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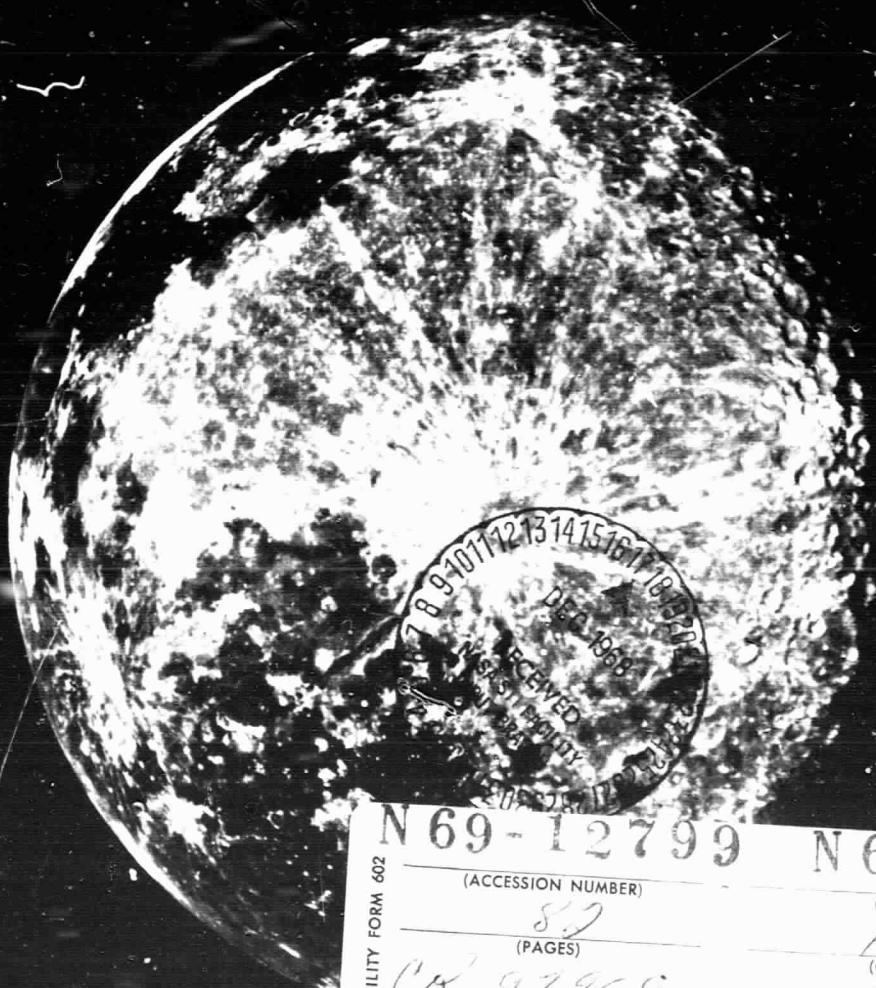
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1968

Communications of the Lunar and Planetary Laboratory

These *Communications* contain the shorter publications and reports by the staff of the Lunar and Planetary Laboratory. They may be either original contributions, reprints of articles published in professional journals, preliminary reports, or announcements. Tabular material too bulky or specialized for regular journals is included if future use of such material appears to warrant it. The *Communications* are issued as separate numbers, but they are paged and indexed by volumes.

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69-12800

NO. 114 THE INFRARED POLARIZATION OF THE MOON

by F. F. FORBES AND P. A. WELCH

November 9, 1967

ABSTRACT

Infrared polarization measurements of the lunar surface have been obtained at 1.25 and 2.2 μ for the lunar phase $-80^{\circ}9$. The infrared polarization of the entire Moon was found to be 3.24 and 2.90 percent at 1.25 and 2.2 μ , respectively. The new infrared polarization results were compared to the visible and ultraviolet polarization obtained by Gehrels, *et al.* (1964), Coyne (1967), and Lyot (1929). As with other wavelengths, the infrared polarization is greater in the maria than in the highlands. In addition to the polarization scans and the determination of the polarization of the entire Moon at $-80^{\circ}9$ phase, the geometric albedo was computed from photometric scans of the Moon at $3^{\circ}48$ and $-80^{\circ}9$ phases and found to be 0.211, 0.259, and 0.321 at 1.25, 1.62, and 2.24 μ , respectively. The ground-based geometric albedo values agree well with those obtained from Project Lamplighter of May 1966 on the Gemini 7 Mission.

1. Apparatus

The polarization and albedo observations were made in November 1965 and March 1966 with the Catalina Observatory 28-in. infrared telescope. The photopolarimeter consisted of a dry-ice-cooled lead sulfide photometer (Johnson and Mitchell 1962), with a rotating infrared polarization analyzer mounted between photometer and the 28-in. telescope. A Polaroid-Corporation-type HR-sheet polarizer (Shurcliff 1962) was rotated at 16 rps in the infrared polarization sandwich, thereby allowing rapid scan polarimetry to be done at the same time that photometric scans were made across the lunar surface. A calibrated micrometer-adjusted 6-in. offset finder was used to change the scan position in uniform increments of declination relative to a prominent central lunar feature recentered on the finder cross-hairs before each scan. The telescope was driven westward in right ascension beyond the lunar limb and then stopped; data were taken as the Moon drifted back through the field. The instantaneous field of view of the photopolarimeter was 29.35 arc sec in diameter. Three times during the mapping process the offset accuracy was determined by repeating the zero offset scans at 1.25 and 2.24 μ .

The polarization and infrared intensity signal and polarization analyzer phase angle were recorded on magnetic tape in the manner described by Forbes (1967). The data tapes were played back in the laboratory with a frequency-to-voltage converter and a true RMS voltmeter, the respective outputs of which gave the infrared intensity (DC component) and polarization (AC component). Ratios of the AC to DC components were then obtained to determine the percent polarization. The polarization phase was determined using the photographic technique described by Forbes (1967).

2. Calibration

The polarization analyzer efficiency and position angle were determined by using the technique described by Gehrels and Teska (1960). The instrumental polarization was found by measuring the polarization of four standard stars whose polarization in the visual and infrared wavelengths was known to be less than 0.5 percent. The probable error on the infrared polarization of the standard stars was found to be ± 0.2 percent.

For the determination of the geometric albedo two calibrations were required. The instrument was

calibrated photometrically with measurements of four standard stars preceding and following the lunar scans. The colors of the Moon at 1.25, 1.62, and 2.24 μ were determined using Johnson's data (1965) and Johnson and Mitchell's technique (1962). The precision of reduction to the JKL photometric system is about ± 0.1 mag. The relative photometric response as a function of position in the diaphragm was measured by making repeated drift scans across a star image for various segments of the diaphragm. From integration of these scans the effective photometric diaphragm size was computed to be $29.35 \pm .05$ sec of arc in diameter.

3. Results

Figures 1 and 2 are maps of the lunar infrared polarization at 1.25 and 2.24 μ , respectively, at a phase of $-80^\circ 9'$. The 1.25 and 2.24 μ polarization scans were positioned on a lunar scan by means of a computer program using equations (Arthur 1965) for transforming topocentric to selenographic coordinates for the particular phase of $-80^\circ 9'$ on March 1, 1966. For clarity, only major lunar features are shown in Figures 1 and 2.

One of the scans is shown in detail in Figure 3 which compares polarization to intensity; this scan was repeated three times in each color to investigate the repeatability. The error bars represent the mean standard deviation of individual sample points based on residuals between the three scans normalized to their mean intensity to remove time-dependent effects, which have little bearing on the polarization errors. The polarization and intensity are related by the fact that the fractional standard deviation of a percent polarization measurement is equal to the fractional standard deviation of the intensity measures on which it is based. However, the errors so derived are strictly internal, and include the results of inexact reproduction of scan position.

From the reference intensity plot in Figure 3, it is evident that in the infrared the maria are considerably more polarized than the highlands. This result is entirely in agreement with the results obtained by other observers in the visible wavelengths (Lyot 1929; Dollfus 1955; and Gehrels, *et al.* 1964). In addition, for regions of similar color on the Moon, no systematic variation in polarization was detected between the bright limb and the terminator.

In Figure 4, the infrared polarization data derived from two regions on the Moon (Nicolai and Mare Crisium) are compared to visible polarization re-

sults obtained for the same locations on the Moon by Gehrels, *et al.* (1964) for the phase of $-80^\circ 9'$, although the fields of view are different.

The behavior of the infrared polarization for the entire Moon at $-80^\circ 9'$ phase is plotted in Figure 5 together with the results obtained in the visible by Lyot (1929) and in the ultraviolet by Coyne (1967). The 1.62 μ in Figure 5 was computed from one scan at 1.62 μ compared to repeated scans, at the same declination, for the points at 1.25 and 2.24 μ .

The lunar geometric albedo was photometrically determined at 1.25, 1.62, and 2.24 μ from measurements at the phases of $3^\circ 48'$ and $-80^\circ 9'$ and found to be 0.211, 0.259, and 0.321, respectively. The albedo computations were done as described by Russel (1916) and Harris (1961). Rougier's phase function (Minnérat 1961) was used, although it was determined for .54 μ so that a direct comparison to the Gemini 7 (AFCRL-Project Lamplighter, 1966) could be made. These results are plotted in Figure 6 together with ultraviolet results and infrared spectral-photometry results of Gemini 7 and the visual measures of Harris (1961). Although the techniques used on Gemini 7 and those we used were quite different, both results show excellent agreement. The photometric tie-in to standard stars assured the photometric accuracy of our measurements and reassured us of the validity of the data taken by Gemini 7.

Higher spectral and spatial resolution are needed to extend the polarization measurements to specific regions of interest, such as hotspots (Middlehurst and Moore 1966) and color discontinuities (Whitaker, referenced by Gehrels, *et al.* 1964). Photopolarimetry of the entire Moon in the visible wavelengths, with an extension to the far-infrared, is also necessary to complete the lunar polarization picture. Furthermore, measurements should be made to determine the infrared phase function for all phases, with particular attention given to the near zero phase.

Acknowledgments The authors wish to thank Mr. R. Modica who prepared the lunar polarization maps and Mr. D. Steinmetz for assisting in the data reduction. In addition to many valuable discussions, Dr. H. L. Johnson made available the Catalina Observatory's 28-inch telescope and the lead sulfide photometer. This work was supported by the National Aeronautics and Space Administration, Contract No. NSR 03-002-048, and the National Science Foundation, Grant No. GP-4999.

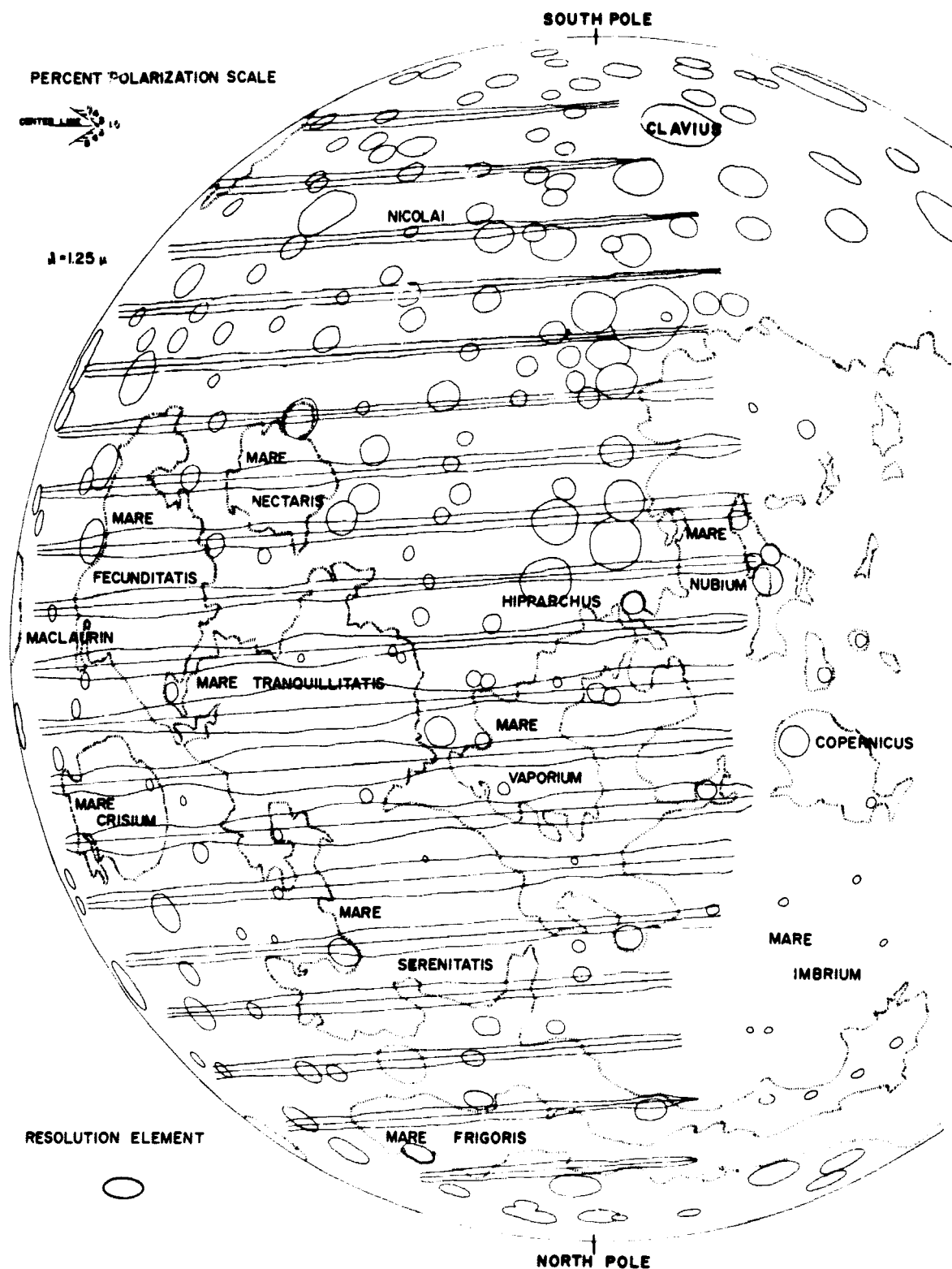


Fig. 1 Lunar Polarization Map at 1.25μ . The center line represents the center of the diaphragm for each scan and has a value of 1.8 on the percent polarization scale. The spatial resolution is approximately 60 by 35 arc sec.

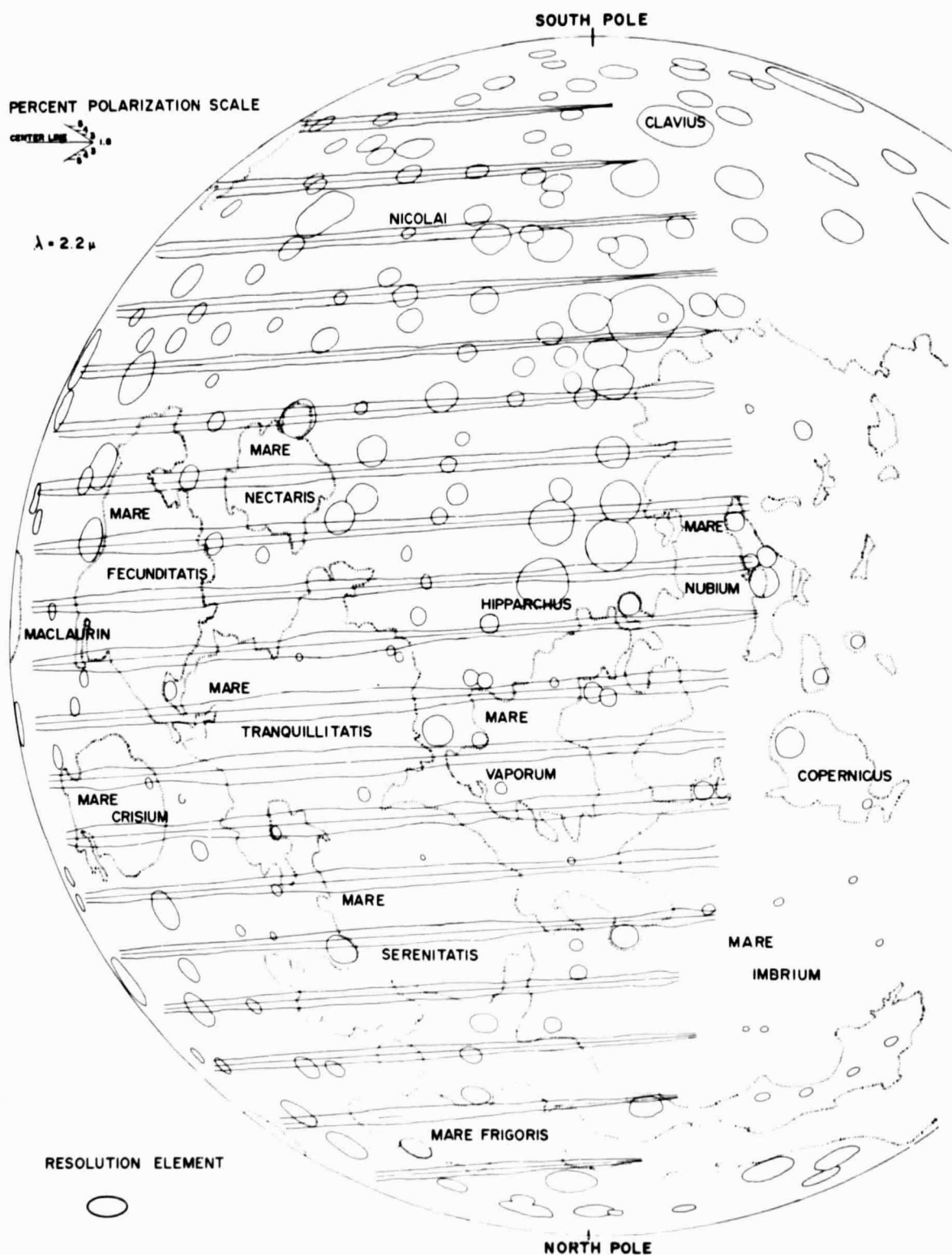


Fig. 2 Lunar Polarization Map at 2.24μ . The center line represents the center of the diaphragm for each scan and has a value of 1.8 on the percent polarization scale. The spatial resolution scale is approximately 60 by 35 arc sec.

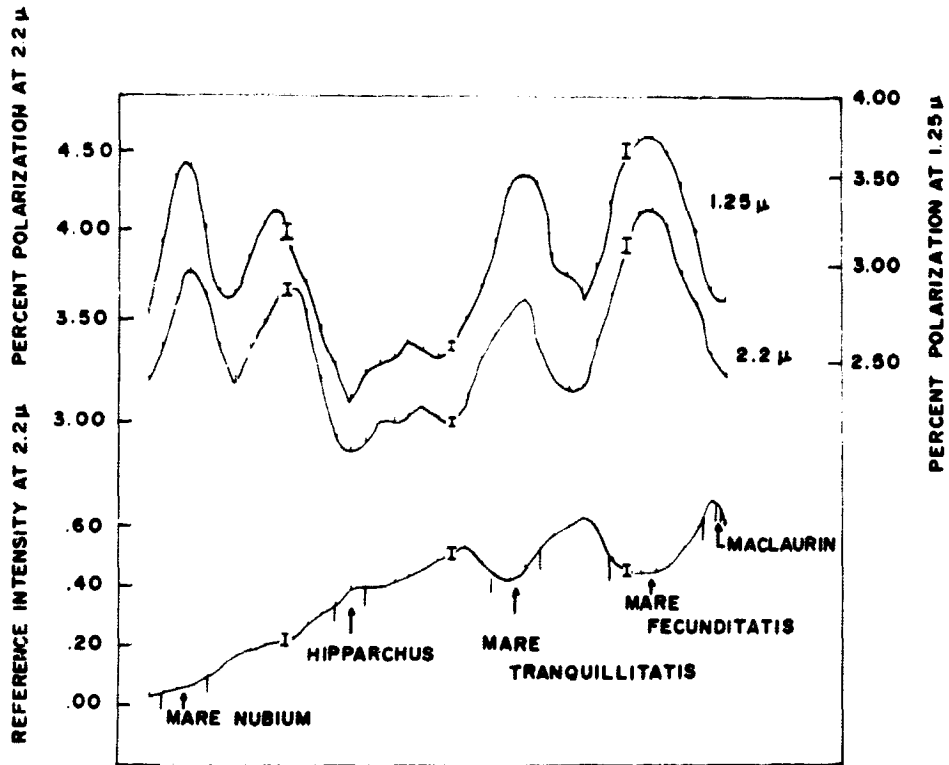
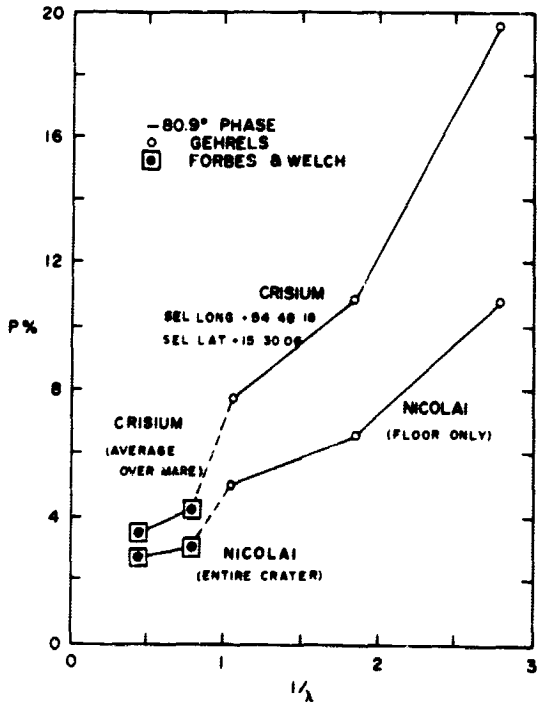


Fig. 3 Percent polarization and corresponding intensity scan for the ninth trace from the top in Figs. 1 and 2.



← Fig. 4 Comparison of visual and infrared polarization percents for Nicolai and Mare Crisium at $-80^{\circ}9$ phase. The field of view used by Gehrels was about 5 arc sec, compared to approximately 30 arc sec for the infrared. The values given by Gehrels have been interpolated to $-80^{\circ}9$ phase.

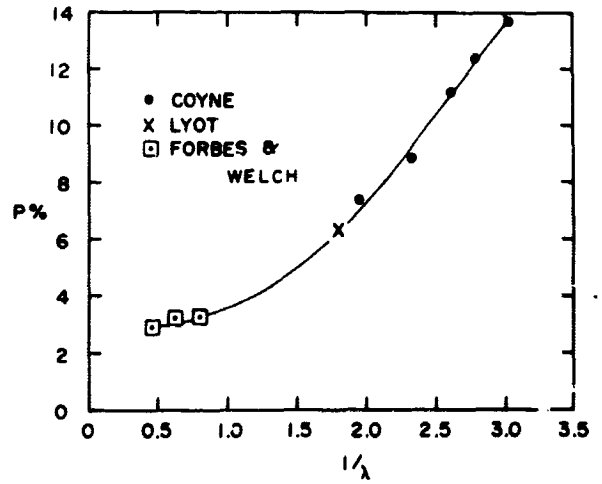


Fig. 5 Polarization of the entire Moon at $-80^{\circ}9$ phase for infrared, visual, and ultraviolet wavelengths. The values for Lyot and Coyne have been interpolated to $-80^{\circ}9$ phase.

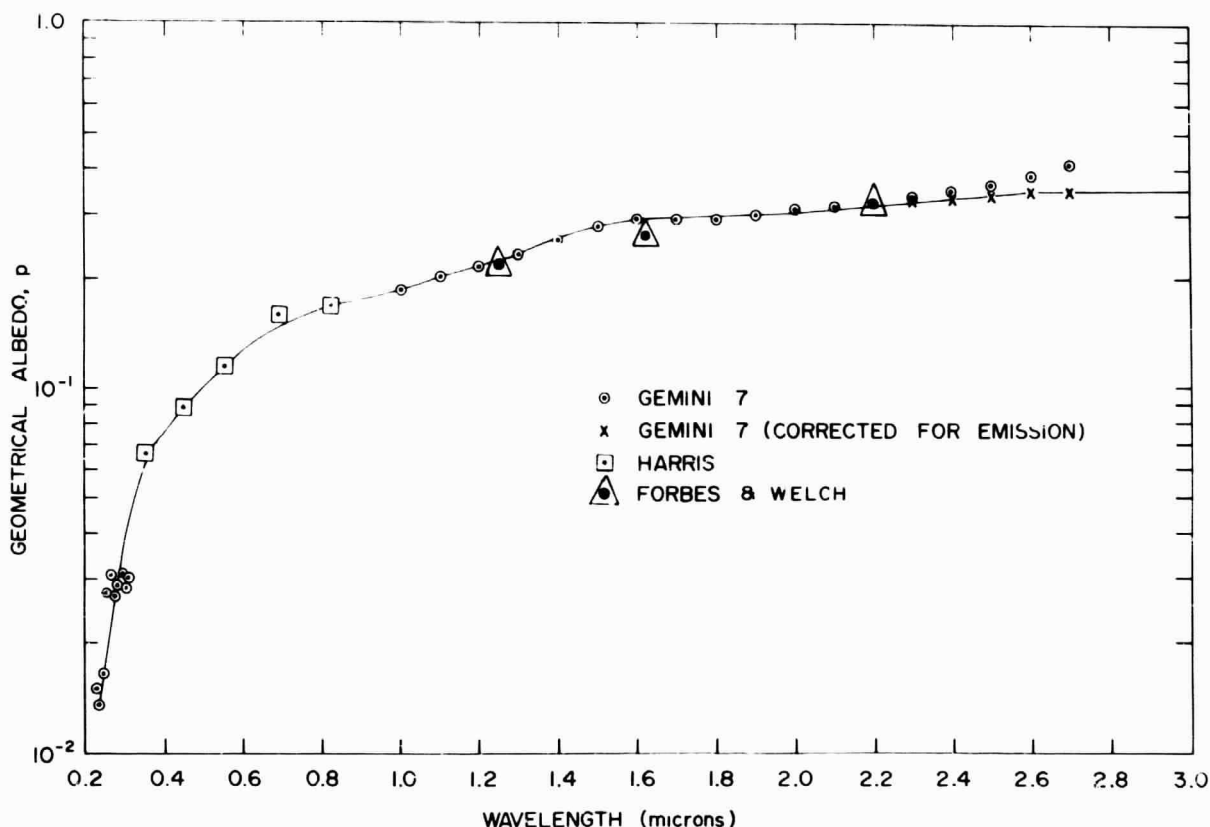


Fig. 6 Geometric albedo for the entire Moon in ultraviolet, visual, and infrared wavelengths.

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N 69-12801

No. 115 EXPLOSION CRATERS ON THE EARTH AND MOON

by G. FIELDER AND J. E. GUEST *

December 6, 1967

ABSTRACT

A comparison of lunar craters with a particular set of similar-sized explosion craters on Earth leads to the inference that explosion craters on the Moon can be picked out with the aid of the following criteria: (a) relative altitude of rim crest and shape of outer rim profile, (b) slumping of inner rim materials, (c) nature and distribution of ejecta.

