and are bright only because of compositional contrast with the adjacent mare terrain. Since the Pytheas ejecta and rays have reached full optical maturity, it should be assigned an Eratosthenian age. An Eratosthenian age for Pytheas is confirmed by crater size-frequency values.

Delisle (D=25 km) and Diophantus (D=18 km) have been mapped as Eratosthenian-aged craters because they lack well-defined rays [e.g.,8]. It is not possible to determine the true degree of maturity of the Diophantus ejecta deposit because it is largely covered by immature ejecta from small, superposed craters such as Diophantus C as well as Aristarchus and Copernicus rays. However, those portions of the Delisle ejecta blanket not covered with fresh, small crater ejecta appear to be fully mature.

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