In 1944 ammunition stored underground near Fauld, England, exploded, producing a crater some 250 m in diameter. A few thousand secondary craters were produced in pastureland and wooded country around the main crater. The shapes of both the main crater and the secondaries, and their mutual spatial relations, find analogy with the shapes of certain craters on the Moon; and this led Baldwin (1963) to present a vertical air-photograph of the Fauld crater (Fig. 1) — which he referred to as the Burton-on-Trent Crater. Further information on the Fauld crater may be gleaned from (a) air and ground-based photographs taken in December 1944 by the R.A.F. shortly after the explosion, (b) an examination of the modified craters remaining in the field in 1967, and (c) Ministry of Defense documents relating to the nature of the explosion. Since the mechanism of formation of the Fauld crater is known, it is instructive to compare its morphology with that of similar sized craters recorded on the N.A.S.A. Lunar Orbiter Missions, with a view to determining which lunar craters are of explosive origin.

Prior to the Fauld explosion, an old alabastine mine with roads forming labyrinths approximately 200-400 feet deep in limestone had been utilised to store bombs and other explosive weapons of various weights. It was estimated that energy equivalent to 5.34×10^6 lbs. of TNT (about 4.54×10^5 calories) was liberated in the explosion. One may predict the size of the crater using Baldwin's (1963) relations with a scaled depth of burst $H/W^{1/3} \approx 1.7$, where H is the depth of the explosive centre in feet and W the energy released in pounds of TNT equivalent. Thus, had the explosive been centrally condensed, the blast would have given rise to a crater no larger than 200 m in diameter. The fact that the actual crater rim is ovoid (Fig. 2) and measures as much as 220 m x 270 m may be explained in terms of (a) the irregular distribution of stored charge, (b) the non-simultaneity of the explosion of individual bombs (many remained unexploded after the event), (c) the controlling effects of the pre-existing mine roads, especially from the standpoint of the shaping of the charge and of creating weaknesses in the country rock. The locations of a few of these roads may be traced across the floor of the crater in Fig. 2, especially when it is combined stereoscopically with Fig.

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1. In spite of these factors, the ellipticity of the Fauld crater — 18.5% — measures an amount of distortion commonly found among the lunar craters, some of which have ellipticities (Fielder 1961a) that exceed 40%.

Field inspection and comparison of records with the early photographs showed that slumping occurred at most points around the rim of the Fauld crater immediately after the explosion. This produced a conspicuous bench (Figs. 4, 5, 6) some meters below the crest of the rim. Mass creep and water erosion have further modified the shape of the rim over the past 23 years (Fig. 7), and debris has covered the floor of the crater to an average depth of a metre or more in places. Under low lighting conditions the bench gives the crater a double-walled appearance similar to that of some small lunar craters (Fig. 8). The latter are usually sharp in outline, and are therefore relatively recent additions to the lunar surface; so it may be speculated that their double-walled appearance is due to slumping incident on an explosive origin.

The 70 m lunar crater in Fig. 8 is surrounded by numerous rocks that apparently have been tossed out of the crater during its formation. Better examples of ejected rocks around the rims of lunar craters 420 m and 30 m in diameter may be seen in Figs. 9 and 10, respectively. The lunar rocks may be compared with the large, angular blocks of limestone (Figs. 11, 12) which were torn from the principal Fauld crater and partially buried themselves or produced shallow depressions on impact with the soil or, again, with the smaller rocks ejected from one of the secondary craters at Fauld (Fig. 13). For the following reasons, this latter is believed to be an explosion crater.

Secondary craters produced by the impact of non-explosive materials range in diameter from 5 to 10% of the primary's diameter according to Fielder's (1961b) experiments with detonators, and from 4 to 11.5% according to Roberts (1964) measurements based on three high-explosive experiments and one thermo-nuclear explosion. By contrast, many of the secondary craters at Fauld exceed the upper limits of these ratios; in particular, one of the Fauld secondaries attains 20% of the diameter of the primary; and this indicates that many of these secondary craters were sculptured by the ejection of live bombs

which exploded on impact. The tendency for some of the secondary craters to form linear arrays (see Fig. 1) may have arisen as a result of the particular disposition of the stacked bombs prior to their having been ejected.

Inspection of the shadows cast by the photographed secondary craters at Fauld leaves no doubt that many of them have rims that are raised above the surrounding terrain. Low velocity secondary impact craters investigated by Roberts (1964) and Hartmann (1967) also show raised rims. The same is true of the lunar craters under discussion in Figs. 8 and 9. In Fig. 10, the rim crest of the 30 m crater is the highest part of the panorama; and stereoscopic viewing of the Fauld crater itself, using the photographs reproduced in Figs. 2 and 3, also shows that its rim is topographically high. Clearly, a high rim is a necessary criterion for the explosive origin of the rim materials in any freshly formed crater. Thus, the similarities in the shapes, sizes and distribution of the rocks discussed above, taken together with the morphologic similarities of their parent craters on Earth and Moon, strongly support the theory that lunar craters of the type discussed here are of explosive origin.

Acknowledgments. We thank Sqdr. Ldr. R. Adam and the Ministry of Defense, Gt. Britain, for access to official data on the Fauld crater. Wing Cdr. J. Blair personally arranged viewing of the crater field and we thank him for his guidance and hospitality. This work was supported by N.E.R.C., London.

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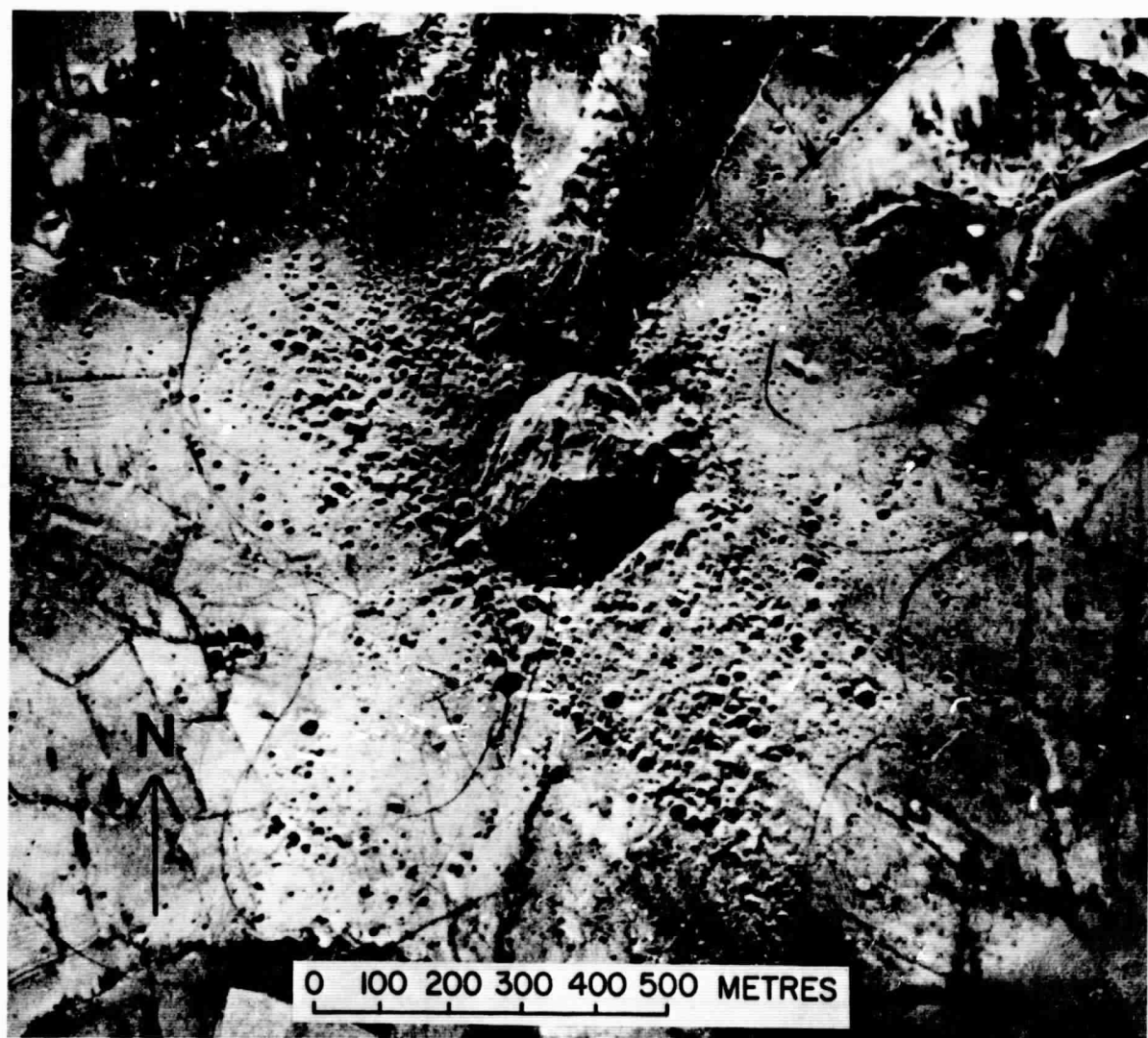


Fig. 1 Vertical air photograph of the Fauld crater and surroundings.

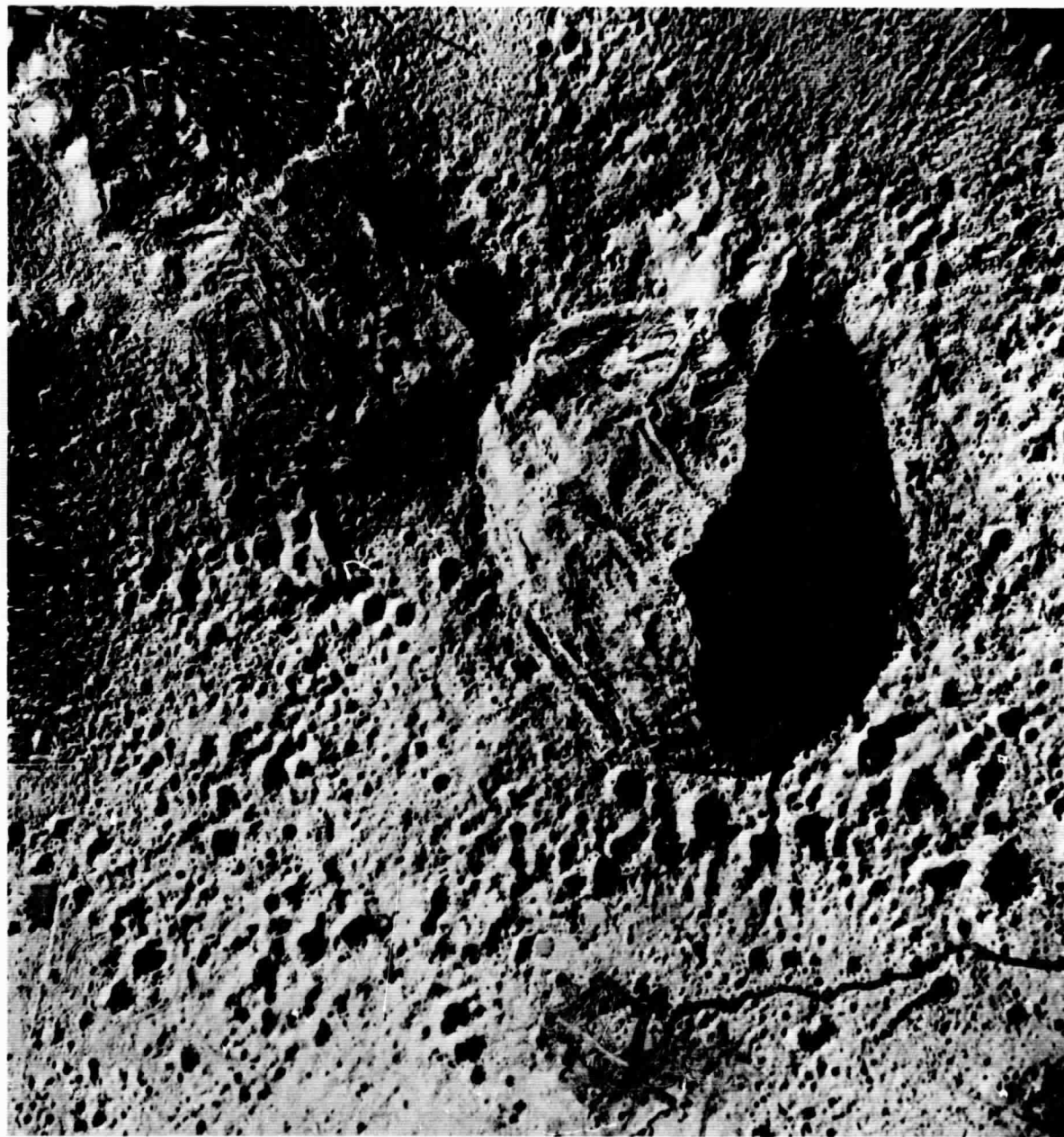


Fig. 2a Aerial view of Fault crater, to be used with 2b (insert) for stereo view.



Fig. 2b (Comm. 114). Right half of stereo view of Fauld crater.

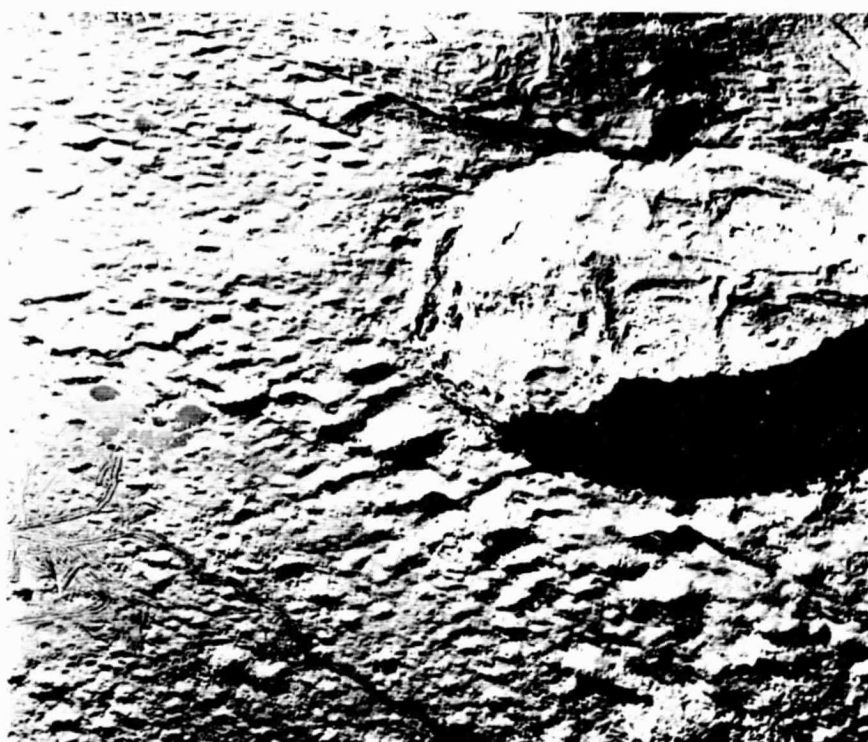


Fig. 3 Oblique aerial view of the Fauld crater showing bench along inner rim.



Fig. 4 Oblique aerial view of the Fauld crater showing bench along inner rim.



Fig. 5 Ground-based photograph taken in 1944 showing bench in Fauld crater.



Fig. 6 Ground-based photograph taken in 1967 showing slumping of materials forming inner rim of Fauld crater.



Fig. 7 Ground-based photograph taken in 1967 showing slumping of materials forming inner rim of Fault crater.

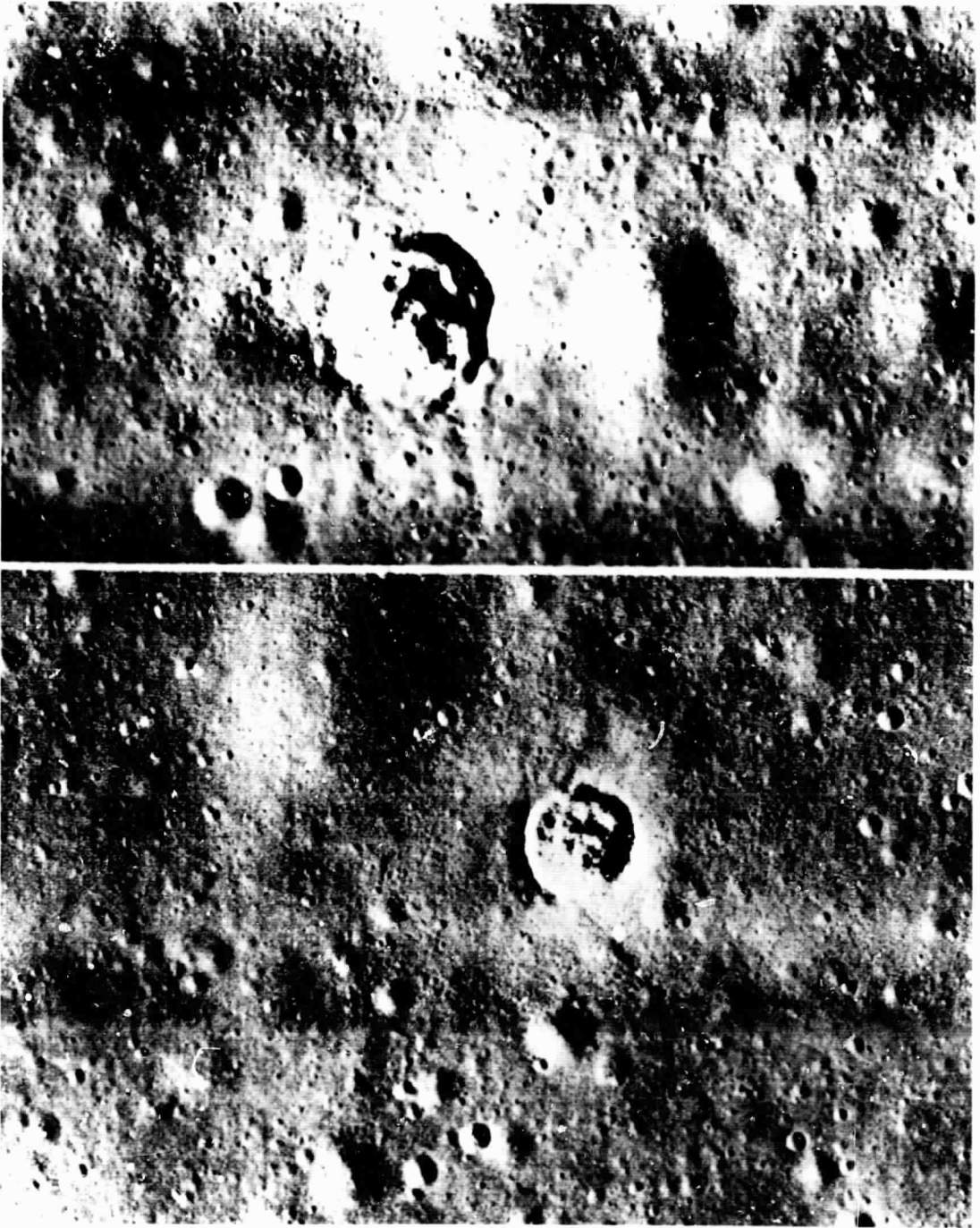


Fig. 8 Possible slumping in two lunar craters near Flamsteed in Oceanus Procellarum. The larger crater measures about 70 m in diameter and has rocks scattered around it. [NASA Lunar Orbiter III, H-194]

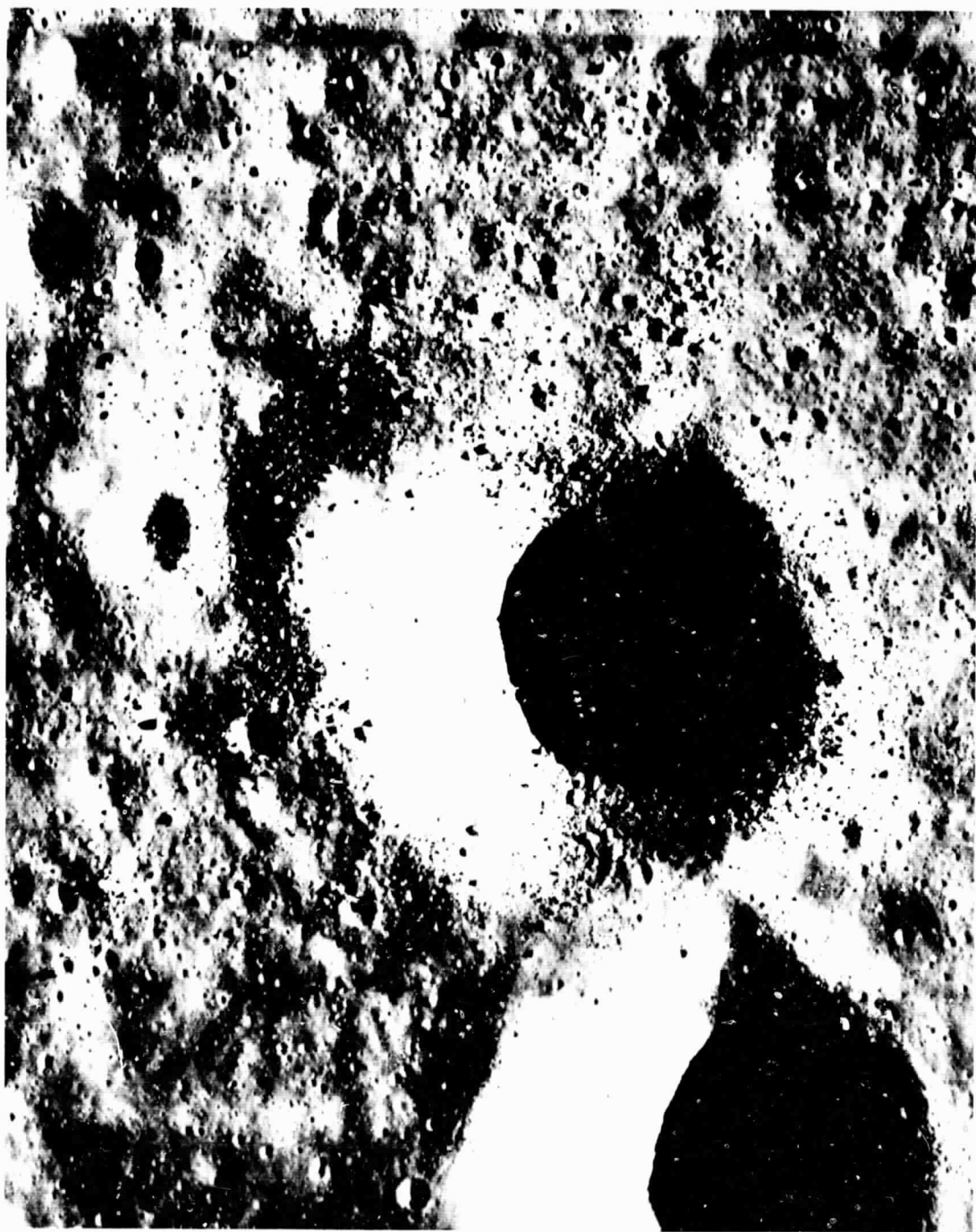


Fig. 9 Rocks around the rim of a lunar crater about 420 m in diameter, near Hortensius in Oceanus Procellarum [NASA Lunar Orbiter II H-16].

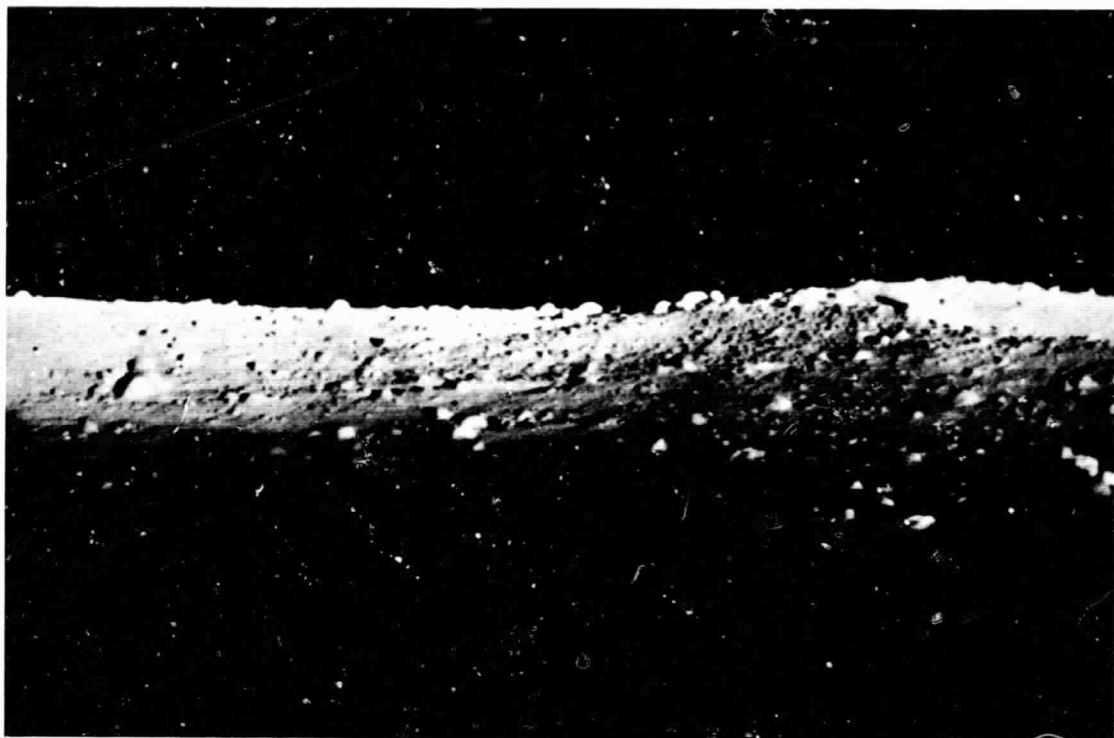


Fig. 10 This Surveyor I mosaic shows part of the rim of a 30 m diameter crater within the ring Flamsteed P. There are many rocks that appear to be related to the crater. [NASA Surveyor I, P.A. about 100°]

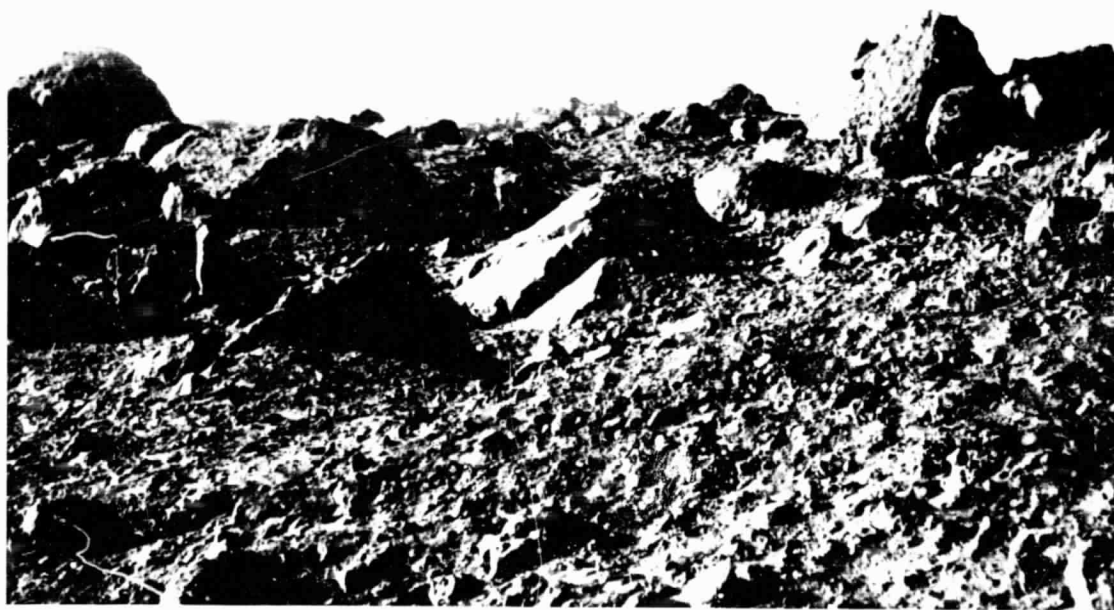


Fig. 11 Rocks on the rim of the Fauld crater.



Fig. 12 Large block of ejected limestone about 400 m from the centre of the Fauld crater.

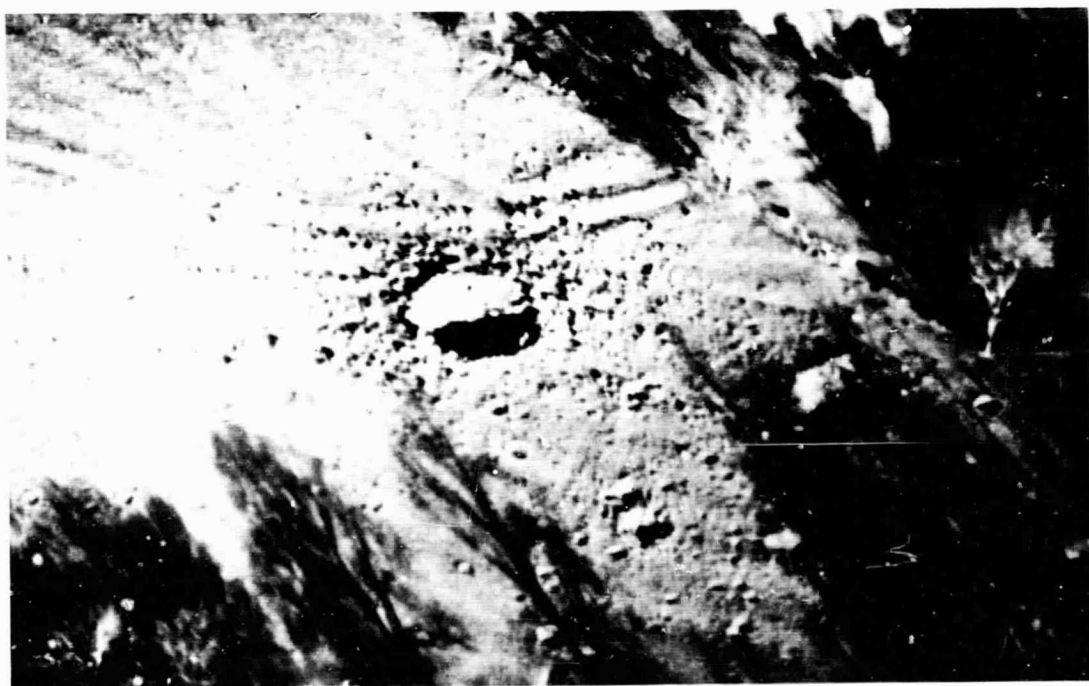


Fig. 13 A secondary explosion crater at Fauld, 15 m in diameter, with ejecta.

N 69-12802

No. 116 LUNAR CRATER COUNTS, III: POST MARE AND "ARCHIMEDIAN" VARIATIONS

by WILLIAM K. HARTMANN

December 1, 1967

ABSTRACT

Figures 1 and 2 and Table 1 present data on inter-mare crater density variations which further support statements made in Paper II. The extreme crater densities (Mare Serenitatis and Mare Tranquillitatis) vary by a factor of approximately 2.5. Table 2 presents quantitative and qualitative estimates of the post-basin crater densities, as well as post-mare crater densities for various basin systems, arranged in order of basin age. The "Archimedian" craters considerably outnumber the post-mare craters. "Archimedian" time periods were finite and variable from basin to basin, thus excluding impact-induced melting as a source of mare material. These data demonstrate a working approach for future crater count programs.

1. Inter-Mare Variations

In the preceding paper (Paper II; Hartmann 1967), I mentioned the variation by a factor roughly 2.5 for the crater density of the larger ($D > 2\text{ km}$) craters on mare surfaces. Figure 1 and Table 1 in that paper present the data on which this statement was based.

From a survey of the more accessible front-side mare surfaces, Mare Serenitatis and Mare Tranquillitatis were chosen as representative of lightly and heavily cratered mare surfaces, respectively. Mare Cognitum, recently named and well-photographed as a result of the Ranger VII mission, was also studied and found to be moderately cratered (Hartmann 1966b). The counts from these three maria are included in Figure 1. The conclusion that Ranger VII landed in a dense cluster of secondary craters associated with the rays of Tycho (Kuiper 1965; Shoemaker 1965; Whitaker 1965) — an area with density over and above the cratered background — is quantitatively confirmed by the excess of smaller craters ($D < 500\text{ m}$) shown in Figure 1. The greater density of large craters in Mare Tranquillitatis than in Mare Cognitum is confirmed by the counts published by Shoemaker, *et al.* (1965, p. 264).

An average mare count, as presented in Paper II, is included in Figure 1; it is a count of all mare craters divided by the total mare area. As expected, the distribution so defined lies between the Tranquillitatis and Serenitatis counts.

Figure 2 presents more clearly the distributions found in Figure 1, without the datum points, and shows the finite band that represents the maria on the log F -log D diagram.

Table 1 synthesizes data relating to this problem. The various authors have published data on cumulative numbers of craters in a variety of maria. These data suffer from various uncertainties: if the limiting diameter is too large, too few craters are available to give good statistics; if it is too small, observational errors become significant. It will be seen that there are inconsistencies among the data, probably due to these uncertainties, but the trend toward increasing density is clear, and it is believed that the final column does reflect significant and detectable differences. This material is slightly modified from an earlier presentation in my Ph.D. dissertation (1966b).

I concluded that significant inter-mare variations in crater density, by a factor of roughly 2.5, exist among the larger, presumably *primary impact craters* ($D > 2\text{ km}$), and that these variations reflect true age differences (by unknown factors in time since the cratering rate as a function of time is unknown). At the same time, it is important to note that there is a definite lower limit to the relative crater density on maria. None is below 0.6, although some young craters, e.g. Tycho, fall below this limit (cf. Paper VI). Hence, the mare-formation period, ranging

TABLE I. PROVISIONAL CRATER DENSITIES ON DIFFERENT MARE SURFACES

Reference: Lower limit D: (KM.)	RBB 1.6	RBB 3.2	WKH 4	DSS 4	RBB 6.4	GF 10	RBB 12.8	ADOPTED VALUE
M. Serenitatis	1.03	.76	0.40	.61	.34*	.28*	.24*	0.6
P. Epidemiarum	.77	.76			.71		.71*	0.8
M. Humorum	.77	.76			.71	.53*	.71*	0.8
M. Nubium	.77	.76			.71	.54*	.71*	0.8
M. Crisium	.92	.70			.74*	.91*	.94*	0.8
O. Procellarum						.73		0.9
M. Imbrium	1.01	.95		1.06	.74	.78	.72*	0.9
M. Orientale †			1.0					1.0
M. Cognitum			0.94					1.0
M. Nectaris	1.11	.96			.38*	.86*	.40*	1.0
M. Frigoris	1.10*	1.26		1.57	1.52	1.13	1.69	1.4
M. Foecundit.	.99*	1.14			1.52	1.62*	.97*	1.5
L. Somniorum	1.10	1.26			1.52	2.10	1.69*	1.6
M. Tranquill.	1.20	1.37	1.11		1.73	2.16*	1.73*	1.6
Appendix (DSS)								
M. Seren., outer dark zone				.54				.6
M. Seren., central portion				.69				.7

Notes:

Values in this table are $\frac{\text{crater density observed}}{\text{average crater density, all maria}}$

*Values given less weight because of paucity of craters, foreshortening, etc.

†See paper IV

RBB: Baldwin 1963, p. 296

DSS: Dodd, Salisbury and Smalley 1963

GF: Fielder 1963

from 0.6 to 1.6 on a relative crater density "time scale," represents a *restricted epoch* in lunar history.

2. Post-Basin, Pre-Mare Intervals

The interval between the formation of lunar basins and their associated mare surfaces can be judged by counts of the post-basin pre-mare, "Archimedian" craters. Though often highly damaged, Archimedian craters having diameters above some critical diameter should, in principle, be detectable where the mare cover is thin enough. Thus, counts were made for zones around the outer edge of various maria, in some cases essentially the inner edge of the rim only. The width of the zone was chosen according to the apparent degree of preservation of Archimedian craters.

The post-mare count, in some cases negligible, is added to the Archimedian count to get a measure of the interval between basin formation and the present. This measure is in terms of the crater numbers only, because a time-measure can be deduced only if we know the cratering rate, which is believed to have been changing rapidly at this epoch. (Kuiper 1954, pp. 1104, 1110; Kuiper 1966 p. 217; Hartmann, 1966a).

Secondary criteria of a more subjective nature were also used to order the basins by age, since in some cases no good crater statistics could be ob-

tained. Morphological differences, such as rim sharpness, rim height, distinctness of ejecta blankets and preservation of radial and concentric systems, are useful in this context.

Table 2 presents the results expressed as the estimated ratio post-basin/post-mare crater density as well as data on post-mare craters. The table, though incomplete and subject to revision provides a rationale and serves as a guide for further studies of lunar crater counts. The present data are modified from an earlier presentation in my Ph.D. dissertation (1966b), and it is desirable to fill in as well as possible the remaining unknown data, which indicate the history of certain lunar regions.

An important conclusion that follows at once from Table 2 is that the "Archimedian" cratering intervals were finite and highly variable from one basin system to another. The large amount of cratering in many cases indicates an extensive time interval and rules out the hypothesis that the mare material is a result of impact-induced fusion, laid down contemporaneously with basin creation (Urey 1960).

Furthermore, the relative constancy of post-mare crater densities and variability of Archimedian densities favors the view that while the maria were formed more or less contemporaneously, during a restricted epoch, the underlying basins were distributed throughout a period during which most of

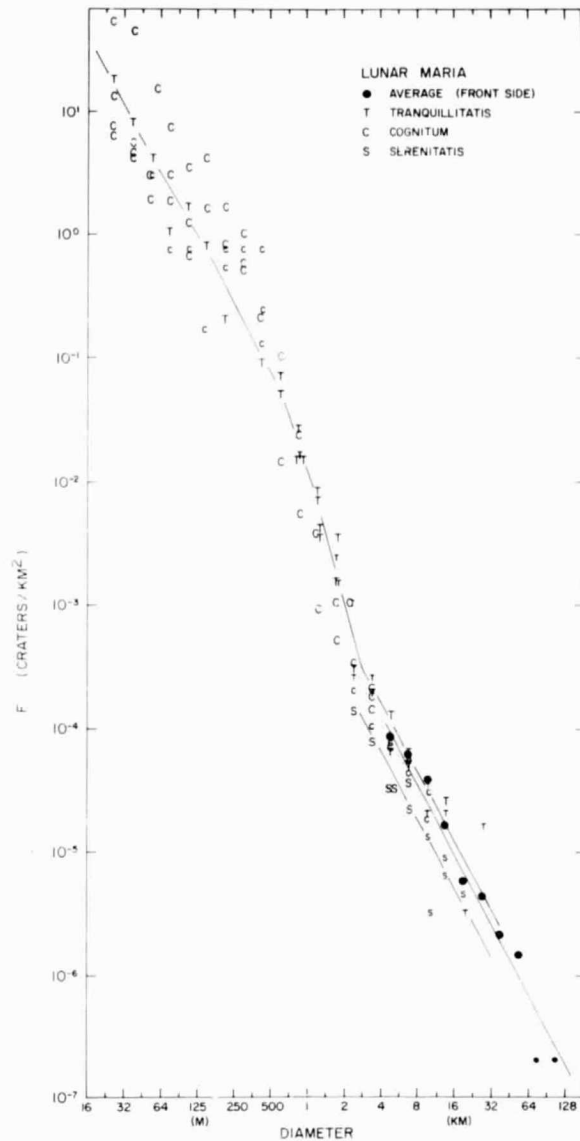


Fig. 1 Diameter distributions of craters on Mare Serenitatis, average mare, and Mare Tranquillitatis, showing significant variations between the latter and the former. F is incremental number of craters/km².

the pre-mare ("continental") craters formed. That is, the quantitative data of Table II are consistent with the model which has been presented earlier in these Communications and elsewhere (Hartmann 1964; Kuiper 1966; Hartmann 1966a) that the basins formed during an early intense cratering close to the end of which most of the major maria were laid down as a result of lunar melting. Much of the variation in inter-mare ages is attributed to the tail-end of the intense bombardment phase, which may have involved a different population of cosmic

TABLE II. PROVISIONAL POST-BASIN CRATER DENSITIES AND RELATIVE BASIN AGES

BASIN* (IN ORDER OF INCREASING AGE)	ESTIMATED POST-BASIN CRATER DENSITY**	POST-MARE CRATER DENSITY***
(Average mare)		1.00†
Oriente ‡	2.4	1.0
Imbrium	6	0.9
Crisium	16	0.8
Humboldtianum		
Nectaris	27	1.0
Near Schiller	28	
Humorum	28	0.8
Grimaldi		
Serenitatis		0.6
S. E. Limb		
Janseen		
Cognitum		1.0
(Pure Upland)	30	

*Cf. Hartmann and Kuiper (1962). Recently discovered far side basins not included.

**Estimated P. E. $\approx$ 25%

***Estimated P. E. $\approx$ 20% (See Table I)

†By Definition

‡See paper IV

bodies than those presently striking the earth and moon.

Acknowledgment. This work was supported by an NSF Institutional Grant of the University of Arizona and NASA Grant NsG 161-61.

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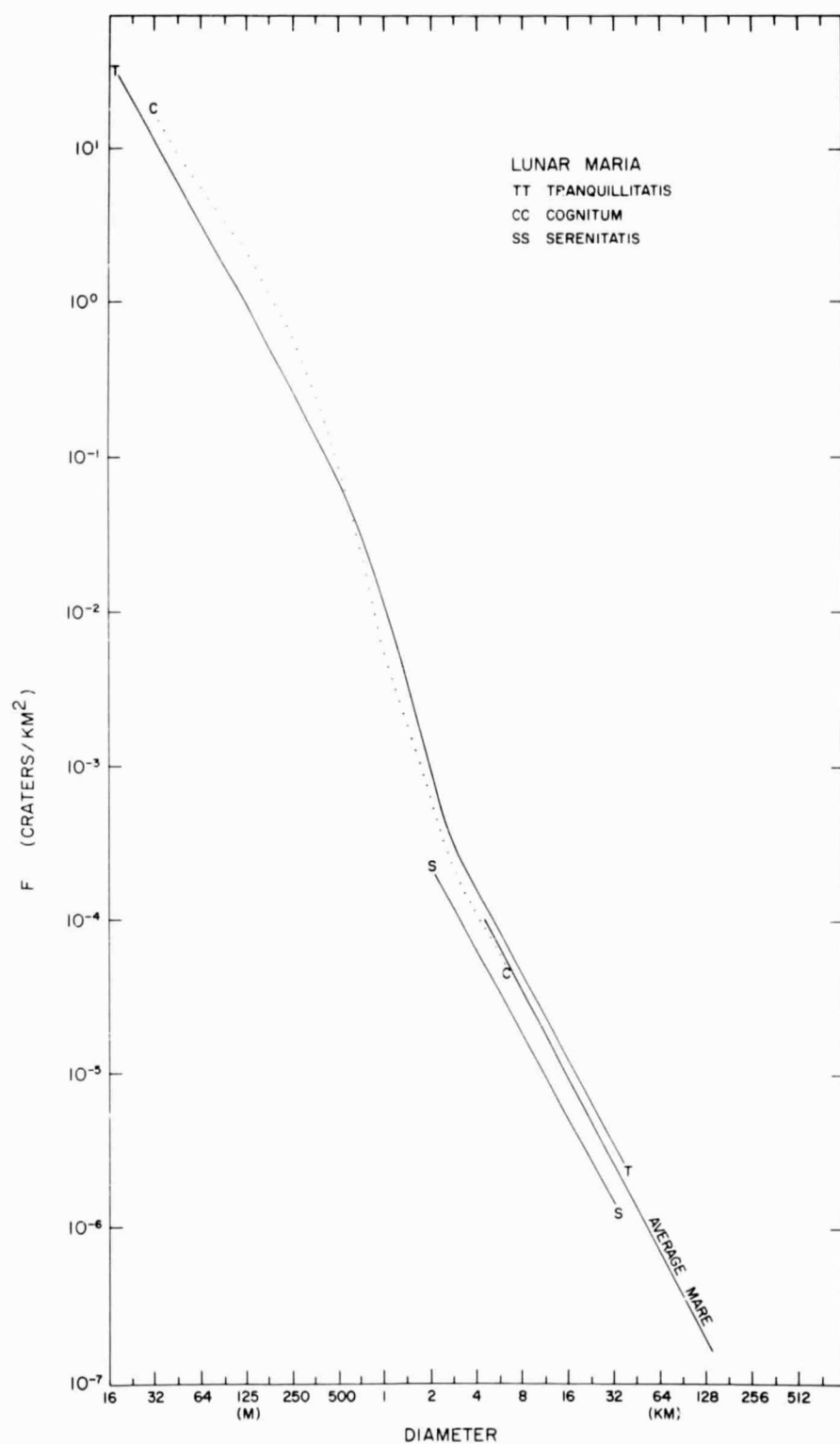


Fig. 2 Diameter distributions of craters on Mare Serenitatis, average mare, and Mare Tranquillitatis with datum points removed for clarification.

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N 69-12803

**No. 117 LUNAR CRATER COUNTS. IV: MARE ORIENTALE
AND ITS BASIN SYSTEM**

by W. K. HARTMANN AND F. G. YALE*

February 1, 1968

ABSTRACT

Parts I and II present crater count observations of the mare surface and the ejecta blanket of the Orientale basin. Mare Orientale has the crater density of average maria, 1.0, and the ejecta blanket has an unusually low crater density for an upland surface, 2.4. This is the lowest known post-basin crater density, testifying to the youth of the system. Supplemental observations, based on Orbiter photography, are presented in part III. Part IV discusses the physics of the hypothetical, nuée ardente-like cloud which swept out from the impact site, depositing the striated, highly-structured blanket shown in the Orbiter photographs. Part V summarizes the history of the Orientale basin system. The extraordinary clarity of the radial and concentric lineaments is attributed to the youth of the system and the probable coincidence in time of the impact and the beginning of the mare-forming period, with the shocked "crust" collapsing into the plastic substratum along impact-produced fractures.

1. The Mare Surface — Observations

Figure 1 shows the floor of Mare Orientale and Figure 2 shows the diameter distribution of craters there. On Figure 2 the average mare crater density has been drawn and it is seen that no significant departure from this is detected. Normalizing to the average crater density, we can list Mare Orientale as having crater density 1.0 ± 0.1 .

The counts used in this determination were made from Orbiter IV photograph 195. Special care was used to avoid contamination from the abundant secondaries of the large unnamed crater in the northern part of the floor, and the data of Figure 2 refer principally to the southern half of the floor. The largest diameters available were limited by the small area of the mare, and the smallest, by the resolution of the Orbiter "medium resolution" photography.

Mare Veris and Mare Autumni, two arcuate strips along the bases of two concentric fault scarps around the basin, appear to have significantly higher crater densities than the central Mare Orientale (see Fig. 2).

2. Orientale Ejecta Blanket — Observations

In view of the relatively young age attributed in earlier *Communications* to the Orientale basin system on the basis of structural studies (Hartmann and Kuiper 1962; Hartmann 1964), it is predicted that the crater density on the ejecta blanket should be considerably less than the ambient, "pure continental" crater density, which refers to the oldest portions of the lunar surface. WRH has speculated (1964, p 177) that the Orientale basin may have originated "late in the period of mare formation," although obviously before the present, uppermost (undisturbed) surfaces of the various nearby maria were laid down.

Now it is possible to test these ideas with the excellent photographic coverage of the whole Orientale region by Orbiter IV. Figure 3 shows a typical portion of the radially striated ejecta blanket east of Mare Orientale, and Figure 4, the crater diameter distribution thereon. It can be seen that the post-basin craters of the ejecta blanket accurately parallel the post-mare craters, and that at least the first of the above predictions is essentially verified: there is more than an order of magnitude deficiency

*On leave from Arizona State University.

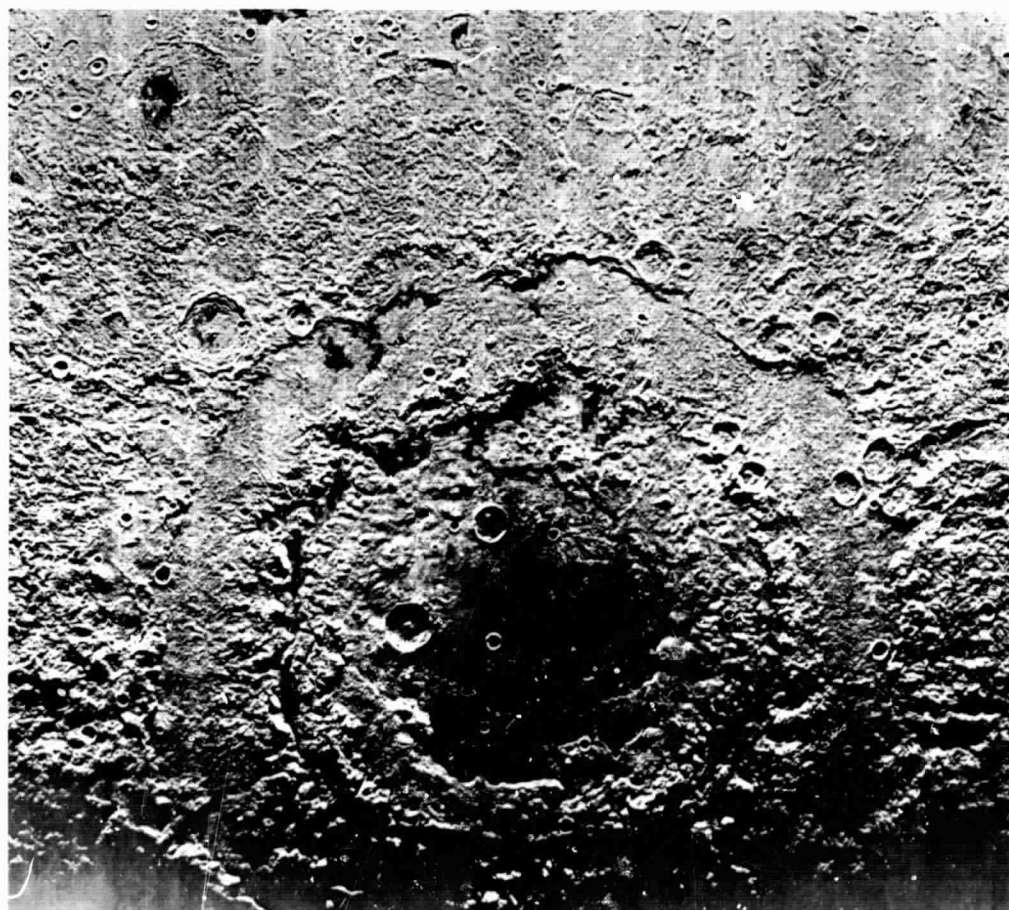


Fig. 1 Mare Orientale and its basin system. The central mare is surrounded by multiple ring-scarps and arcuate maria Veris (NW to E) and Autumni (patchy mare on E). NASA Orbiter IV, Frame 187, medium resolution.

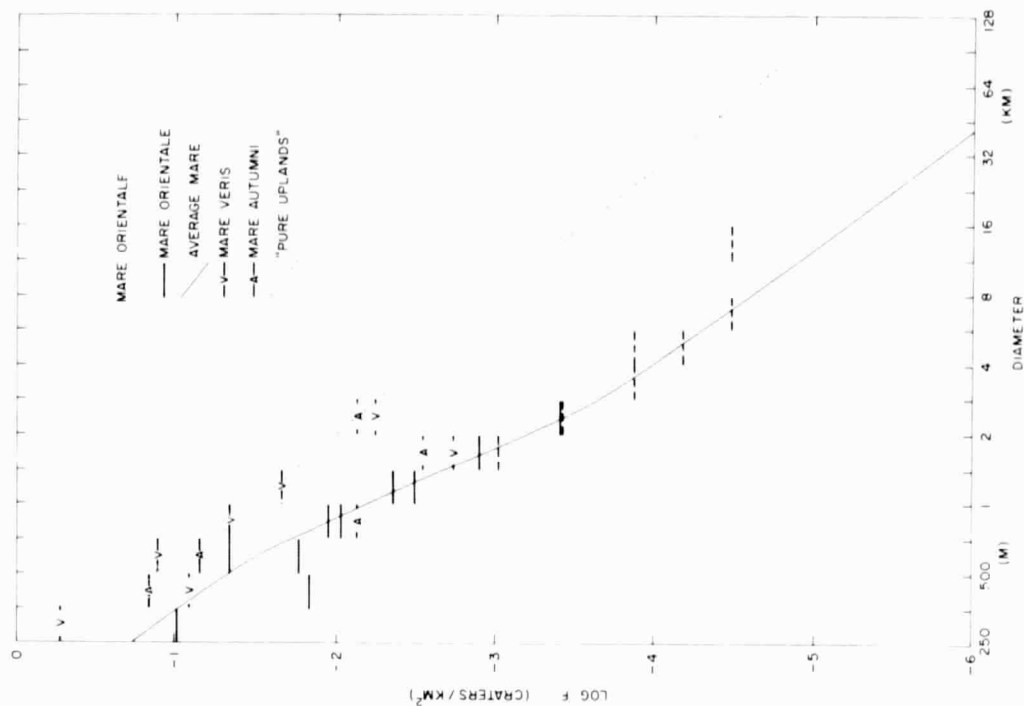


Fig. 2 Incremental diameter distribution of craters in Mare Orientale and nearby arcuate maria, showing coincidence with counts for all maria averaged over the front side. Dashed bars given $\frac{1}{2}$ weight. F defined in Paper I.

of post-Orientale craters over normal "pure continental" density. As for the formation of the Orientale basin late in the mare-forming period, it can be seen that there are measurably more post-basin craters than post-mare craters, by a factor of about 2.4 ± 0.2 (est. P.E.). When compared with the results of Paper III (Hartmann 1968a), this figure indicates formation of the Orientale basin somewhat before the oldest exposed mare surfaces were laid down, such surfaces having crater densities of about 1.6 (normalized to average maria). The point in time indicated by crater density 2.4 may have been well into the period of mare formation, even though the earliest of the now-visible surfaces had not yet been formed. Note that these crater density figures do not give relative ages; the flux was probably decreasing rapidly at this time and hence the figures are wide upper limits on the relative ages (cf. Paper III). In any case the present data suggest that the Orientale basin is best described as forming not "late" in the mare-forming period, but rather shortly preceding or during that period, before any of the other present maria were intact. The factor 2.4 is the smallest known post-basin crater density (cf. Paper III), indicating that the Orientale basin is the youngest of the great, multi-ring basin systems.

3. The Basin System — Miscellaneous Observations

Figure 3 shows the fine parallel striations of the ejecta blanket surface. These structures have widths of several hundred meters up to 1 km, considerably smaller than the radial and concentric structures attributed to faults and tectonic adjustments in *Comurication LPL 36* (Hartmann 1964). Additional dissimilarities are (1) lack of orthogonal (radial and concentric) gridding and (2) occasional pronounced curvature of the striations, often near major relief, (see Fig. 3). The latter characteristic gives the striations a pattern suggestive of turbulent flow.

The faces of the concentric scarps surrounding the Orientale basin are poorly exposed to sunlight in the Orbiter photographs, but in the few locations where the lighting is good, the face appears smooth, perhaps layered over with talus, with only a few outcrops or boulders (Fig. 5). No diagnostic features have been found to date the scarps positively as pre- or post-ejecta blanket.

Within the Orientale inner basin can be seen concentric rilles similar to those of *Humorum* and other circular maria except that they distinctly *cut across old, unflooded portions of the surface*, (Fig.

6). This shows that the concentric rille patterns are *not* intrinsic to the surficial mare material, but rather are deep-seated products of the basin system development. Probably they result from the sagging of the newly flooded basin, just as the concentric fault scarps are the result of sagging of the "crust" as a whole. Consistent with this, the major rille shown in Figure 6 follows exactly the arc of the incomplete "second ring" of the concentric ring system.

4. Physics of the Ejecta Cloud

It was noted above that the surface of the ejecta blanket around the Orientale basin has the appearance of having been striated by the flow of a fluidized medium over its surface.

One can show that turbulent flow would indeed be expected in cloud expanding from the central explosion and passing surface obstacles of dimension about 10 km, such as those indicated. The Reynolds number is

$$R = \frac{vL\rho}{\nu} \quad (1)$$

where v is the expansion velocity, L the obstacle or eddy dimension, ρ the density of the expanding cloud, and ν the cloud's viscosity (ν/ρ is the kinematic viscosity). Assuming $v \geq 10^4$ cm/sec and $L = 10^6$ cm, and since ν for a variety of volatiles and temperatures is $\sim 2 \times 10^{-4}$ gm/sec cm, we have

$$R \geq 5 \times 10^{13} \rho \quad (2)$$

It remains to find a value for ρ . The volatile content of meteoritic, basaltic, and granitic material is of the order 10^{-2} by mass. Thus, if only 10^{-4} of the 10^{22} grams dislodged in the Orientale impact were degassed (i.e. even if only the impacting projectile were degassed) we would have 10^{18} gm of gaseous material erupted from the impact site. The striated pattern is clear even beyond the "Rocca ring" of the concentric pattern, which has a radius of about 650 km, and thus if the expanding cloud were of uniform density and hemispherical, then as it swept over the surface 650 km from the impact site, the gas density would be of the order 10^{-6} gm/cm³, with a much higher density of solid particles, perhaps 10^{-2} gm/cm³. The figures derived above are lower limits, and it appears clear that the Reynolds number greatly exceeds unity. Taking into account the entrained solids, one finds the gas pressure insufficient to support the cloud, which would thus be compressed against the surface.

The gas cloud will propagate outward at not more than about 10^5 cm/sec, and hence to an



Fig. 3. Portion of the striated ejecta blanket of the Orientale basin (toward bottom). Width of this view is approx. 94 km; the striations are of the order 1 km wide. NASA Orbiter IV, Frame 173, high resolution.

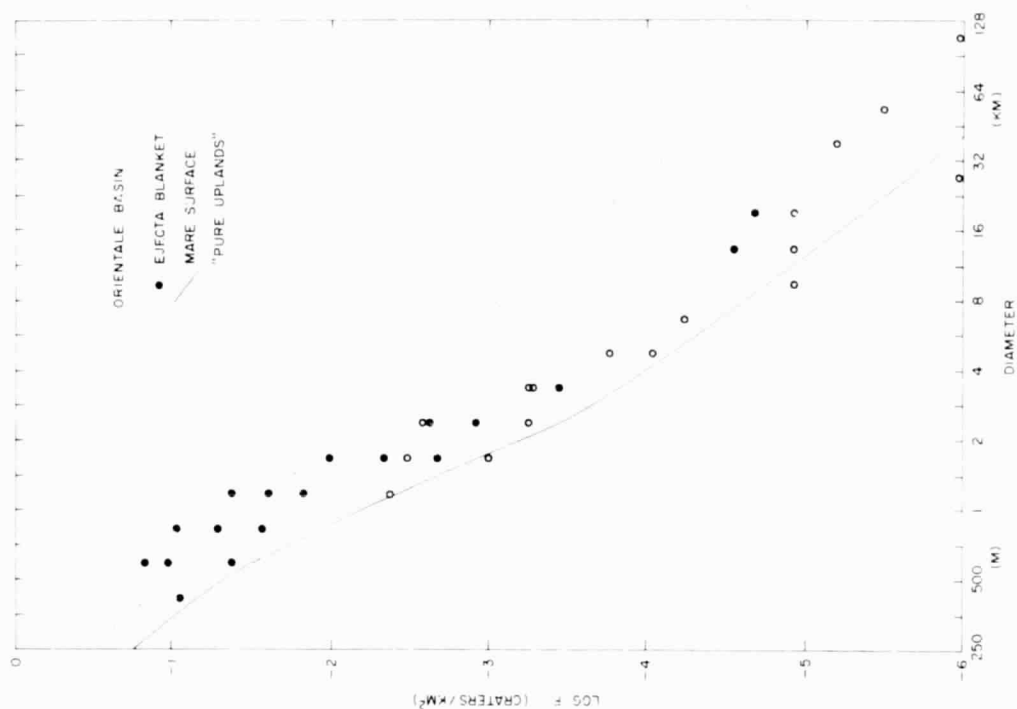


Fig. 4. Incremental diameter distribution of craters on the Orientale ejecta blanket WNW of Mare Orientale. There are significantly more craters than on the mare surface, but with a similar diameter distribution. Open circles given $1/2$ weight.

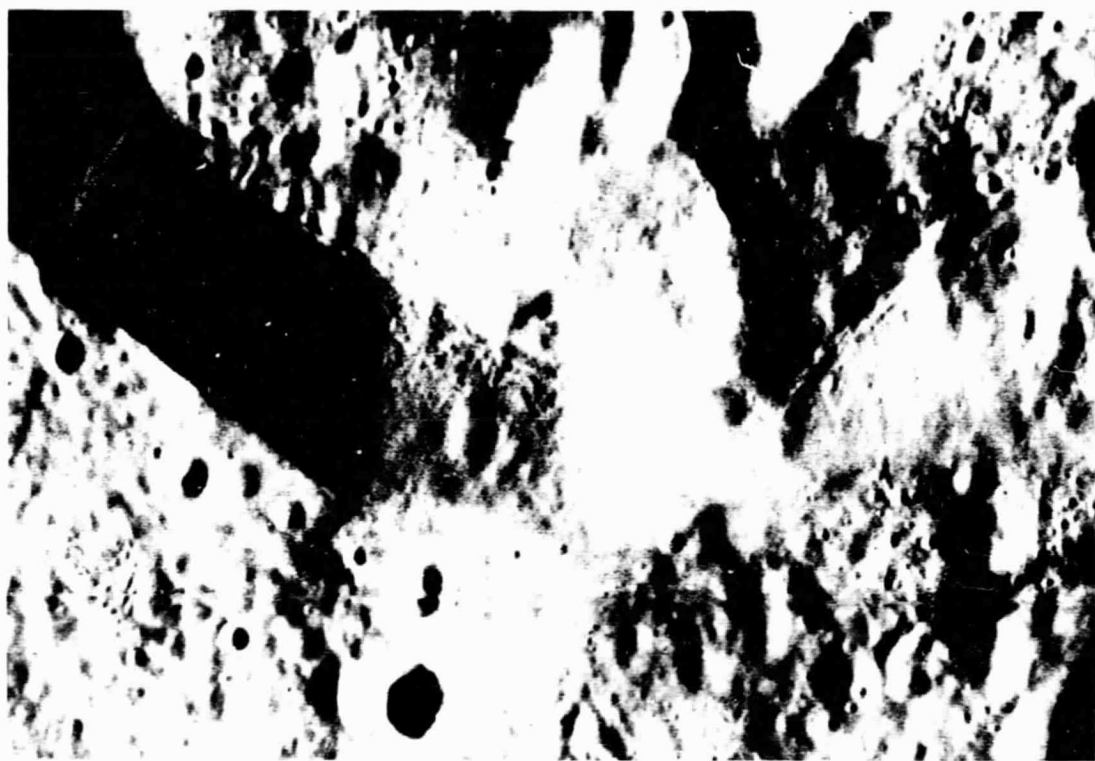


Fig. 5 Portion of the face of the "Fischstadt ring" scarp N of Mare Orientale, showing possible outcrops on the scarp face. NASA Orbiter IV, Frame 195, high resolution.

observer 650 km from the impact site, the rain of material would probably have a duration of several minutes. It would be, in essence, a *fluidized* system. This hypothetical phenomenon has many of the characteristics of a terrestrial *nuée ardente* flow, "highly heated gas so charged with incandescent ash particles that it resembles a mobile emulsion, yet dense enough to maintain contact with the surface as it rushes down the slopes of the mountain with hurricane force" (Bullard 1962).

The famous Pelée *nuée ardente* eruption of 1902, which destroyed the city of St. Pierre and 30,000 people, travelled at velocities approaching 10^4 cm/sec and swept over the city in only a few minutes, smashing meter-thick concrete walls and carrying along three-ton masses (Bullard 1962).

The lunar surface, and presumably a freshly deposited ejecta blanket, is loosely coherent particulate matter of no great structural integrity. It thus appears likely that a major impact would send out a *nuée ardente*-like cloud which would, in the process of depositing an ejecta blanket, cause a storm of several minutes' duration, capable of leaving a

surface covered with fine striations of width up to several hundred meters, as observed.

It should be noted that this section represents a supplement to conclusions drawn earlier. In Communications 24 and 36 (Hartmann 1963, 1964), it was argued that the large-scale radial lineaments shown on earth-based photographs were produced by tectonic action, not scouring or grooving by flying fragments. This view is still held, in essence, although some of the best photographs, e.g. Plate 24.7, show some of the fine striations now attributed to scouring by the ejecta. The striated surface, not only near Orientale but also in the case of other basins, was then fractured and broken by radial and concentric faults. Among the older basins, the striations have since been eroded and blanketed. This process has started on the Orientale lineaments, and only the youngest features, e.g. Tycho, lack such masking blankets.

5. Interpretation of the Orientale Basin System

In this section we will attempt to give a chronological history of the events that produced the pres-

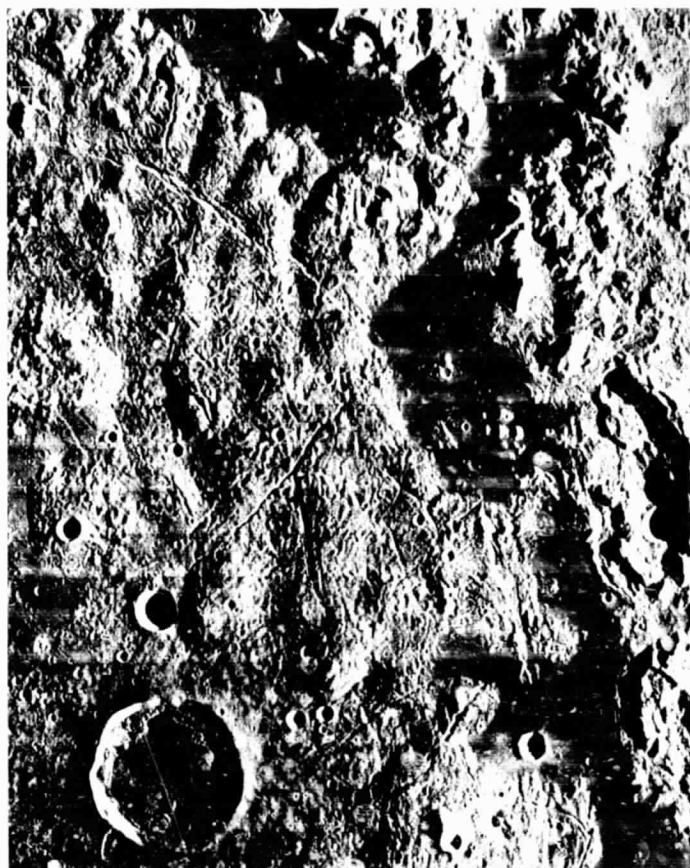


Fig. 6 NE quadrant of the "2nd ring," just inside Mare Veris, showing its expression as a concentric rille cutting across unflooded upland surfaces. This rille is a continuation of the mountainous scarp which forms most of the "2nd ring." NASA Orbiter IV, Frame 187, high resolution.

ent Orientale system. The argument that an impact, rather than a volcanic explosion or collapse, touched off these events is beyond the scope of this paper. Observations contributing to the argument are: the continuity of the crater diameter distribution from craters to basins, correspondence between this distribution and the asteroid fragment mass distribution, evidence for a point-source explosion, huge ejecta blanket, high-order radial and concentric symmetry, and energy considerations.

Baldwin's equation 8-3A (1963, pp 158-162) indicates that an energy of 4×10^{31} ergs (factor 4 est. P.E., depending on scaled depth of burst) was expended in creating the inner Orientale basin, which has a diameter of 390 km. If the impact velocity was 3 km/sec, the projectile's mass was about 9×10^{21} gm and its radius, 40 km (± 20 km est. P.E.). It was thus of size comparable to a moderate present day asteroid and close to or slightly smaller than (especially if the velocity was higher) the most common of Anders' "original" asteroids (Anders 1965).

It is an interesting support of Anders' model of size distribution of planetesimals that the largest bodies striking the moon may have just reached the size of his most common "original" planetesimals and that the rest of the impacting bodies display just the distribution of size of their fragments.

The impact occurred at a time when the surface was already pre-stressed by the grid-forming forces, causing the preferential development of fractures by the expanding shock wave in the NE-SW direction and to a lesser extent, NW-SE (Hartmann, 1964; Strom 1964). Inclination of the projectile's trajectory may have also been a contributing factor. The time of this impact, on the crater density scale, was 2.4 ± 0.2 , immediately preceding or just at the beginning of the mare flooding, in accord with the high susceptibility of fracture along the grid lines (subsurface melting and heating being near maximum). Fig. 7, parts 1 and 2 show the impact and the immediately produced, fractured surface.

In the minutes following the impact, a cloud of

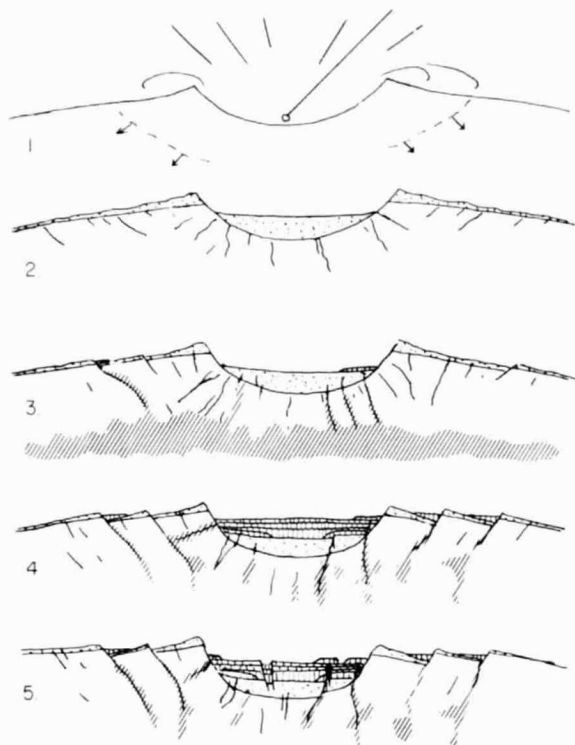


Fig. 7 Schematic history of the Orientale basin structure. Stippling represents ejecta; diagonal hatching, magma; and vertical hatching, lava flows. See text.

vaporized silicate material, volatiles, finely pulverized rock in suspension, and large fragments on ballistic trajectories was erupted and swept across the surface, in nuée ardente fashion, dropping the ejecta blanket now observed and scouring its surface.

The surface beneath the blanket, having been already fractured and perhaps faulted by the grid-producing forces, and still more highly fractured by the impact shock, was ripe for any tectonic adjustments. As subsurface melting and intrusions stepped up, approaching the climax of the mare-forming period, the Orientale surface area resembled a fractured roof, poorly supported from below. As, or perhaps even before, the subsurface magmas extruded onto the surface, gaining access particularly through the breccias of the central basin, the roof sagged and faulted in concentric rings, in the manner proposed by Fielder (1963), except that Fielder pictures the entire process from the beginning to have been endogenic; (it is difficult to account for the highly aligned radial striations and faults in this way). Fielder has pointed out that this sagging and faulting mechanism provides theoretical justification for the

$\sqrt{2}$ radius ratios found by Hartmann and Kuiper (1962).

Mare material worked its way up to the concentric faults and extruded at their bases, forming the arcuate maria Veris and Autumnis. Since these maria have a crater density nearly equal to that of the ejecta blanket (Figs. 2 and 4), it appears that the collapse, formation of the scarps, and welling up of the arcuate maria occurred just after the impact, before completion of the central mare. (A number of dark halo craters, probably endogenic and typically two or three km across, increase the crater density in the arcuate maria and support the idea of deep, fault-induced volcanism there.)

The central mare was completed at about the same time as the other average maria (crater density 1.0 ± 0.1). The flooding is illustrated in Fig. 7, parts 3 and 4.

The weight of the mare fill caused the inner basin to continue to buckle downward, and the adjustments took the form of concentric rilles (Fig. 6; Fig. 7, part 5), in some cases the last lavas were extruded along these concentric inner faults, forming mare wrinkle ridges (the wrinkle ridges have been shown by R. Strom to be the sites of some of the last flows in the maria (Kuiper 1966)).

Acknowledgments. This work was supported by an NSF Institutional Grant of the University of Arizona and NASA Grant NsG 161-61.

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N 69-12804

**No. 118 LUNAR CRATER COUNTS. V: LATITUDE INDEPENDENCE
AND SOURCES OF IMPACTING BODIES**

by WILLIAM K. HARTMANN

March 1, 1968

ABSTRACT

The larger pre-mare lunar craters are concentrated toward the lunar poles by a factor two over their equatorial densities. Post-mare craters are almost uniformly distributed, with only a marginal trace of the polar concentration. It is concluded that the moon's obliquity has not changed since the pre-mare craters formed; that impacting bodies during the early intense lunar bombardment were concentrated toward high latitudes by an uncertain mechanism, possibly related to the gravitational field of the nearby earth; that the early bombardment involved a different population of bodies than the post-mare and current influx; and that the declining early bombardment lasted into early post-mare time. The early projectiles may have been residual planetesimals in solar orbit or members of a circum-terrestrial swarm. Celestial mechanical studies of such bodies are highly desirable.

1. Introduction

If the bodies that are assumed to have struck the moon to produce the craters were confined to high-velocity* orbits with low inclinations, one would expect a concentration of craters toward the equator, in view of the moon's obliquity of only 1:5. Alternately, if the bodies entered the moon's gravity field with very low velocities, or were randomly inclined, one would expect a more random distribution of craters with respect to latitude. Specifically, one might expect to detect an equatorial concentration in the case of asteroidal projectiles, while circum-terrestrial or cometary impacts would be random.

These ideas led to the present search for latitude effects in the distribution of lunar craters, with the hope of obtaining some clue as to the source of the projectiles. As was demonstrated in Paper II (Hartmann 1967), the pre-mare craters (which dominate the upland, or "pure continental," group) and post-mare craters can be easily divided. Thus we have the opportunity to perform a test for latitude effects among both the earliest and the more recent craters.

*High velocity in this paper means velocities that would produce lunar impacts at considerably higher than lunar escape velocity, i.e. selenocentric approach velocities greater than, say, 3 km/sec.

Kuiper (1954) has suggested that the moon in its early history may have changed its obliquity radically, as would follow from an equation by Tisserand (1891). Or the other hand, this equation was developed for small values of the obliquity and may break down for large values so that one cannot prove on this basis that the moon would "topple over." Therefore the crater count test here proposed is useful and may in fact yield information on the obliquity of the moon in its earliest history. Furthermore, it is highly unlikely that the moon has changed orientation significantly in post-mare time, since there were no major (basin-forming) post-mare impacts to provide changes in angular momentum nor is there any morphological or structural evidences for marked post-mare changes in the direction of the angular momentum vector (although the grid system may indicate pre-mare changes in the magnitude of the angular momentum).

2. Observations

The crater catalogs of Arthur, et. al. (1963, 1964, 1965, 1966) provide ideal data for the latitude tests. He had catalogued all of the craters on the front side larger than 3.5 km diameter on IBM cards, with both "continental" and post-mare craters

designated.* Limb regions (defined in Hartmann 1964) were omitted here since they introduced a selective loss of smaller craters, especially at high latitudes. It is noted that any selection effect in the limb regions reduces the frequency of high-latitude craters. Continental and post-mare craters were separated, to test the two populations separately, and "mare-continental" craters, along the mare borders, were rejected. Thus only relatively pure continental and mare surfaces were used.

In order to reduce selection effects further, to limit the counts to craters of impact origin, and to avoid a discontinuity in the Arthur catalog diameter distribution at $D = 35$ km (of uncertain but probably partly observational origin — cf. Hartmann 1964, 1967), only the continental craters of $D \geq 40$ km were used. To get a sample of equal statistical size, N_M for the mare craters, the diameter distributions of Paper II were used, such that

$$\frac{N_M}{N_C} = \frac{1}{30} \frac{D^{-2}}{40^{-2}},$$

giving a limiting diameter for mare craters of $D \geq 7$ km.

These two crater samples, continental $D \geq 40$ km and post-mare $D \geq 7$ km, were sorted by η in zones, the mean η values being convertible to latitudes. The counts were made for each hemisphere separately, but the results were later combined, since the southern hemisphere is sparse in maria and the northern in continental area. The continental and mare areas in km^2 were determined from the *Orthographic Lunar Atlas*, and crater densities in km^{-2} were plotted for the indicated craters as a function of latitude.

Fig. 1 shows the result for the continental (upland) craters: surprisingly, there is a polar concentration of craters. This result was so unexpected that it was checked both by re-plotting the same data for two other limiting sizes and more significantly by making completely independent counts (especially in polar and equatorial zones) from Orbiter and Zond photographs. These data, included in Fig. 1, are quite consistent. As noted above, any selection effects in the Arthur catalog would be expected to act in the opposite direction.

Fig. 1 was then checked in another way. Hartmann (1964) shows that the "classes" in Arthur's catalog, 1 (well-preserved) though 5 (highly damaged), consistently correlate with apparent age, and

*Arthur used the term "continental" in his catalog. The preferred term "upland" is used here interchangeably.

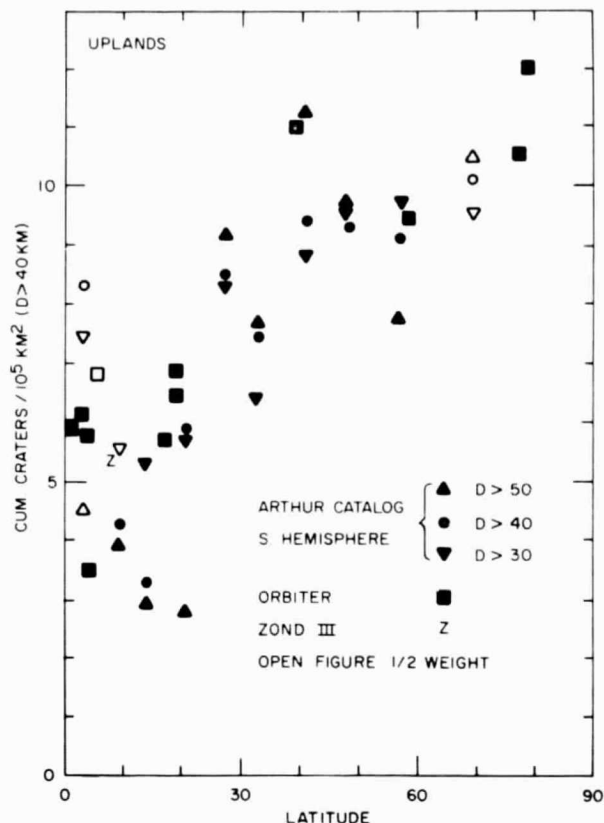


Fig. 1 Crater density vs. latitude for craters of $D > 40$ km (unless otherwise marked) on upland (i.e. "continental") surfaces. A pronounced polar concentration is found.

that the class 3 (damaged rims, generally pre-mare) is complete at diameters $D \geq 40$ km although the older classes 4 and 5 are not. Therefore, class-3 continental craters were sorted as an independent check on Fig. 1, with the results shown in Fig. 2.

The results all appear consistent: there is a smooth increase in crater density with latitude among the continental craters, with polar densities approaching twice the equatorial densities. The result is found to apply at the several longitudes investigated separately, and is confirmed with data from the central far side. *Therefore it is not merely a reflection of the front-side mare distribution.* Figs. 3 and 4 present a direct comparison of polar and equatorial areas at the same scale; the effect can be visually confirmed.

A group of craters of intermediate age, not as young as the post-mare craters, are those of class-1. A. C. Hartmann (private communication 1967) has shown that there are 2.2 times as many class-1 craters per km^2 in continental areas as in maria, indicating that class-1 craters as a group date into pre-mare

time. Fig. 5 plots the class-1 latitude distribution for $D \geq 10$ km corrected in the following way to give the number of class-1 craters/km² on a pure continental surface. Let N be the (known) total number counted in a given latitude strip and n , the number on maria. Let T/M be the (known) ratio of total to mare area in the strip. Then

$$\frac{T}{M} = \frac{1}{n} \left(\frac{N-n}{2.2} + n \right)$$

whence

$$n = \frac{N}{2.2 T/M - 1.2}$$

Thus, the total number of class-1's that would have been counted in a continental strip of given latitude is NF where F is a correction factor

$$F = \frac{(N-n) + 2.2n}{N} = 1 + \frac{1}{1.83 T/M - 1}$$

This factor, always < 1.71 , was applied merely to give units in Fig. 5 more consistent with those of the other graphs.

Fig. 5 shows only a marginal trace of the polar concentration, suggesting that the younger lunar craters do not demonstrate the effect.

Fig. 6 confirms this in a plot of the *post-mare* data for two limiting diameters. There is only a marginal trace of the polar concentration, as if the effect were declining or being diluted with time.

3. Interpretation

The effect is judged to be physically real: there is a concentration by a factor 2 of the oldest craters toward the poles, while the post-mare craters show almost no concentration. Figs. 1, 2, 5, and 6 present a time-sequence indicating a secular decline in the effect. This is strong support of the hypothesis that the earliest bombardment of the moon involved a group of impacting bodies different from those in post-mare time (and presumably now), and that there was a transition between them during the late pre-mare period, and that early post-mare impacts included the tail-end of the early intense bombardment. This hypothesis of a *separate* early population of pre-mare projectiles was first advanced by Kuiper (1954)*, and has been further advocated by Levin (1963), Öpik (1965), Hartmann (1965, 1966), and Marcus (1967). These authors have considered the possibility of a circum-terrestrial cloud of bodies

*Gilbert (1893) hypothesized that all the craters were produced by debris from such a circum-terrestrial "ring," from which the moon accreted. Ruskol (1961) also considers in detail accretion from such a ring.

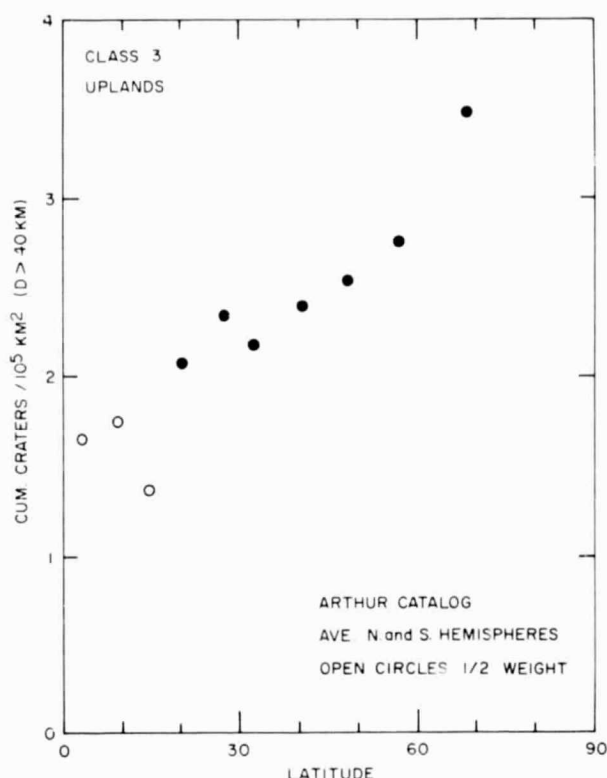


Fig. 2 Crater density vs. latitude for Arthur catalog class 3 craters on upland surfaces.

in some way associated with the moon's unique formation near, or capture by, the earth. Hartmann (1966) and Kuiper, Strom, and LePoole (1966) pointed out that the apparent absence of early intense Martian cratering is consistent with this.

Members of a circum-terrestrial swarm would have low velocities, and even if the swarm were not highly flattened it would be expected to produce craters randomly distributed, if not slightly concentrated toward the equator. There is the possibility that earth-moon-particle inter-actions in such a cloud would so strongly deplete the low-inclination orbits by ejection and collision that the last remaining objects, which caused the visible craters, were preferentially in high-inclination orbits.

In view of the difficulty of producing a polar concentration from a circum-terrestrial swarm, we may consider other possibilities. In 1966, I considered six hypothetical sources of the intense early lunar cratering and argued against four of them. The circum-terrestrial swarm discussed above was judged the most acceptable, but the second choice is possibly more compatible with the present data. It pictures the last remaining planetesimals at the conclusion

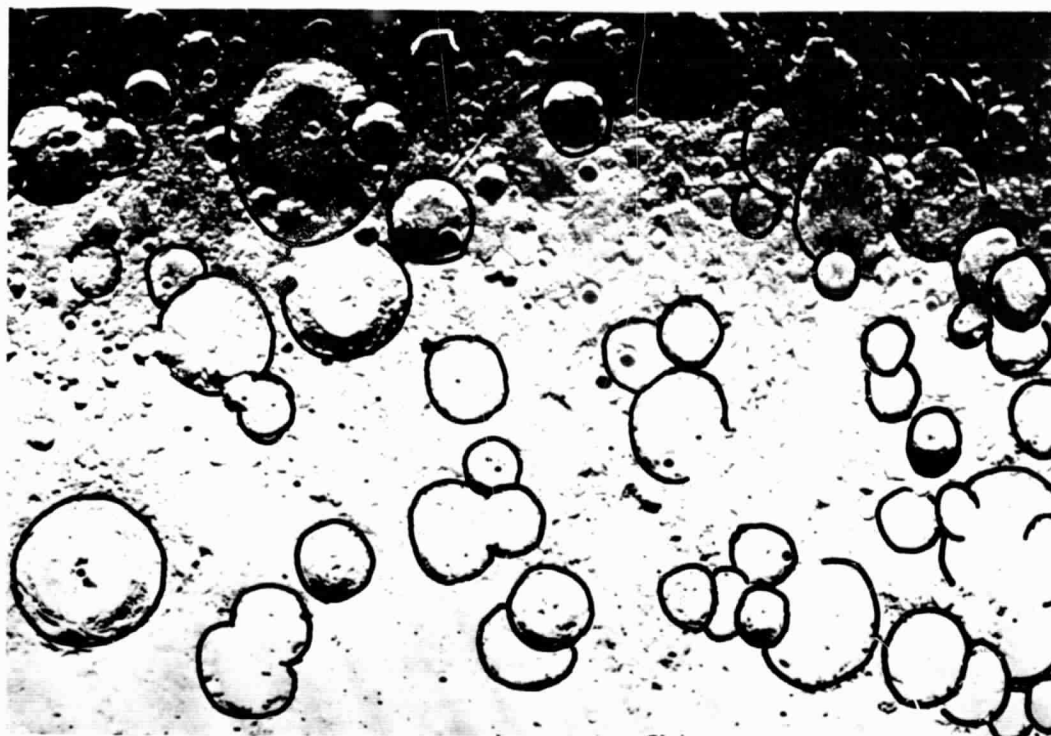


Fig. 4 North polar region (pole at lower right). Orbiter IV Frame M-190. Scale is same as Fig. 3. Craters of $D > 40\text{km}$ number 59, giving a polar/equatorial density ratio of 1.7 for these two areas (Figs. 3 and 4).

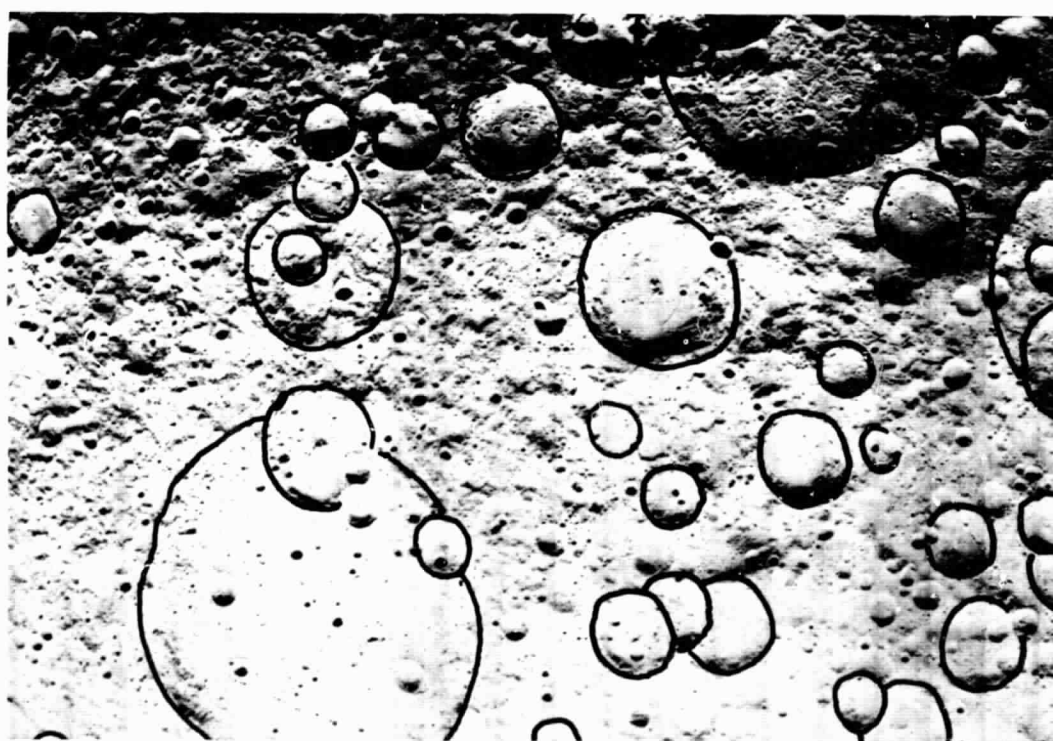


Fig. 3 Equatorial region on moon's far side, centered on lunar equator. Orbiter I Frame 116, with craters of $D > 40\text{km}$ outlined. Centers of 35 such craters are included in this area.

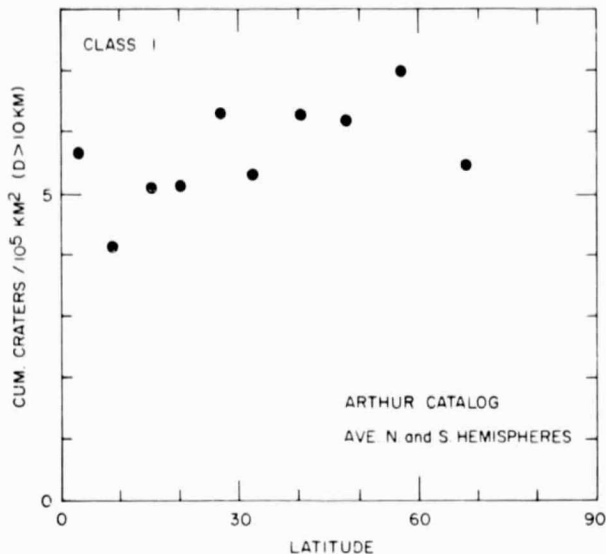


Fig. 5 Crater density vs. latitude for Arthur catalog class 1 craters. The density values are corrected to equal the values found on *upward*, not *mare*, surfaces (see text). Only a marginal polar concentration is detected.

of the planetary accretion process, still in orbit around the sun, being swept up by the planets. These would be in very low-inclination orbits (the solar nebula being highly flattened) and would approach the moon, or the earth-moon system, with low relative velocities.

It is conceivable, as indicated in Fig. 7, that if the moon were quite close to the earth, there could be an efficient shielding effect that would reduce the number of bodies striking the center-of-face, but increase the number at the apparent limb. (The so-called gravitational lens focussing effect, by which the center-of-face is alleged to receive increased impacts, can apply only to a given combination of velocity and "focal" distance; the result of variable velocities and distances is a screening.) If the moon's rotation were non-synchronous, the poles would constantly receive an increased flux, while an equatorial point would be periodically screened. If the moon were close enough, the screening could be quite efficient, this model has the qualitative advantage that as the moon moves away as a result of tidal interactions, the effect diminishes with time as is observed.

It may be possible to make a selection between the two hypothetical sources — the circum-terrestrial swarm or circum-solar planetesimals — by studies

of the celestial mechanics of such particles. Questions that need to be answered are: What fraction of particles would be entirely ejected from the earth-moon-particle and sun-earth-particle systems? What would be the distribution of inclinations in the two systems? What fraction of bodies in each system would strike the earth? What fraction would strike the moon? Given the total mass of bodies required to form all the visible impact craters, and given the fraction of all bodies that would strike the moon in each system, would the total required mass of particles be reasonable?

If nearness to the earth does have a bearing on the observed polar concentration, either in the context of a circum-terrestrial swarm or a screening effect, then we have an argument that the moon formed near the earth or that any hypothetical capture occurred *before* the early intense cratering. The very presence of a latitude effect provides an argument that the moon has not radically changed its obliquity since the early large craters formed, and also suggests that the craters are not endogenic (unless it can be shown that there are latitude effects to be expected in volcanism). If screening by the earth is involved, the compatibility of back-and-front-side data indicates that the moon's rotation was not originally synchronous.

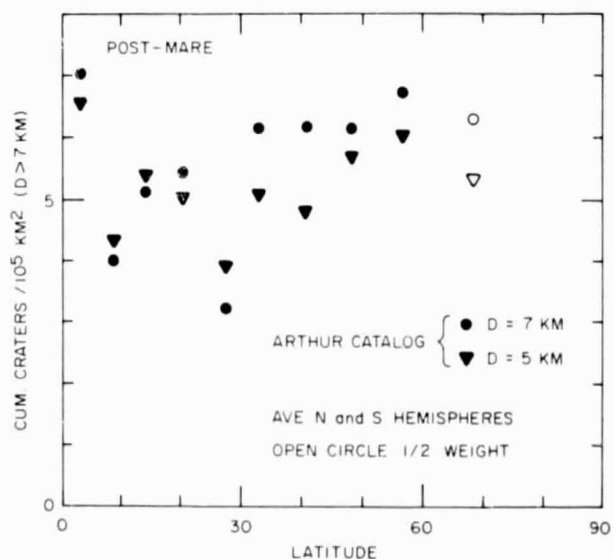


Fig. 6 Crater density vs. latitude for post-mare craters. The density values are corrected for $D > 7$ km, although two diameter ranges are plotted.

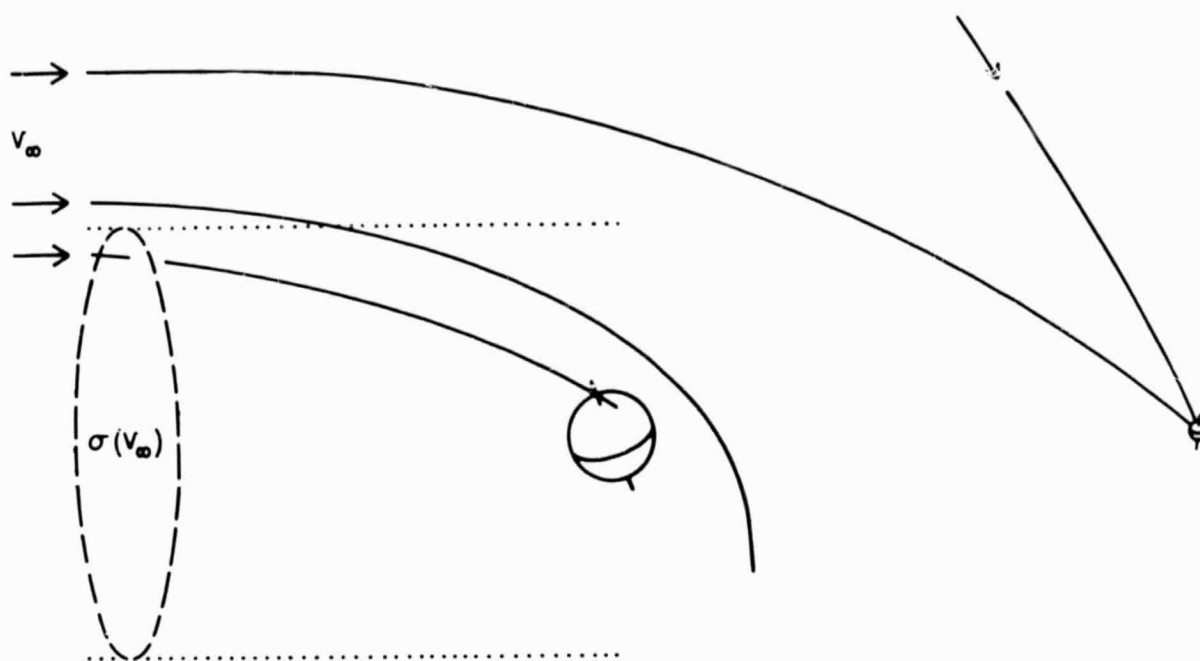


Fig. 7 Schematic diagram of possible dynamical explanation of polar concentration of old craters. Low-inclination planetesimals approaching the earth-moon system with velocity V_{∞} strike the moon preferentially at high latitudes because of shielding by the earth's gravitational cross section σ . A possible high-inclination orbit is also shown at right.

Acknowledgment. I am indebted to G. P. Kuiper for helpful discussions on several points. This work was supported by an NSF Institutional Grant of the University of Arizona and NASA Grant NsG 161-61.

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No. 119 LUNAR CRATER COUNTS. VI: THE YOUNG CRATERS
TYCHO, ARISTARCHUS, AND COPERNICUS

by WILLIAM K. HARTMANN

March 15, 1968

ABSTRACT

The crater densities inside the craters Tycho, Aristarchus, and Copernicus are found to be respectively 0.1, 0.3, and 0.5 times the mean crater densities on maria. Ages of 2×10^8 , 1×10^9 , and 2×10^9 yr are inferred. The interior of Copernicus exhibits a number of recognizable volcanic structures. Rays accompanying these craters are probably finely pulverized ejecta and are destroyed on a time scale of about 3×10^9 years by stirring and mixing of the upper layers of the lunar surface to a depth on the order of a centimeter. Primary impact craters exhibit approximately a -2 power law diameter distribution to diameters as low as 250m, indicating that most hectometer-size craters (which together define a much steeper power law) are not primary impact craters.

1. Introduction

One method of dating lunar features is to divide the observed crater densities (craters/km²) by the adopted cratering rate (craters/km² yr). Unfortunately, the cratering rate for the larger craters ($D > 2$ km) is uncertain, probably by a factor at least three (Vedder 1966, Hartmann 1965), while for smaller craters it is widely believed that there is significant contamination by non-primary-impact craters, probably including collapse depressions and secondary impact craters (Kuiper 1965, Shoemaker 1965). These make it difficult to identify the true primary impact craters and hence lead to uncertainties in the crater density.

Nonetheless, this method has recently been applied to the lunar crater Tycho by Strom and Fielder (1968) who counted craters of diameter D of the order 100 m and, using the best estimates of flux for appropriate sized meteorites, derived an age for Tycho of 1.6×10^8 years. (Strom and Fielder are presently applying the method to Aristarchus and Copernicus as well).

An independent approach is the method of this series of papers: we compare the observed crater densities with the average mare crater density, noting that the maria apparently mark a quite restricted epoch in lunar history (paper III, Hartmann 1968). In this series we use *relative* crater densities, 1.0 being the value assigned to the average mare. The usefulness of the scale lies in the fact that empirically-determined crater densities can be expressed *independent of D* for various lunar structures, giving a relative age scale. Absolute ages can later be given if one has further knowledge of the age of the maria and the time-development of the cratering rate. However, it is important to note that the relative crater density is most reliably determined only for $D > 2$ km, again because of the difficulties of interpretation of smaller craters of varied origin (e.g. paper I, Hartmann 1967).

2. Observations

Orbiter photographs show that Tycho has an unusually rough interior, that Aristarchus is only slightly less rough, and that Copernicus is noticeably

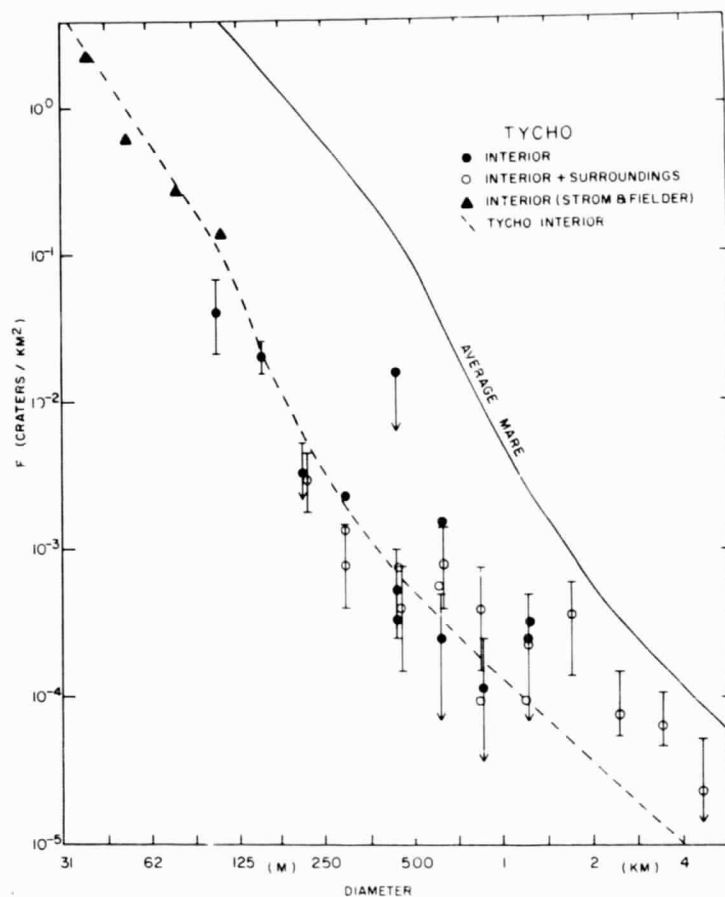


Fig. 1 Crater diameter distribution for Tycho; numbers refer to increments of $\sqrt{2}$ in D . Statistical errors are indicated for some of the data points based on few craters. The dashed curve (Tycho interior) is fairly well determined, being based on both the adopted slope of -2 at $D > 2$ km and on the data points.

smoother than Tycho, some sections having a flooded appearance. Coupled with their well-known ray systems, the sharp rim detail, and their thermal anomalies, this is strong evidence not only that the craters are young, but also that in the sequence named they increase in age. While no observable debris blanket overlies Tycho, one is just beginning to form in Aristarchus. Most of the rest of the moon, as shown by the Surveyors (Gault, et.al. 1967, p. 203) is blanketed by a fragmental layer of meter or decameter depth.

Crater counts bear out these inferences. Since all three craters have few overlying craters, the statistics are poor, particularly for the larger D values. Tycho, for example, has only one crater of $D > 1$ km within its rim. While it would thus appear difficult to get a meaningful relative crater density applicable at $D > 2$ km, it must be remembered that diameter distribution law apparently universally has an exponent (slope) of $-2 (\pm 0.1)$ at these larger diameters, and this knowledge aids us in obtaining a well-defined crater density.

Figure 1 shows the results obtained from Tycho. Strom and Fielder have allowed me to convert their data to my system of plotting, and their counts are included. Although counts outside the rim of Tycho were made in an attempt to get more area and better statistics, these were kept separate from the interior counts, because Strom and Fielder (1968) showed that the exterior counts were both higher and variable from one stratigraphic unit to another. From this fact, they concluded that Tycho had a "multi-phase" development in time, and that the exterior flow units may in fact be older than Tycho. Alternate interpretations are that Tycho secondary craters cause the variable excess in exterior crater counts, or that some other type of crater (e.g. collapse depressions) have not been adequately sorted out of these counts. In my own counts of Tycho, as in previous papers of this series, no effort was made to sort out craters of different origins, unless stated.

It can be seen that the relative crater density (measured at $D > 2$ km) in Tycho is 0.1 with an estimated P.E. of 20%. The curve drawn in Figure 1

is an estimated fit, using not only the datum points but also the slope of -2 at $D > 2$ km as parameters. Strom and Fielder's finding that crater density is higher outside Tycho than inside is now confirmed for diameters larger than those used by them.

Figure 2 shows the data for Aristarchus. Among craters larger than 125 m diameter, all counts for Aristarchus fall above those of Tycho. However, at smaller diameters the curve has a significantly different behavior, testifying again to the density irregularities among the craters of $D \sim 100$ m in various regions. Aristarchus is found to have a relative crater density of 0.3 with 20% estimated P.E.

Copernicus presents a more complicated problem because of its modified interior, apparently partly flooded and peppered with volcanic structures. For this reason, separate counts were made on the walls in an effort to obtain data less affected by the presence of non-impact craters. Figure 3 presents this data. Copernicus is found to have a relative crater density of 0.5, with 30% estimated P.E. The exterior crater density, as in the case of Tycho, is larger than the interior crater density.

3. Volcanism in Copernicus

Figures 4-7 illustrate several features of the Copernicus floor indicative of extensive volcanic activity. These include structures which match in morphology both cinder cones and rimless collapse calderas. Many of the pits are closely clustered, again suggesting volcanism.

The normal lunar maria, which lack abundant cinder cones and calderas, appear to be fluid basalt flows on the basis of both morphology (Kuiper 1965) and chemistry (Turkevich, et al. 1967). The deficiency of cinder cones and kilometer-scale calderas is probably correlated with the fluid nature of the lunar flood basalts (Rittmann 1962). The floor of Copernicus, on the other hand, is closer in form to many terrestrial volcanic fields. The Pinacate field of Sonora, Mexico, for example, is about 40 km across (compared with 50 km for the Copernicus floor) with central peaks, calderas (up to $D = 1.6$ km), tuff rings, and scattered cinder cones. Figure 8 illustrates some of these features. The "crater density" of Pinacate calderas, rings, and cones combined

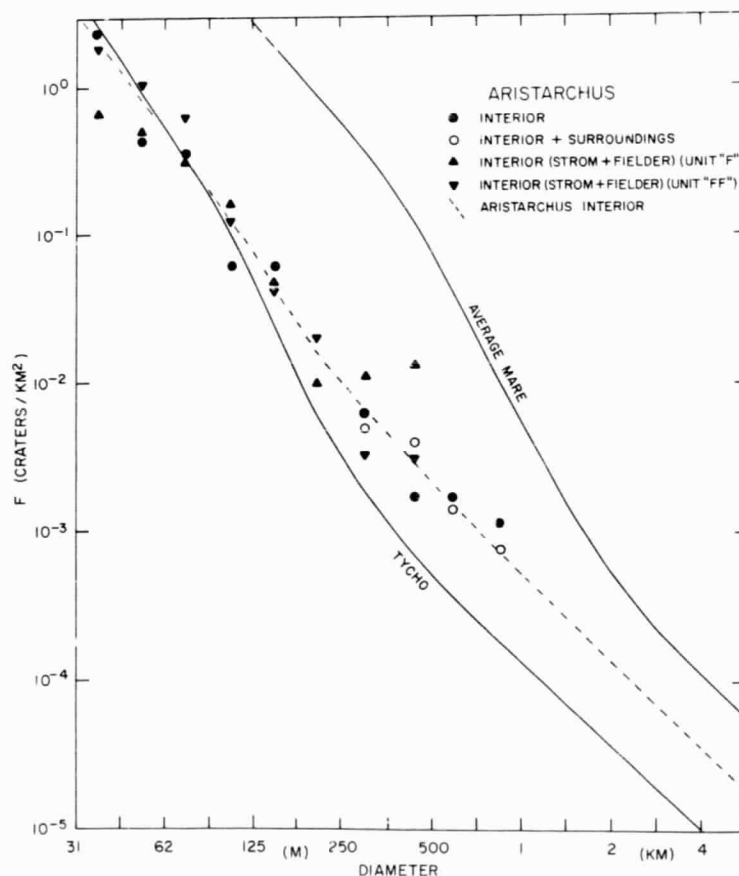


Fig. 2 Crater diameter distribution for Aristarchus. The curve of Fig. 1 is added for comparison.

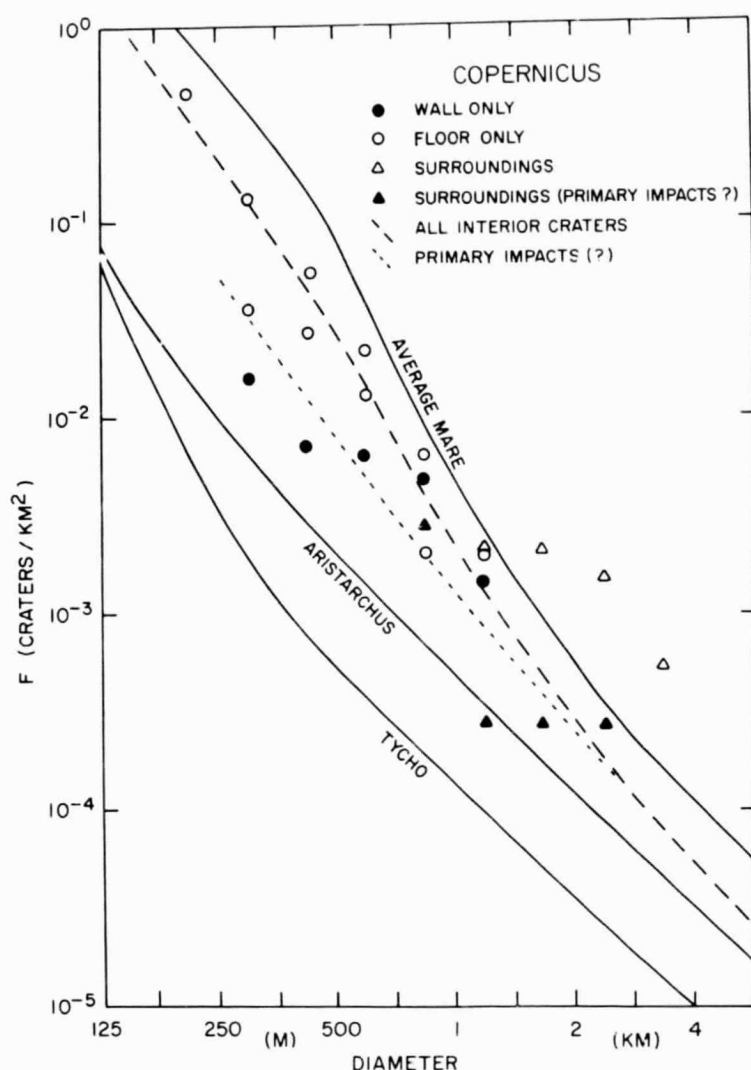


Fig. 3 Crater diameter distribution for Copernicus. The Tycho and Aristarchus curves are added for comparison. The curve with the short dashes, based on the solid data points, indicates the inferred distribution for primary impacts. The curve with the long dashes includes *all* craters (open data points), many of which are evidently endogenic or due to secondary impacts.

runs within an order of magnitude of the combined crater density, less suspected impacts, on the Copernicus floor at all diameters charted in Figure 3. Again, Figure 9 illustrates a rimless collapse pit characteristic of the Hawaiian shield volcano, Kilauea. The late volcanism in Copernicus may well have been less fluid than the mare volcanism, with less volatile content, i.e. more like terrestrial shield volcanoes than like flood basalts.

It is concluded that the floor of Copernicus initially resembled the floor of Tycho, and then began to be blanketed, reaching and passing an intermediate state exemplified by Aristarchus, and that at some stage, about a third of the floor was flooded by mare material during a period of volcanic activity. This material did not come from outside, as the

Copernicus wall is nowhere breached, but probably was aided in its rise from the moon's interior by the subsurface brecciation and fracturing resulting from the Copernicus impact. The marked slumping and terracing of the Copernicus walls may have aided by this activity, and in fact may be directly due to settling to conserve the volume of the extruded lava. Further, since crater walls define zones markedly out of isostatic adjustment, faulting and lava extrusion around walls and the edges of crater floors is not unexpected.

4. Conclusions

The results for the three craters studied are combined with other areas in Figure 10. Tycho appears to be the youngest structure of its size on the moon. The volcanism in Copernicus explains the rapid rise

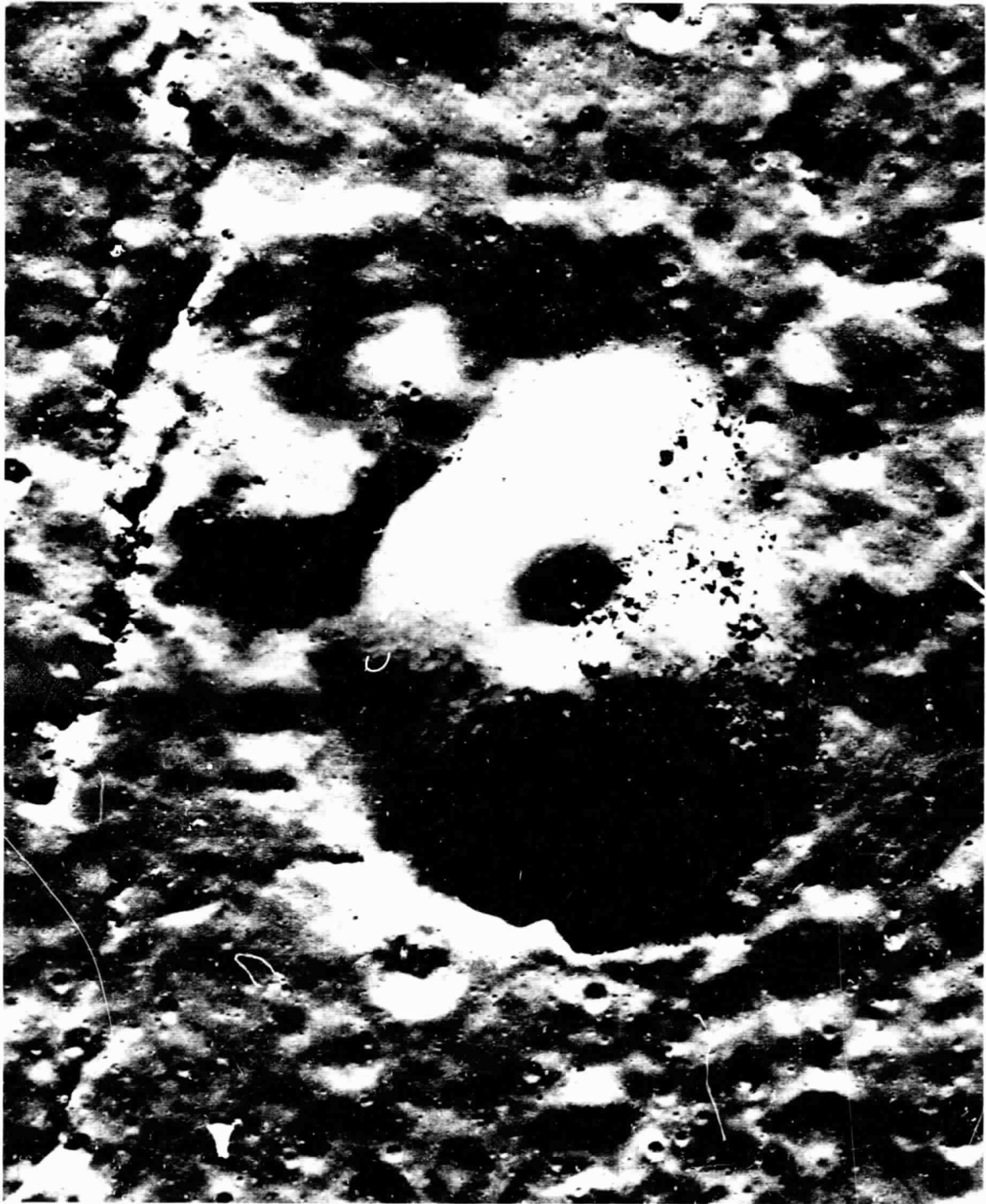


Fig. 4 Cinder cone-like structure on the floor of Copernicus. Oriented with light from above. Orbiter photograph courtesy NASA.

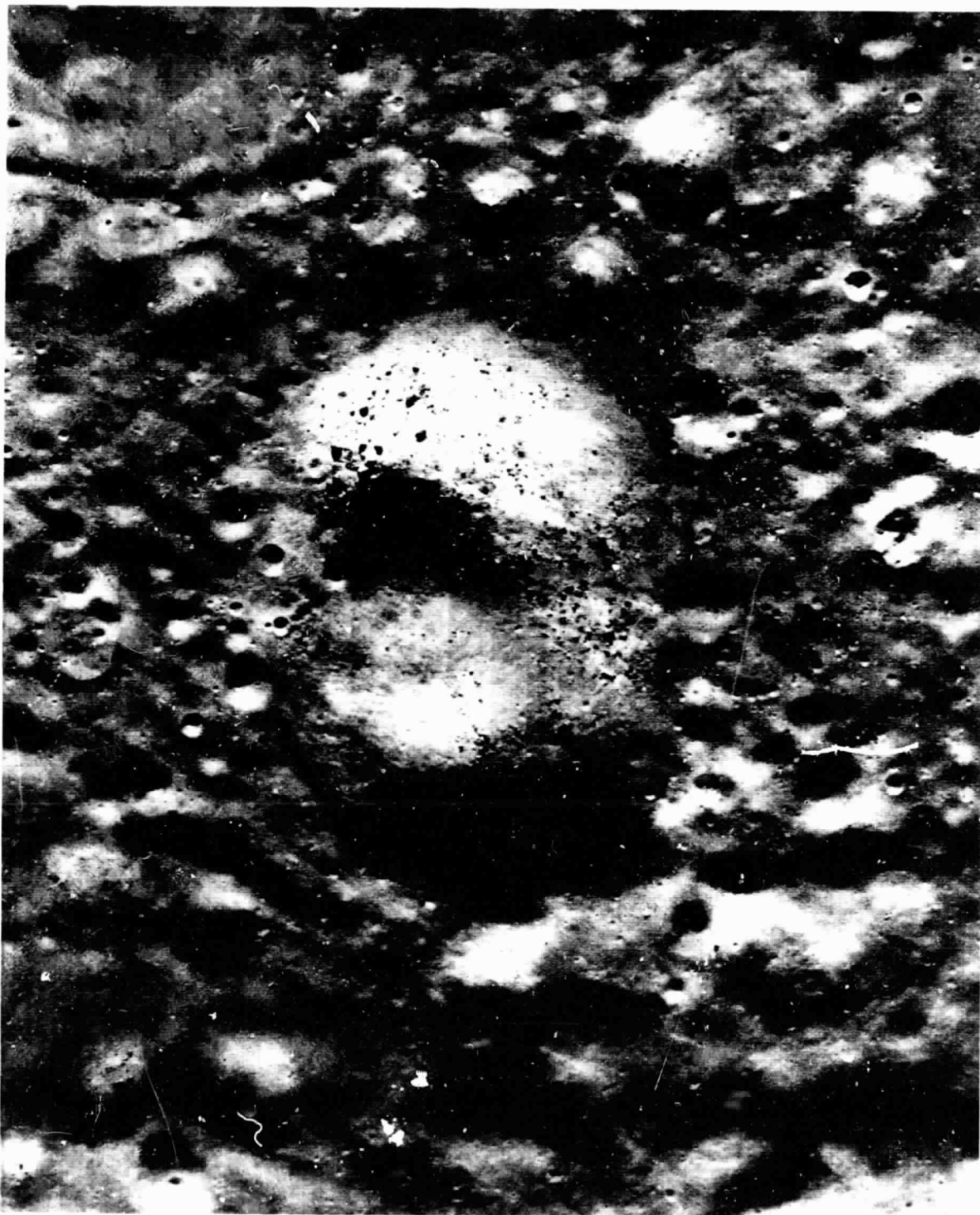


Fig. 5 Breached cinder cone-like structure on the floor of Copernicus. Oriented with light from above. Orbiter photograph courtesy NASA.



Fig. 6 Apparent rimless collapse pit on the floor of Copernicus. Oriented with light from above. Orbiter photograph courtesy NASA.



Fig. 7 Apparent primary impact crater (note raised rim, debris, rays) cf. Fielder and Guest in this volume of *Comm. LPL*. Oriented with light from above. Orbiter photograph courtesy NASA.

in Figure 10 of craters of $D < 2$ km relative to the density in Tycho or Aristarchus; many of these hectometer-scale craters must be endogenic. Figure 10 contains support for a speculation in paper I, based in turn on a suggestion by Kuiper, Strom and LePoole (1966), that the size distribution for primary impact craters continues at a slope of about -2 , gradually steepening, well below the $D = 2$ km limit to as little as $D = 250$ m. That is, in Tycho and Aristarchus, where the crater density is very low and contamination by still younger secondaries or volcanic pits is minimal, the curves retain a low slope, but in Copernicus and the mare it is already quite steep at $D = 1$ km because of non-impact contamination. The former behavior was found in paper I for craters on the wall of Alphonsus, but not on its flooded floor.

Absolute ages may be estimated on the basis of previous models of the cratering rate and the age

TABLE I
AGE SCALE

	RELATIVE CRATER DENSITY	ESTIMATED EQUIVALENT AGE
"Pure" Uplands	30	4.5 (10^9) yr
Average Mare	1.00	4 (10^9) yr
Copernicus	0.5	2 (10^9) yr
Aristarchus	0.3	1 (10^9) yr
Tycho	0.1	2 (10^8) yr
Oldest Martian Craters*		4 (10^9) yr

*The compatibility of the Martian crater ages with the expected formation epoch of the Martian surface supports the other values given here (cf. *LPL Comm.* 65). Recently reported increases in the number of Martian craters counted on reprocessed Mariner photographs can only push the age further back toward 4.7×10^9 yr.

of the maria, as estimated in current literature. Various LPL publications, including my own, have argued (for a number of reasons including thermal histories of meteorites, meteorite fluxes, and analysis of Martian craters) that the mare age is approximately 4×10^9 yr and that the post-mare cratering rate has gradually increased with time, so that it is now of the order of twice its average post-mare value (for a detailed model, see Hartmann and Hartmann 1968). Further defense of these conclusions is beyond the scope of this paper. On the basis of these inferences, ages can be assigned to the Tycho, Aristarchus, and Copernicus on the basis of the observed crater densities, and these ages are reported in Table I.

Although Table I gives the interpretation favored here, it should be noted that an alternative interpretation holds that the cratering rate is roughly ten times higher than that inferred from meteorites

because of a cometary component that does not survive passage in the earth's atmosphere (Shoemaker, private communication), and that the maria are only about 2×10^8 yr old, the cratering rate having been nearly constant since the beginning. According to this model the ages of the three craters (and the Martian features) are only about $1/20$ of the values in Table I, or even less. Such values already have been suggested at Surveyor news conferences (e.g. an age of "one million years . . . 500 times younger than that of the lunar maria" — *Aviation Week*, 88, p. 17).

Such low ages are not supported by considerations of terrestrial impacts. The body which formed Tycho was probably of the order of 10^{17} or 10^{18} gm mass, on the basis of cratering theory. Even if it were cometary, with density 1 gm/cm^3 , and velocity as high as 40 km/sec , it must have had a diameter exceeding 2 km . The compression wave velocity in lake ice is 3.4 km/sec (a value approximately valid for many materials), indicating that the shock wave generated as the bolide struck the atmosphere would propagate through it in about a second (while heating effects, etc. would necessarily take longer). But since most deceleration occurs below 40 km height (Heide 1964), a 40 km/sec bolide would strike the ground by the time its rear portion received a signal that it had struck the atmosphere. Slower projectiles would still have only a few seconds to break up, and the ablative effects would be less. Heide (1964) estimates that at 40 km/sec , a 10^6 gm mass would lose only 32% of its mass, and hence much larger masses would survive intact, consistent with the above. Therefore, even cometary bolides large enough to create Tycho would survive to strike the earth's surface, and if Tycho's age were only 10^7 years there should be several examples of 80 km astroblemes of such youthfulness on the earth's continents, which is not the case.

The preferred value of 2×10^8 years would lead to a prediction of several Tycho-sized craters on earth formed in *this* time span, but in this case, few or none would be observable because of erosion and major cycles of orogeny. Of possible large candidates for astroblemes, the Rieskessel is 2×10^7 years old (but only 23 km in diameter), and Clearwater Lakes ($26, 31 \text{ km}$), Manicouagan (65 km), Sudbury (48 km), and Vredefort Ring (40 km) are all 10^8 years old or older, in support of our conclusion.

The conclusion that Tycho, Aristarchus, and Copernicus are about $0.2, 1$, and 2×10^9 years old,



Fig. 8 Collapse craters, cinder cones, and lava flows on flanks of Pinacate shield volcano, Sonora, Mexico (photo by R. Laidley).



Fig. 9 Rimless collapse pit Halemaumau, Kilauea shield volcano, Hawaii (photo by author).

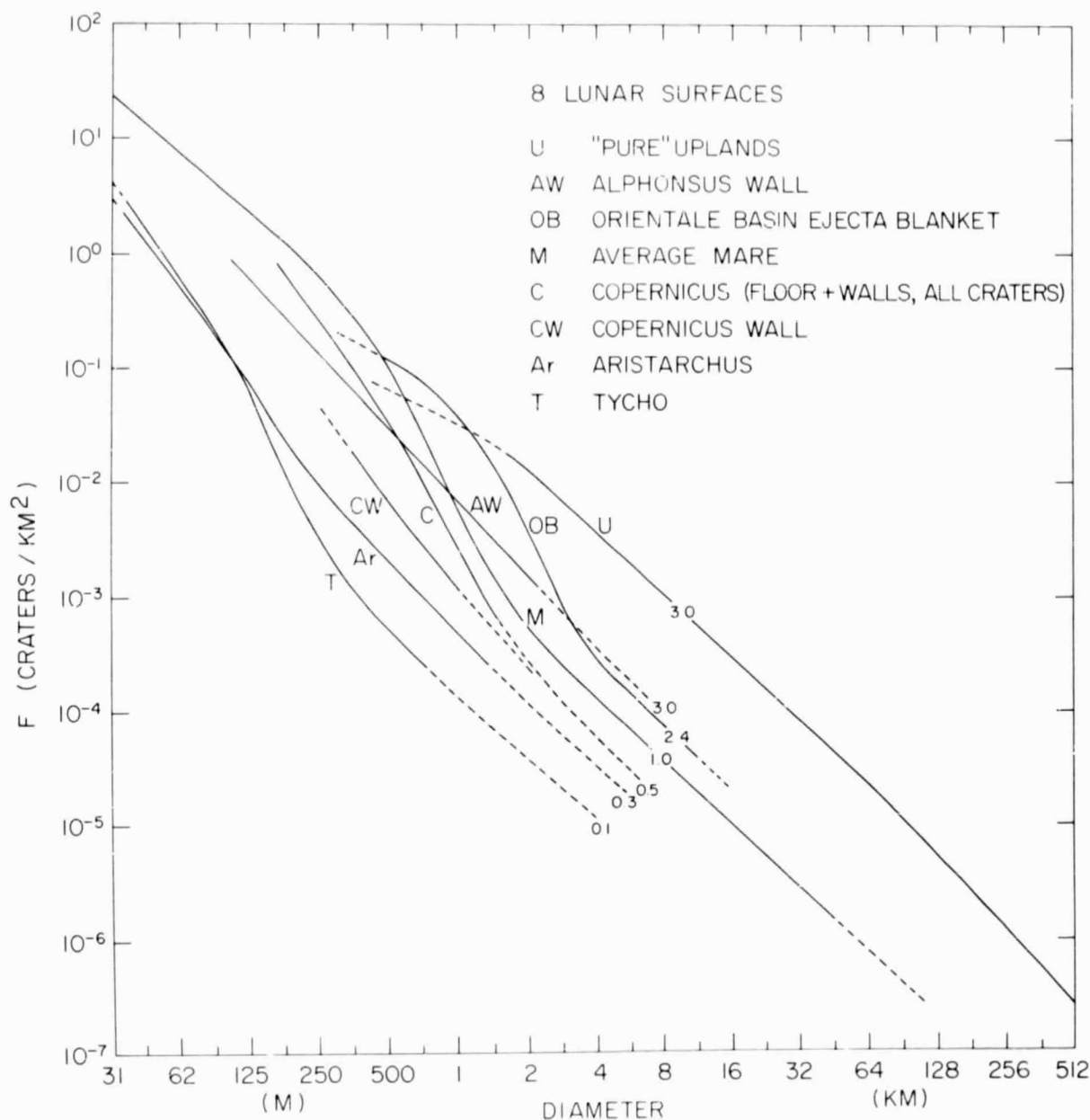


Fig. 10 Summary of crater counts for three young lunar craters compared with other type-areas. Note approximate parallelism at $D > 2$ km with a slope of about -2 , and varying slopes for $D < 2$ km, apparently due to admixtures of endogenic craters and secondary impacts.

respectively, raises problems about their ray systems. Hapke's (1965) conclusion that exposure to the solar wind causes darkening of the lunar surface in some 10^5 years would appear to account not only for the uniform and unique colorimetry of the moon, both in the visual (Hapke 1965) and infrared (Binder, Cruikshank, and Hartmann 1965; Wattson and Hapke 1966; Cruikshank 1968) but also loss of rays

among the older ray-craters. A longer ray-lifetime than 10^5 years is not a qualitative problem, since Hapke himself pointed out that the meteoritic flux causes a turnover of the uppermost microns of the lunar surface in about 10^5 years. Thus, a thick ray deposit (of depth < 10 m; Kuiper, et al. 1965, p. 61) should last considerably longer than the darkening time. However, the implication of the present

work is that more than 10^9 years, i.e. 10^4 turnover-times, is required to erase rays. One might expect the surface layers to be saturated with darkened material more rapidly.

This suggests that radiation-darkening is neither the principal nor the only agent destroying rays. Probably the rays owe much of their brightness to small particle size relative to background particles; i.e. they are finely pulverized rock ejecta. Therefore, it requires not mere turnover of the upper microns or millimeters of surface, but thorough surface mixing of the ray deposit and background fragmental layer, with preferential burying of the fine particles, to destroy a ray. [Moreover, the relevancy of radiation-darkening has been called into question by two observations: 1) the difficulty of avoiding oil discoloration in the irradiation experiments, and 2) the observation that the uppermost surface layers of the moon are lighter, not darker, than the subsurface; Gault, et al. 1967]. Mixing to a depth of 1 cm, sufficient to bury the small particles, requires a period of the order of 3×10^9 years at the present bombardment rate, and thus this model is compatible with our derived crater ages.

It is concluded that the ages of the three craters studied are essentially as given in Table I; that Copernicus displays a number of familiar volcanic structures on its floor; that the diameter spectrum of primary impact craters does not rise as steeply at $D < 2$ km as the observed spectrum of all craters in the maria; and that the derived crater ages are consistent with a model which holds that the rays are finely pulverized material being mixed with the background material and hence rendered invisible in a time period of the order 3×10^9 years.

Acknowledgments. I thank R. G. Strom and G. Fielder for making much of their raw data available before publication for comparison with my own, and G. P. Kuiper for helpful discussions. This work was supported by a University of Arizona NSF Institutional Grant and NASA Grant NsG 161-61.

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N 69-12806

No. 120 STATISTICS OF CENTRAL PEAKS IN LUNAR CRATERS

by CHARLES A. WOOD

June 10, 1968

ABSTRACT

Statistics of central peaks are drawn from the large catalog, "The System of Lunar Craters." Only about 3% of all cataloged craters have peaks (cf. Table 3); this value is much smaller than has been previously reported. However, the percentage of craters with observed central peaks increases markedly with size and approaches 100% for undamaged craters of diameter 70km and larger (cf. Fig. 2). Young (undamaged) craters have peaks more frequently than older craters.

MacDonald (1931) and Young (1940) initiated modern statistical studies of lunar crater heights, depths, and diameters. This paper intends to improve the statistical data on the occurrence of central peaks in lunar craters.

As a compiler of the catalog, "The System of Lunar Craters" (Arthur, *et. al.* 1963, 1964, 1965, 1966), the author was responsible for determining which of the approximately 17,000 entries possessed a central peak. This decision was based on the examination of the original prints of the *Photographic Lunar Atlas* (Kuiper, *et. al.* 1960) and newer photography, including the Ranger #7, 8, and 9 records. (Orbiter photographs had not yet been obtained when the catalog was completed.) Each of the central peaks was classified as "weak" or strong," and "single" or "multiple." Classification was qualitative: the category for each peak depended on its height, brightness, and size relative to the crater diameter. The catalog was put on punch cards and the IBM 407 accounting machine of the University of Arizona was used to sort central peak data with respect to other crater parameters.

The data in "The System of Lunar Craters" were used to determine what percentage of craters have central-peaks, and how such central-peak craters differ from craters without peaks. Some of the 17,385 craters in the catalog were so small that it was impossible to determine if they had a peak. Likewise some craters were so near the limb that the detection of central peaks was unreliable. To avoid these selection effects *we included in the statistics only those craters with diameter D larger than 10km, and whose centers were 70° or less from the center of the moon's face.* Within these limits only 6.8% of the lunar craters on the earthward hemisphere have central peaks. (Only 3% of *all* craters, $D \geq 3.5\text{km}$, have peaks.) This may appear a startling result, for even a poor photograph will show many central peak craters: Copernicus, Aristillus, Tycho, Bullialdus, etc. Indeed, Goodacre (1931) found that 19.2% of lunar craters have central peaks, in close agreement with Young's (1940) percentage of 21.1. Recently Baldwin (1963) compiled central-peak statistics from a sample of 342 craters and concluded that 68% of craters larger than 8km have central peaks. This

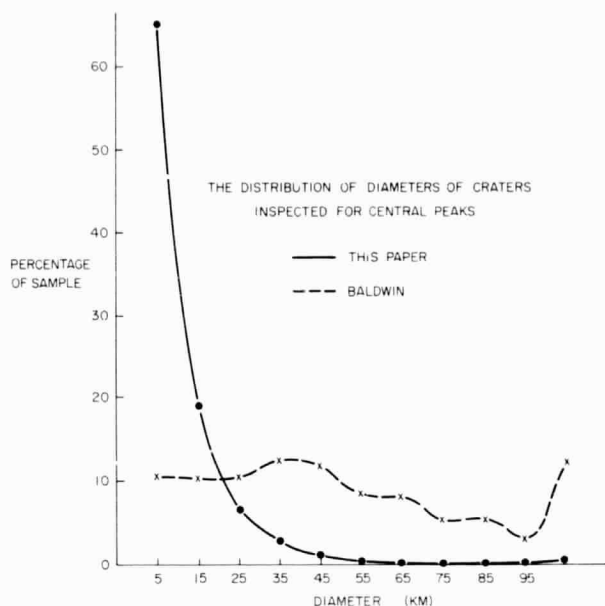


Fig. 1 Comparison of diameter distribution from the catalog, used in this paper, and that used in an earlier analysis of central peak statistics.

exceptionally high percentage is not representative, as may be seen by comparing the diameter distribution of Baldwin's 342 craters with the distribution of diameters in "The System of Lunar Craters." Figure 1 shows that Baldwin's sample is biased in favor of prominent, named craters larger than 20km. Similarly, the search for central peaks by members of the British Astronomical Association, reported by Goodacre, included "generally those [craters] of large diameters," so that his sample was not representative of the entire population of craters either. Young stated the diameter interval for his central peak statistics: 21.1% of 1126 craters between 16 and 208km, and 35.4% of 209 craters between 54 and 208km. At approximately the same intervals the values from "The System of Lunar Craters" statistics are 10% and 25% respectively. The difference is due to Young's sampling procedure: he included only craters conspicuous enough to warrant designations. Such craters are usually large or fresh looking and frequently possess central peaks.

Each crater in "The System of Lunar Craters" was classified on a 1 to 5 scale according to the sharpness and completeness of its rim. Class-1 craters have very sharp, complete rims, while craters whose rims are either blurred or broken are classed as 2 or 3. Ruins are class-4 objects, and class-5 is restricted to ghost craters and other structures so battered or fragmentary that they are not easily recognizable as former craters.

In Figure 2 the percentage of central-peak craters of each class is plotted against crater diameter. It is found that:

- (1) The probability of a crater possessing a central peak increases with diameter.
- (2) For any diameter interval, the percentage of peaks in class-1 craters is greater than for class-2 craters; the percentage of peaked class-2 craters is greater than class-3; etc.
- (3) In each class of craters the percentage of peakedness reaches a maximum at a particular diameter and then remains nearly constant for larger diameters. Above 90km there is a slight decrease in the percentage of central peaks for classes 2, 3, and 4. At these large diameters, unless a crater is relatively "new," it has suffered the overlap of many newer craters which may in some cases have obliterated the peak. There is no decrease for class 1, and the falloff for class 2 is small.
- (4) For all craters irrespective of class the maximum percentage of central peaks (30%) is reached at about 60km. This disagrees with Tyurk's finding (Sharonov 1964) that the maximum frequency of central peaks occurs at 25 to 30km.

If the classification series 1 to 5 indeed represents an age sequence (with class-1 craters being the most recent), and if most of the craters are due to a single process of formation, the implication of (2) could be that craters are normally formed with peaks, but the peaks are destroyed with time. Alternatively, peak formation may have been less likely early in lunar history.

Table 1 presents data bearing on these hypotheses. The ratio of "weak" to "strong" peaks is found to increase with the age of craters (class). This again suggests that weak peaks may have formed as strong peaks which have been "eroded" or that peak formation was favored during the "class-1" period of lunar history. Further, since crater classification is determined by rim sharpness, this result suggests that peak age is highly correlated with crater age.

Using fewer data, Fielder (1965) found that the ratio of weak to strong peaks was not correlated with crater class and concluded that "erosion" has not been an effective peak destroying agent. While this conclusion is not confirmed here, Fielder's observation that both weak and strong peaks occur in craters of various ages is accepted.

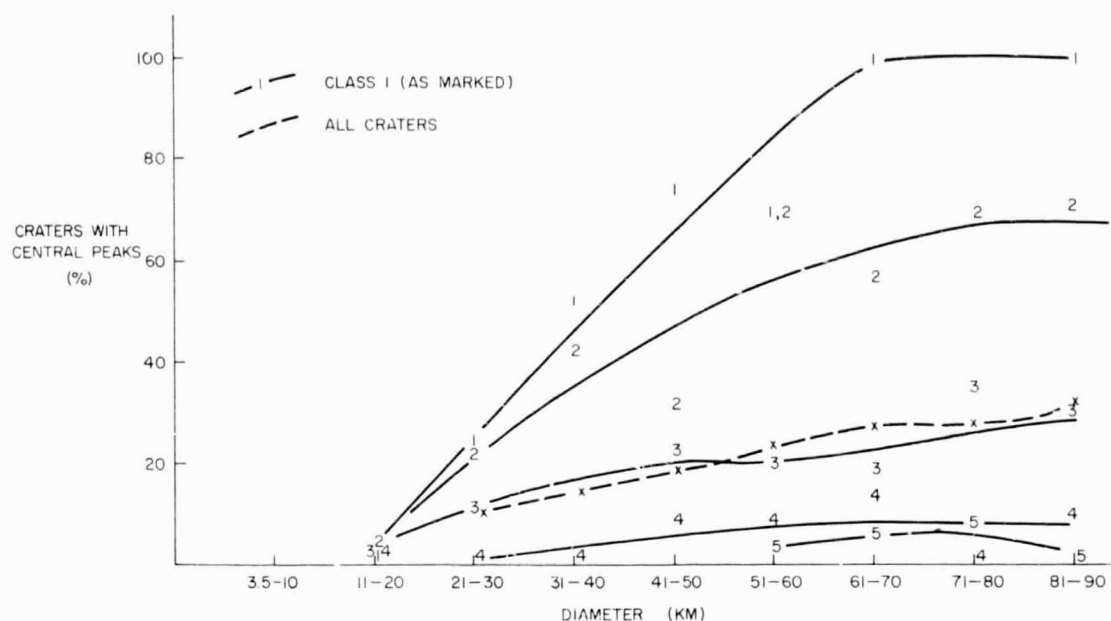


Fig. 2 Systematic trends in central peak frequency as a function of "class," based on crater preservation.

Statement (1) is not unexpected. If craters were formed by impact, the depth of brecciation would be proportional to crater diameter. If peaks are the result of volcanic activity they would be formed only if the fracture zone under the crater extended to an area of magma; hence large craters with their deeper zones of brecciation should have a greater percentage of central peaks than small craters. Similarly if peaks are thought to be rebound structures, the likelihood of peak formation would increase with the strength of the initial explosion, and hence crater diameter. If peaks were uplifted following gravitational slumping of rim material onto the crater floor, this effect also would be more pronounced if the initial explosion were greater, and the crater, larger and deeper.

The percentage of multiple central peaks varies only slightly with class, being 25%, 20%, 21%, and 29% for classes 1, 2, 3, and 4 plus 5. This indicates that single and multiple central peaks were produced in about the same ratio throughout lunar history. However, the multiplicity of peaks is correlated with crater diameter as Table II shows.

TABLE I
RATIO OF WEAK TO STRONG PEAKS

CLASS	WEAK	STRONG	RATIO
1	36	20	1.8
2	124	65	1.9
3	120	45	2.7
4	38	12	3.3
5	8	1	8.0

Table III compares the statistics of central-peak craters with those of all craters in "The System of Lunar Craters" for different age groups or 'backgrounds.' The figures indicate that the fraction of central-peak craters is uniform in different areas. However, this table does not have as much interpretive value as Fig. 2, in terms of lunar history, because *all* craters in the catalog were used ($D \geq 3.5$ km instead of the previous $D \geq 10$ km). This dilutes the sample with small, non-CP craters, and the percentage of CP craters drops from the 7% found earlier to only 3% for *all* craters in the catalog. It does appear, however, that craters with central peaks do not have a unique location, age, or mode of formation. There may be a spread of ages, central peaks being most common in craters formed during the mare-forming epoch or early post-mare time (i.e. including most class-1 craters as found from Figure 2).

TABLE II

DIAMETER INTERVAL	% MULTIPLE CENTRAL PEAKS
0- 50 km	16
50-100 km	34
100-150 km	37
150-200 km	75

TABLE III

CRATER TYPE	TOTAL CRATERS	CP CRATERS	% CP CRATERS
Post-mare	2039 or 11.7%	60 or 12.3%	2.9
Ante-mare	964 or 5.5	26 or 5.3	2.7
Continental	14382 or 82.7	403 or 82.6	2.8

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N 69-12807

No. 121 LUNAR VOLCANIC ERUPTIONS NEAR ARISTARCHUS

by W. K. HARTMANN AND D. H. HARRIS

July 26, 1968

ABSTRACT

The characteristics of five glowing spots observed near Aristarchus by Greenacre, et. al. (and of similar glows reported by Herschel) are shown to be compatible with moderate-sized eruptions of molten material. Orbiter photographs of the area show that at least three of the sites occur near well-defined lava flows, and either open rifts or cone-like structures. None of the sites contains volcanic structures so anomalous or fresh-looking as to be identified as products of a 1963 eruption. Nevertheless, it appears probable that the 1963 events were volcanic eruptions, probably including "fire fountains."

A report by the Aeronautical Chart and Information Center (ACIC 1964) and an additional paper by Greenacre (1965) describe the 1963 observations, by ACIC observers, of transient red spots near Aristarchus. On October 30, 1963, Greenacre and Barr saw three colored spots in the Aristarchus region, indicated as areas 1, 2 and 3 in our Figure 1. The spots were seen in the 24-inch visual refractor of the Lowell Observatory for about 20 minutes. On November 28, 1963, with the same instrument Greenacre, Barr, Dungan, and (Lowell Observatory Director) Hall observed one or possibly two colored spots, 4 and 5, with the more prominent, 4, confirmed by Boyce at the nearby 69-inch reflector of the Perkins Observatory.

The salient features of the phenomena were: (1) estimated intensity of the spots, varying between 5 and 25 percent fainter than the normal background; (2) colors, described in varying instances and at various times, as "reddish-orange," "light ruby-red," "pinkish," and "pinkish-red," at times "quite brilliant;" (3) a "sparkling" appearance in some cases, with barely resolved "downward flowing motion;" (4) durations, from discovery to disappearance, of

20 and 75 minutes and; (5) "deep violet" or "blue" hazes that formed inside and partially circled Aristarchus persisting for about an hour, obscuring and dimming the floor several hours after each observation of red spots.

In an attempt to confirm his visual observations on November 28, 1963 Greenacre took photographs of the area on Panatomic-X SO 136 emulsion using the Lowell 24-inch refractor, and observed visually with the 12-inch guide instrument. Neither set of observations showed any evidence of the color phenomena. The film used, SO 136 (Greenacre, 1968), is sensitive to longer wavelengths than the eye. We believe that the black-and-white film, by virtue of this *red* sensitivity, probably compensated for the relatively decreased integrated *visual* brightness of the spots, rendering the spots undetectable.

All of these observations appear to be qualitatively consistent with the expected appearance of partially-resolved volcanic eruptions. We have therefore attempted to test this idea by calculating the visibility of an assumed lunar volcanic eruption and by studying the regions of reported events on high-resolution Orbiter photographs.



Fig. 1. Aristarchus, Herodotus, and a portion of Schröter's Valley, showing the locations of the five Flagstaff red spots, numbered in order of appearance. Orbiter IV photo, courtesy NASA.

One can test the eruption hypothesis by calculating the area of hot lava required to produce the observed phenomenon. This requires knowledge of the light flux from the observed red spots. In the eruption hypothesis, the flux at the earth from the spots would be due to the "lava," plus reflected sunlight from unresolved adjacent areas. Thus lava eruptions alone can only add to the background intensity, yet Greenacre (1968) reports that the spots were fainter than the normal background. A typical spot was area number 4, on the exterior rim of Aristarchus, where the average of Greenacre's estimates is a deficit of 15% relative to the background. Therefore, we assume that obscuring material was present over the "lava." This is consistent with observations of terrestrial lava eruptions, where eruptions are frequently accompanied by large quantities of obscuring agents ranging in dimension from molecular to cinder-size. The Aristarchus observations give some evidence for the presence of obscuring material. First, there is the violet haze which dimmed and obscured the floor of Aristarchus several hours after

each color phenomenon and second is Greenacre's (ACIC 1964) report of "sparkling" which he later (1965) describes as due to motion of barely resolved white, bright spots, *with the intensity of the adjacent normal surface*, moving downhill inside the colored regions. These could have been areas of normal surface visible through breaks in the obscuring material. The violet haze and bright spots might be used to argue for gas-borne smoke, although such smoke would be brighter than the dark lunar surface and in any case should rapidly dissipate. (Sunlit clouds obscuring eruptions at Halemaumau [WKH-June, July, 1968] strongly scattered blue light, noticeably reddening transmitted light, but were generally brighter than the dark volcanic background.)

Most satisfying as an obscuring agent would be a fountain or enclosing "cloud" of particles. Small particles would be favored on the moon because of the difference between vapor pressure and ambient pressure and because of the violent frothing action of erupted material. The smoke-sized particles produced by condensation would be the most efficient

use of available mass in producing scattering and obscuration. Interparticle shadows among the dark, rapidly cooling particles would contribute to the dark appearance of the red spots. Black-and-white and color plates accompanying *Comm. L.P.L.*, 3, No. 49 (Kuiper 1965) are instructive in this regard. It can be seen that the glowing red fountain of lava and cooling cinders appears no brighter than the background rocks in the black-and-white photographs.

If we assume for purposes of calculation the simplest model, with neutral absorption from particles of albedo similar to the background, and with a low optical depth, then the light from the red spots would be a mixture of twice-absorbed sunlight from the surface and once absorbed blackbody radiation from the "lava." For a transmission of the obscuring "cloud" of 67% (comparable to the terrestrial case), a red spot observed to be 15% fainter than the background (spot 4) would have thermal radiation (from lava over an undetermined fraction of the area) amounting to 61% of the ordinarily reflected sunlight. Using the photometry of Gehrels, Coffeen, and Owings (1964) we find the ordinary background intensity is 4.7 mag/ (arc sec)². Thus the intensity of the unobscured lava is 5.2 stellar magnitudes per arc second square. As will be seen, the conclusions of this paper are not extremely sensitive to the uncertainty of this estimate.

Given the intensity of the "lava" we may calculate the area required to produce that intensity. This calculation may be made by comparing the visual intensities of the sun and the spots. Let,

- F = visual flux at the observer (ergs/cm²sec),
- T = temperature of radiating surface (°K),
- a = absorptivity of the radiating surface,
- f = fraction of the flux at all wavelengths visible to the eye,
- A = area of visible radiating surface (cm²),
- m = apparent visual magnitude of the entire source,
- r = distance of source (cm),
- C = solar constant (ergs/cm²sec),

and let the subscripts L , $\odot$, and $\ominus$ refer to "lava," moon, and sun. Then the ratio $F_L/F_\odot$ given by $(m_\odot - m_L)$ can be also expressed in terms of A_L and C . Solving for A_L gives

$$A_L = \frac{\pi r^2 \zeta C}{\sigma T_L^4 a_L \cos \zeta} \frac{f_\odot}{f_L} 10^{0.4(m_\odot - m_L)}. \quad (1)$$

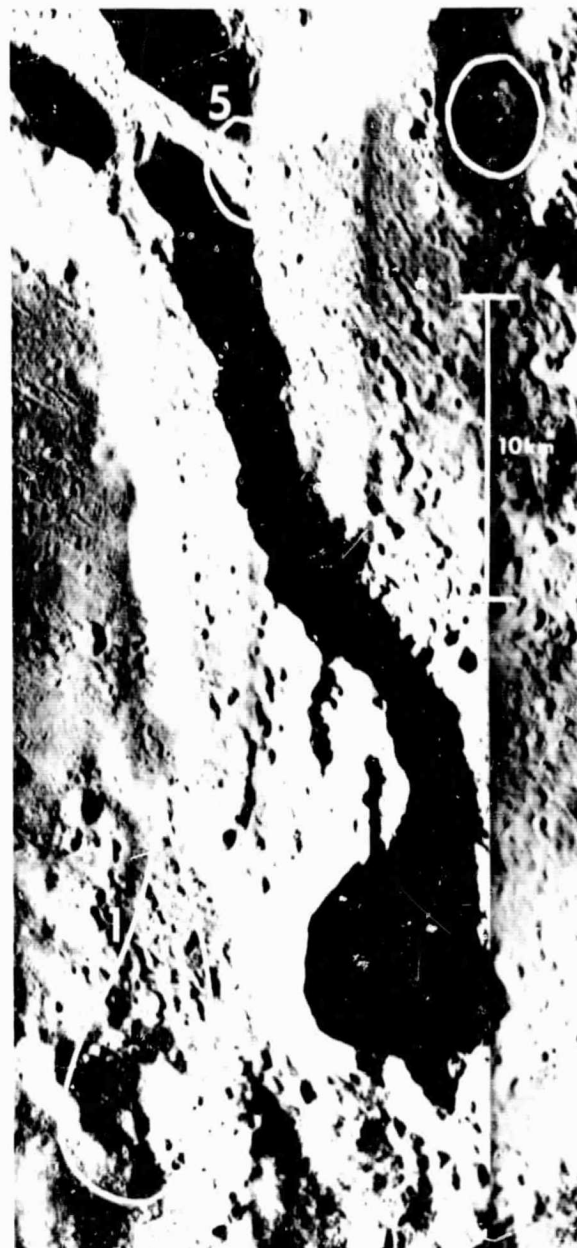


Fig. 2 Head of Schröter's Valley. White lines lie just outside the boundaries of the red-spots as mapped by ACIC (1964). Orbiter V photo, courtesy NASA.

The solar constant, the sun's magnitude, and the moon's distance are well known. Values for the temperatures of erupting terrestrial lavas are in the range 1300–1700 K (Rittmann 1960). For convenience we assume $T_L = 1580$ K (because the bolometric correction is available). We take the absorptivity, a_L , of the volcanic material to be 0.80. The ratio $f_\odot/f_L$ is just the ratio of the inverse bolo-

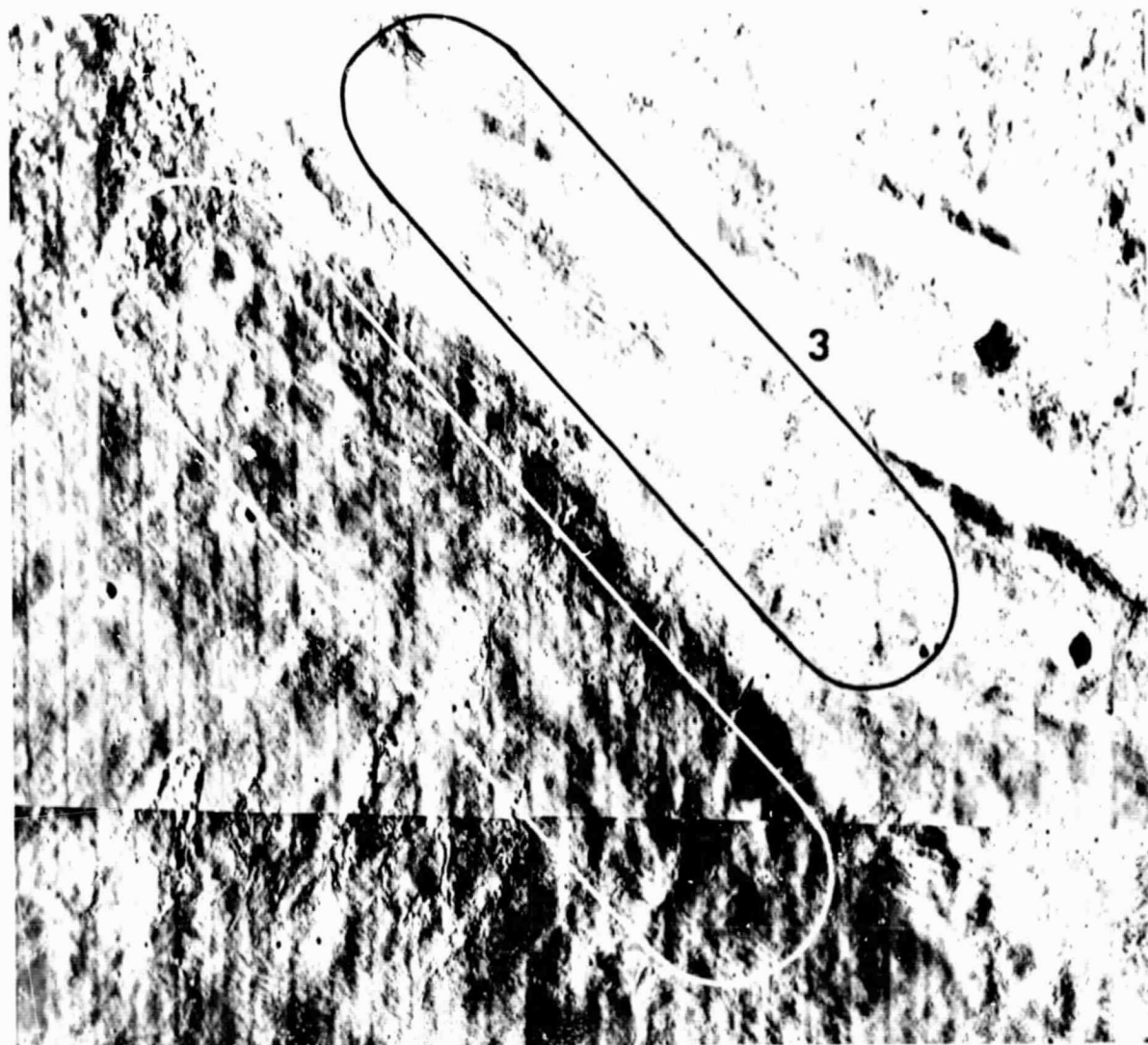


Fig. 3 Southwest rim of Aristarchus. Black and white lines lie just outside the "streak" boundaries by ACIC (1964). Between the two streaks, on the rim, are three fissures. Orbiter V photo, courtesy NASA

metric corrections at 5750 K, and is here taken to be 450 (Allen 1963). To find the magnitude of the "lava," we integrate the intensity [$5.2 \text{ mag}/(\text{arc sec})^2$] over the area, again taking spot 4 as representative. The area is $4.1 (\text{arc sec})^2$, yielding a magnitude, m_l , of 3.7. The smaller spots were typically two to three times smaller, with a somewhat higher surface brightness.

It is of some interest that this calculation of the magnitude of the source in the Flagstaff observations comes very close to the estimate of "4th magnitude" made by Herschel when he observed what he thought was a volcanic eruption on the unilluminated moon near Aristarchus (Middlehurst 1964).

Substituting the above values into equation (1), we derive an area of about $8.1 (10^9) \text{ cm}^2$, comparable to a square 0.9 km on a side of *glowing* material. This constitutes an acceptable fraction of the observed area and is entirely acceptable as a dimension of an eruption. Areas of 19 historic flows in Hawaii tabulated by Stearns (1966) range from 5 km^2 to 90 km^2 , and fire fountains there commonly reach kilometer scale in length. Rittmann (1962) notes that the Icelandic fissure eruption of 1783 was 25 km long, at it may be compared with the "streaks" on the Aristarchus rim.

The observed area of spot 4 was about 18 km^2 . Literally interpreted, our result suggests that a small

fraction (about 4½%) of the colored area was actually covered by glowing material. However, it must be noted that changes in the assumed temperature (within the range 1300 to 1700°K) cause large changes in both the luminosity and the bolometric correction ratio. Such changes, along with the uncertainty in the unobscured brightness, give our area calculation an uncertainty of about a factor of 10. The calculated dimensions could thus cover a range comparable to that observed on earth. We conclude simply that the calculation demonstrates the compatibility of the reported observation with a volcanic eruption on the moon. The other areas as mentioned above were generally smaller and more intense, although spot 3 is comparable in area to spot 4 but less prominent (only 5% below background intensity). All of the observed areas appear to be compatible with lava eruptions.

In view of this conclusion it is important to search the Orbiter photographs of the region for evidence of recent volcanic activity.

Figures 2 and 3 show in greater detail the red spot areas. The spot positions shown have been carefully transferred from the ACIC (1964) map of the events. We believe the positions are accurate to within two kilometers (the marked boundaries in Figures 2 and 3 lie just outside the edges of the reported spots).

Area 2 occurs in a 3km crater-like depression near the rim of a scarp (as shown by Orbiter stereo views). Neither this area nor the doubtful area (5) on the rim of Schröter's valley show any distinctive or diagnostic volcanic structures.

Area 1, on the other hand, contains an unusual and distinctive dome-shaped hill with a summit pit. This structure lies at the apparent source of the "white, bright" spots (see above) which had the "flowing motion." Greenacre and Barr (ACIC 1964; Greenacre 1965) noted the feature's dome-like shape which has been confirmed using Orbiter stereo views. The dome is gently sloped, not as steep as a terrestrial cinder cone, and is part of a larger ridge extending NW-SE. The rim of the summit pit appears to be the highest point on the ridge. To the northeast (the direction of the flowing motion of the "small, bright, white spots") lies a complex of features reminiscent of flows and flow channels. Figure 4 shows the area in detail.

Areas 3 and 4 were described as "streaks" and parallel the crest of the Aristarchus rim on either side. The Orbiter photographs show that this part of the rim is broken by three radial fissures connect-



Fig. 4 Dome and flow structures associated with spot 1. The dome is marked in the margin.

ing unusually clear flows that run down the outer (southwest) wall (see Figure 5). The three open fissures, though perpendicular to the length of the red streaks, lie on a line parallel to the streaks.

Area 3, on the inner rim, did not show the flow-



Fig. 5 The rim of Aristarchus showing two fissures and associated flow structures. Aristarchus interior is at the top.

ing motion that characterized spots 1 and 2. It consisted rather of individual "pink streaks" paralleling the numerous concentric scarps and stepped faults of the wall's inner slope. In contrast, spot 4 was described as a "pinkish-red streak" with a "more intense reddish-orange" spot "near the southern extremity." A complex of flows lies in the later area (Figure 5).

Of the four well established red spots, then, three appear to be associated with structures of unusual nature. We infer that these structures, a low cone, flows, and fissures, are volcanic. The flow structures are obvious, with well defined boundaries, and appear similar to terrestrial lava flows. It has long been suspected that dome-shaped structures on the moon are volcanic; there is striking similarity to low cones and small shield volcanoes on the earth.

Further interpretation becomes somewhat subjective. It is perhaps surprising that none of the structures appears unusually fresh. We cannot claim detection of any structure that appears only five years old, nor do we find any highly discolored spots (although the area of the cone in area 1 appears somewhat darker than the surroundings). For these reasons we suspect that the 1963 events did not deposit any great volumes of material. Rather, a brief fire-fountain type of pyroclastic eruption might widely disperse cinders and ash (especially on the moon), producing a visible flare without noticeably deforming the surface. The expected small particle size, discussed above, may also contribute to a fresh deposit's anonymity.

We conclude that the Flagstaff observations almost certainly represent volcanic eruptions on the moon, that at least three of the four definite red

spots can be shown to have occurred in areas of demonstrable past volcanic activity, and that the 1963 eruptions were probably genetically associated with these older vents. It should not be inferred that this evidence establishes the volcanic origin of larger associated features, such as Aristarchus. While many local structures, e.g. Schröter's valley, sinuous rilles, and the many domes and flows are undoubtedly endogenous, the rims of larger craters (of whatever origin) would be expected sites of eruptive activity because of known slump faulting, subsurface brecciation, and maximized isotatic instability (especially if the region is already tectonically active).

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No. 122 MINOR PLANETS. I. THE ROTATION OF VESTA*

by THOMAS GEHRELS

July 17, 1967

ABSTRACT

A set of 13 light curves for 4 Vesta was obtained between November 1958 and May 1959. The set is compared with light curves observed in 1950 (by H. L. Johnson), in 1952 (D. L. Harris), in 1954 (L. Binnendijk), and 1967 (this paper). The speed as well as the sense of rotation are derived from the effect of aspect change on the apparent rotational period ("photometric astrometry"). The rotation is direct, the true period is $5^h20^m31^s.665 (\pm 0^s.003 \text{ p.e.})$, and the ecliptic longitude and latitude of the north pole are $126^\circ (\pm 5^\circ)$ and $+65^\circ (\pm 4^\circ)$. Vesta differs from the other asteroids in that its light curve has only one maximum and one minimum, indicating a nearly spherical shape for Vesta with a darker, and slightly bluer, region on one side. The brightness-phase function shows a nonlinear increase near opposition ("opposition effect"). The colors $B-V$ and $U-B$ increase with the orbital phase angle (reddening with phase).

1. Observations

PHOTOELECTRIC observations of Vesta have been made by Hall (1940), Giclas (1951), Stephenson (1951), Cuffey (1953), Johnson and Harris (Groeneveld and Kuiper 1954), Binnendijk (unpublished), Haupt (1958), and Chang and Chang (1962). The previous work is inconclusive, especially as to whether Vesta's light curve has one or two maxima. Therefore, Vesta was observed during 13 nights in 1958/59, and an additional light curve was obtained in 1967. The sense of rotation and the true period of rotation are determined in Secs. II-IV. In Sec. V, the light curves are intercompared in order to obtain the brightness-phase relations at three wavelengths.

The observations were made with the 91-cm Cassegrain reflector at the McDonald Observatory, 5 November 1958-10 May 1959. In addition the McDonald 208-cm reflector was used on 2 November and 24 January. One more light curve was obtained, on 10 April 1967, with the 53-cm Catalina reflector situated near Tucson, Arizona.

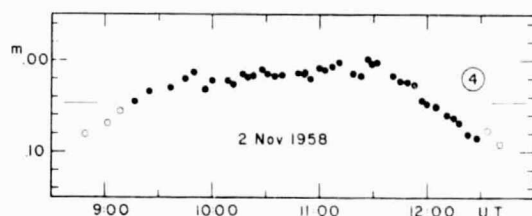
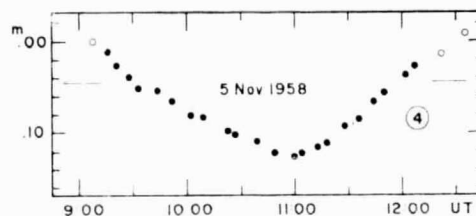
A standard UBV photometer is used with an RCA 1P21 photomultiplier that is cooled with dry ice. The light curves are made, with the V filter, by comparison with a nearby star about once every 6 min. The calibration is made at least three times per light curve with a " UBV transfer," consisting of observations of a red

and a blue UBV standard star. The light-curve intensities are read from a strip chart or, more recently, from the printout of a system with a digital voltmeter and papertape punch (shown in Fig. 1 of Coyne and Gehrels 1967). Extensive use is made of the computer equipment of the Numerical Analysis Laboratory at the University of Arizona. Further details of the observations and reductions have been described by Groeneveld and Kuiper (1954) and by Gehrels and Owings (1962); the present series of papers is a sequel to that work, published in this Journal, which has the

TABLE I. Summary of observations of 4 Vesta.

Obs. date 1958/59 UT	Mean V (mag)	$B-V$ (mag)	$U-B$ (mag)	Mean V corr. to unit dist. (mag)	Figure
2 Nov.	7.880:	...	...	4.045:	1
5 Nov.	7.847	+0.793	+0.503	4.050	2
	$\pm .002$	$\pm .0014$	$\pm .0017$	$\pm .002$	
11 Dec.	7.211	.795	.491	3.933	3
19 Jan.	6.354	.771	.458	3.489	4
24 Jan.	6.232	.763	.455	3.384	5
26 Jan.	6.211	.755:	.446:	3.369	6
28 Jan.	6.227	.761	.452	3.387	7, 8
31 Jan.	6.290	.766	.453	3.452	9
5 Feb.	6.407	.768	.468	3.562	10
20 Feb.	6.695	.783	.492	3.777	11
25 Feb.	6.780	.786	.495	3.823	12
6 May	7.809	.802	.522	4.087	13
10 May	7.852:	+0.802	+0.518	4.092:	14

*Reprinted from *Ast. J.*, Vol. 72, No. 8, Oct. 1967.

FIG. 1. Observations at -23° phase.FIG. 2. Observations at -23° phase.

same format as that of the *Communications of the Lunar and Planetary Laboratory*.

Table I gives some details of the observations on

Vesta. "Mean V " is the visual magnitude that has equal areas—over one cycle—enclosed by the light curve above and below the line of "Mean V ." This is

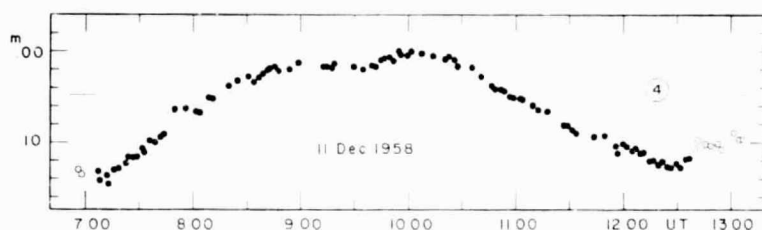
FIG. 3. Observations at -19° phase.

TABLE II. Aspect data for Vesta.

Obs. date UT	Phase angle	Distance from sun (a.u.)	Distance from earth (a.u.)	Light time	R.A. 1959	Dec. 1959	Ecliptic		Phase shift
							Long. 1950	Lat. 1950	
58.11.02	$-23^\circ 05'$	2.533	2.3086	0 ^h 013.332	8 ^h 42 ^m 7	+18°24'	128°06'	+0°17'	-12°25'
	$\pm .03$	$\pm .001$	$\pm .0001$	$\pm .000$ 001	$\pm .1$	± 1	$\pm .03$	$\pm .02$	$\pm .04$
58.11.05	-23.00	2.532	2.2687	13 102	8 45.5	+18 19	128.73	0.27	-12.20
58.12.11	-18.51	2.511	1.8023	10 408	9 03.5	+18 42	132.72	1.76	-8.62
59.01.19	-3.77	2.484	1.5067	8 700	8 42.4	+22 23	126.98	4.02	-0.54
59.01.24	-1.94	2.480	1.4963	8 641	8 37.4	+22 57	125.72	4.27	-0.09
59.01.26	1.73	2.478	1.4943	8 630	8 35.5	+23 10	125.20	4.36	...
59.01.28	$+2.10$	2.477	1.4930	8 622	8 33.1	+23 25	124.63	4.45	+0.11
59.01.31	$+3.19$	2.474	1.4936	8 626	8 30.0	+23 44	123.86	4.69	+0.36
59.02.05	$+5.46$	2.471	1.5000	8 663	8 24.7	+24 14	122.55	4.79	+1.13
59.02.20	$+12.22$	2.458	1.5599	9 008	8 11.2	+25 24	119.29	5.24	+4.48
59.02.25	$+14.22$	2.454	1.5917	9 192	8 07.9	+25 39	118.51	5.32	+5.68
59.05.06	$+24.65$	2.390	2.3245	13 424	8 39.3	+23 58	125.86	5.36	+13.65
59.05.10	$+24.67$	2.386	2.3685	13 678	8 44.2	+23 38	127.04	5.32	+13.66
67.04.10	-17.93	2.178	1.3259	0.007 657	16 01.5	-10 09	240.22	+10.29	-8.21

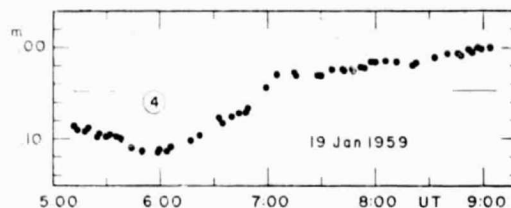
TABLE III. Comparison stars and quality of nights.

Obs. date 1958/59 UT	R.A. 1959	Dec. 1959	V (mag)	$B - V$ (mag)	Scatter of comp. readings (mag)	Remarks
2 Nov.	8 ^h 42 ^m 8	+18°30'	9.866	+0.945	± 0.004	
	$\pm .2$	± 3	$\pm .002$	$\pm .002$		
2 Nov.	8 43.0	18 30	9.000	0.412	...	
5 Nov.	8 45.7	18 12	9.229	0.455	.003	
11 Dec.	9 03.2	18 54	8.736	1.572	.004	
19 Jan.	8 44.2	22 29	8.198	0.235	.003	Cloudy
24 Jan.	8 36.7	22 57	9.227:	1.015:	.003:	Cloudy
26 Jan.	8 35.7	23 15	9.879	1.310:	.005	Stopped by clouds
28 Jan.	8 32.2	23 20	9.830	0.490	.002	a
31 Jan.	8 30.0	23 54	8.625	0.514:	.005	Clouds about
5 Feb.	8 24.6	24 06	10.339	0.489	.005	
20 Feb.	8 10.8	25 24	9.190	1.055	.003	
25 Feb.	8 08.0	25 38	5.718	0.823	.002	
6 May	8 38.9	24 08	10.370	0.960	.003	
10 May	8 42.3:	+23 38:	10.988:	+0.837	± 0.003	Clouds about

* Asteroid passed a 12th mag star, 2:50-4:00 UT.

determined by planimetry for the light curve of 28 January 1959, and the position of "Mean V " is given by the horizontal thin line in Fig. 7. Next, with the epochs of Table X (see Sec. V) and by superposition of Fig. 7 on the shorter light curves, the position of the horizontal line is found for the other figures. The calibration is with UBV transfers to standards in the Praesepe cluster (Table I of Gehrels and Owings 1962). No UBV calibration was made on 10 April 1967. The correction to unit distances in Table I is with $5 \log r \rho$, where r is the distance of the asteroid to the sun and ρ that to the earth (Table II). Whenever possible, probable errors are given in the tables.

Table II gives various data for Vesta at the epochs listed in the second column of Table IV. The orbital phase angle is computed with Method B of Gehrels (1957); the values differ appreciably from those in the *Ephemerides*. The first column lists F , the displacement of the center of light on the apparent disk due to the effect of phase, for 90° latitude of the pole (see Sec. III).


 FIG. 4. Observations at -4° phase.

January (Fig. 7) has a thin vertical line that defines an epoch of maximum at $6^h 47^m 00$ UT (uncorrected for light time). By fitting this curve onto the individual ones of other dates, the epochs of maximum light are found. This fitting of the curves had as principal requirement that the horizontal time axes be parallel, with the assumption that the comparison star is not variable and neglecting the brightness change with phase during the night.

The light curve becomes steeper at larger phase angles

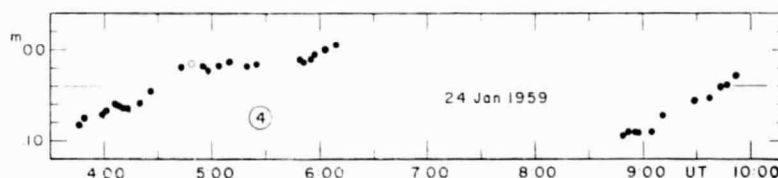

 FIG. 5. Observations at -2° phase.

Table III gives various data for the comparison stars. Under "Scatter of Comp. Readings," the table gives the average deviation from a smooth curve of comparison-star magnitudes versus time. Checks were made for variability of the comparison stars by plotting the results of their UBV transfers as a function of time. No conclusive evidence of variations was found, but there is some doubt in the case of the stars used on 11 December and on 10 May.

Figures 1-15 show the various light curves. The ordinates are in magnitudes, and the abscissas in Universal Time without correction for light time. Each point is the average of two, or sometimes four, integrations lasting about 30 sec each. Open circles are used when the probable error is greater than about three times that of the nightly average.

2. Sense of Rotation

Table IV gives observed epochs of maximum light in the second column. The long light curve of 28

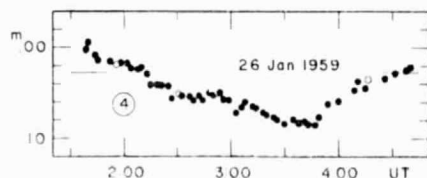


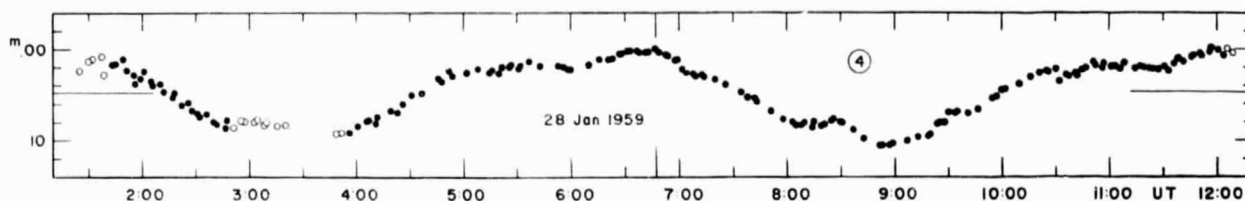
FIG. 6. Observations of Vesta made on the night of opposition, 26 January 1959.

(see Sec. V). Because of the systematic changes with phase, only *adjacent* light curves and epochs are used to derive periods of rotation.

An approximate period of rotation is derived from the light curve of 28 January; it is either $5^h 20^m$ or $10^h 41^m$. With a second approximation, determined from adjacent light curves, $P_{syn} = 5^h 20^m 4$ or $10^h 40^m 8$. The short light curves usually can be fitted to more than

TABLE IV. Observed epochs and synodic periods.

Obs. date 1958/9 UT	Observed UT	JD(c) 2436000+	Interval	No. of cycles	P_{syn}
2 Nov.	11 ^h 23 ^m 5	509 ^d 9613	3 ^d 1155	14	0 ^d 222 536
	$\pm .5$	$\pm .0003$	$\pm .0005$		
5 Nov.	14 09.4	513.0768	35.6201	160	626
11 Dec.	4 58.5	548.6969	39.1751	176	586
19 Jan.	9 08.2	587.8720	4.8927	22	396
24 Jan.	6 33.6	592.7647	1.7830	8	874
26 Jan.	1 21.1	594.5477	2.2263	10	631
28 Jan.	6 47.00	596.7740	3.1160	14	571
31 Jan.	9 34.0	599.8900	4.8980	22	637
5 Feb.	7 07.2	604.7880	15.1350	68	573
20 Feb.	10 22.1	619.9230	4.8981	22	643
25 Feb.	7 55.7	624.8211	69.9053	314	628
6 May	5 45.4	694.7264	4.0051	18	0.222 504
10 May	5 53.1	698.7315			

FIG. 7. Light curve of Vesta observed at $+2^\circ$ phase.

one part of Fig. 7, giving various epochs. One of the epochs is chosen such that there is an even number of cycles in Table IV, allowing solutions for the double period as well as for the single.

Table IV next gives the derivation of the apparent periods of rotation. The Julian day numbers are listed after correction for light time (Table II). The number of rotation cycles for each interval is found using the above period of $5^h 20^m 4$. For illustration, the shorter period is adopted in Table IV, but the question of single or double period is not resolved until Sec. III.

Table V shows the effect of a change in longitude—

change in aspect—on the synodic period. First, the weighted average of the periods is taken over intervals that have an increase in longitude; namely, 2 November–11 December, 5 November–11 December, 20 February–6 May, and 25 February–10 May. The weighting is done with the number of cycles. The second group in Table V, with longitude decreasing, gives the weighted average synodic period of the eight adjacent intervals between 11 December and 25 February.

The difference between the two mean periods of Table V is about 30 times the probable error. With a high confidence level, therefore, it can be stated that

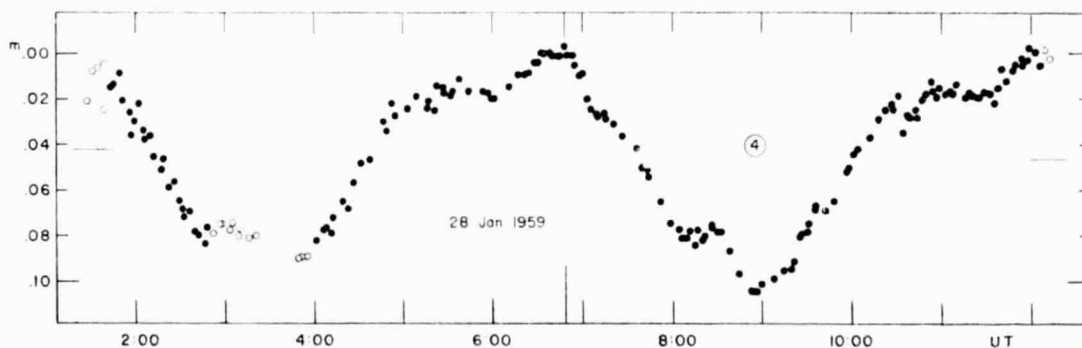


FIG. 8. As for Fig. 7, plotted on an expanded ordinate scale.

the rotation of Vesta is *direct*, which is the same sense of rotation as that of the earth, for instance. For retrograde rotation, the lower period in Table V would have been the larger one.

3. Speed of Rotation

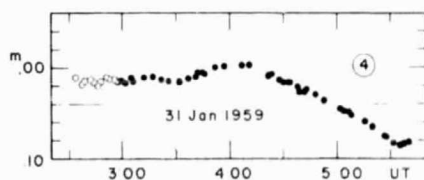
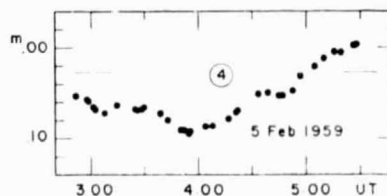
Let an epoch—of maximum light, for example—be denoted by E , its ecliptic longitude by λ , the following epoch by E' at longitude λ' , and the number of cycles between them by N . The number of cycles is increased for direct, and decreased for retrograde, rotation when

the longitude is increasing. For direct rotation, provided β_0 , the ecliptic latitude of the pole, is equal to 90° ,

$$(E' - E) = \left[N + \frac{(\lambda' - \lambda)}{360} + \frac{(F' - F)}{360} \right] P_{\text{true}}, \quad (1)$$

while for retrograde rotation the two plus signs are replaced by minus signs.

In addition, there is a shift due to the change in phase. At small phase angle α , the illuminated part of the projected disk of a spherical body (unit radius)

FIG. 9. Observations at $+3^\circ$ phase.FIG. 10. Observations at $+5^\circ$ phase.

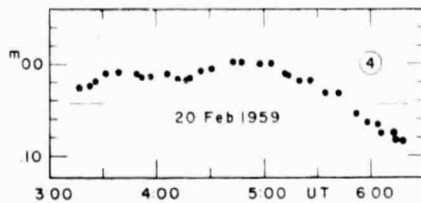


FIG. 11. Observations at +12° phase.

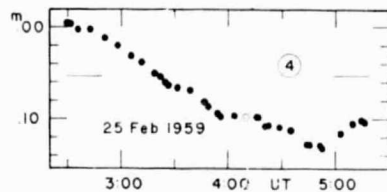


FIG. 12. Observations at +14° phase.

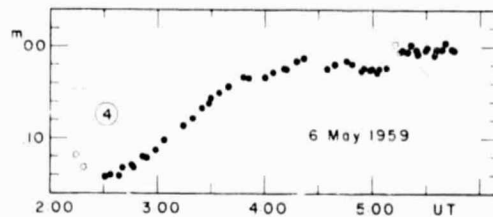
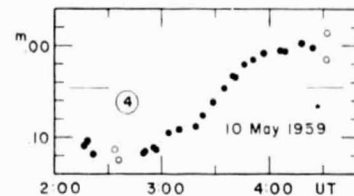


FIG. 13. Observations at +25° phase.

FIG. 14. Observations at +25° phase.



still is approximately circular with apparent radius of $1 - \frac{1}{2}(1 - \cos \alpha)$. For isotropic scattering, the center of light would be shifted by f degrees, where $\sin f = \frac{1}{2}(1 - \cos \alpha)$. For scattering predominant in the backward direction, the center of light would be shifted by α degrees. The asteroidal scattering law is intermediate, and an intermediate function F is defined,

$$F = \{[I(0) - I(\alpha)]/I(0)\}(\alpha - f) + f. \quad (2)$$

The relative intensities at various phase angles, $I(\alpha)$, are computed with Table XI; $I(0)$ is actually taken at 1.5 phase. The results are listed in the last column of Table II. Before opposition the phase angle is defined with negative values and so is the phase shift in Table II.

When $\beta_0 \neq 90^\circ$, the longitude differences, $(\lambda' - \lambda)$, are replaced by differences in L ,

$$\sin L = \cos \beta \sin(\lambda - \lambda_0) / \cos B, \quad (3)$$

$$\sin B = \sin \beta_0 \sin \beta + \cos \beta_0 \cos \beta \cos(\lambda - \lambda_0), \quad (4)$$

where λ and β are the ecliptic longitude and latitude of observation, and λ_0 and β_0 are the ecliptic longitude and latitude of the pole. Similarly, one could derive a differential relation for the phase-shift corrections, $(F' - F)$. We actually use a mechanical coordinate converter designed by Dr. G. Van Biesbroeck.

Approximate values of λ_0 and β_0 are first obtained from a plot (Gehrels and Owings 1962) or analytic expression (Cailliatte 1956) for amplitude versus longitude of light curves observed in various years; the amplitude is the largest when the asteroid is seen equatorially and the least when observed pole-on. Next, values of λ_0 and β_0 are tried in the above expressions in order to have all intervals yield the same, true, period.

Table VI gives the rotation period computed first with expressions (1) and (2). The first line gives the weighted mean of the periods computed for the 12 intervals of Table IV, weighted with the respective number of cycles. In the second line is the weighted mean residual, without regard to sign, of the individual periods with respect to the mean of the first line. Under "Direct Rotation," the analysis is made with the plus signs in expression (1), and with minus signs for the last two columns. Under "single" the computation is made with the number of cycles shown in Table IV, while under "double" half that number is used.

There are some indications that Vesta has the period of about $0^d 2226$, or $5^h 20^m$, with single maximum and minimum. In the light curves of Figs. 1-14 no systematic difference between the one maximum (or minimum) and another can be found. Furthermore, the time difference between consecutive maxima and

FIG. 15. Observations made in 1967.

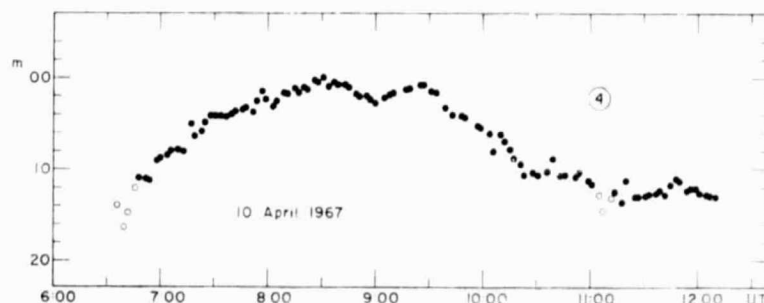


TABLE V. Period changes with longitude.

When the longitude	No. of cycles used	No. of epochs used	$\bar{P}_{syn}$	Difference
Increases	501	7	0.222 624	0.000 038 ± 1
Decreases	342	9	0.222 586	

minima appeared to be about 5^h20^m , at all times that this could be checked. The principal criterion, however, is the extent to which expressions (1) and (2) describe the importance of the longitude and phase corrections relative to the speed of rotation. The residual, $|\bar{\Delta}|$ in Table VI, is the smallest for the first of the four cases. $\bar{P}_{sid,incr}$ and $\bar{P}_{sid,decr}$ are determined by groupings exactly as for the two periods of Table V. It is seen that the periods are about the same only in the first case. In the other three cases, expressions (1) and (2) did not describe the physical situation as the two periods differ by amounts much larger than the precision ($\pm 0.000\ 001$). It is of interest to compare each value of $\bar{P}_{sid,incr}$ and $\bar{P}_{sid,decr}$ with its value of $\bar{P}_{sid}$ (first line of Table VI) in order to see the overcorrection or lack of correction. It is noted, however, that even in the first case the two periods differ appreciably. In the lower part of Table VI, therefore, the computations are repeated with expressions (3) and (4) using the longitude and latitude of the pole of expressions (5) and (6).

In summary, Vesta's light curve has the shorter period. Additional proof is found with Table VII, below, where the observations of various years can only be fitted together with the short period and direct rotation.

4. Orientation of the Pole

Table VII gives the comparison of observations made at seven different longitudes. Johnson's light curve, at longitude $36^\circ33'$ and latitude $-7^\circ55'$, was superposed on the present Fig. 8; the epoch of maximum defined at 6^h47^m00 of 28 January 1959 UT is found to occur at 3^h26^m0 ($\pm 0^m9$ p.e.) of 22 December 1950 UT. Incidentally, an error was found in the

TABLE VI. Attempts at finding the rate and direction of rotation.

	Direct rotation		Retrograde	
	single	double	single	double
$\bar{P}_{sid}$	0.222 588	0.445 140	0.222 625	0.445 285
$ \bar{\Delta} $	.000 024	.000 039	.000 042	.000 108
$\bar{P}_{sid,incr}$	.222 595	.445 130	.222 654	.445 367
$\bar{P}_{sid,decr}$	.222 586	.445 171	.222 586	.445 171
$\bar{P}_{sid}$	.222 586	.445 131	.222 627	.445 295
$ \bar{\Delta} $	.000 021	.000 049	.000 046	.000 124
$\bar{P}_{sid,incr}$	.222 589	.445 107	.222 660	.445 390
$\bar{P}_{sid,decr}$	0.222 587	0.445 179	0.222 584	0.445 163

TABLE VII. Period determinations, for 90° latitude of the pole.

Epochs	Interval	No. of cycles	Period
50.12.22-59.02.25	2987.1888	13420.2216	0.22258 863 (± 7)
52.03.07-59.01.28	2517.8997	11311.9136	831 (± 7)
54.12.21-67.04.10	4493.2677	20186.4137	871 (± 9)
58.12.11-67.04.10	3041.9665	13666.2998	0.22258 889 (± 5)

original records for Fig. 1 of Groeneveld and Kuiper (1954): a point plotted at 3^h30^m4 UT was actually observed at 3^h26^m0 UT. The "Interval" in the second column of Table VII is listed after the usual correction for light time and a nearly negligible correction to Ephemeris Time. Similarly, by superposition of the original light curve worksheets, the epoch of maximum is found to occur at 9^h10^m5 ($\pm 0^m4$) of 7 March 1952 UT, and 9^h25^m2 ($\pm 0^m9$) of 10 April 1967 UT. The 1952 light curve was obtained by Harris (Fig. 2 of Groeneveld and Kuiper 1954) at longitude $155^\circ26'$ and latitude $+10^\circ15'$.

I am indebted to Dr. L. Binnendijk for sending his unpublished observations made on 21 December 1954, at the Cook Observatory in Pennsylvania. The longitude (1950) is $82^\circ90'$, the latitude $-3^\circ70'$, and the epoch of maximum is found to occur at 2^h59^m ($\pm 2^m$) UT. The combinations of epochs in Table VII are selected such that the phase corrections are at a minimum. In the third interval, however, there is an

TABLE VIII. Period^a determinations for various latitudes and longitudes of the pole.

Lat. β_0	Long. λ_0	For the epochs of Table VII:				$\bar{P}$	$ \bar{\Delta} $
		1950	1952	1954	1958		
72°	118°	866	849	863	880	868	10
	128	875	848	861	876	868	10
	138	882	848	860	870	867	10
62	118	863	865	857	884	872	11
	128	880	868	854	875	872	6
	138	895	864	852	857	866	13
52	118	858	886	852	894	879	16
	128	888	896	846	869	876	14
	138	915	897	842	841	869	32
72	348	863	835	871	892	871	19
	358	864	834	871	891	870	18
	368	864	833	872	891	870	19
62	338	872	843	869	890	873	15
	348	873	841	870	885	871	13
	358	875	837	869	881	869	14
52	328	872	857	865	887	874	11
	338	888	855	863	877	873	10
	348	892	849	864	867	868	10
45	318	864	868	861	909	884	22
	328	885	873	857	882	877	7
	338	891	867	858	864	870	9
40	318	885	884	858	909	892	15
	328	898	885	853	875	879	11
	338	917	878	854	852	872	22

^a Only the last three decimals are listed; 866, for instance, stands for $P=0.22258\ 866$.

TABLE IX. Longitudes* (and latitudes) on Vesta, for five dates and two combinations of latitude and longitude of the pole.

Lat β_0	Long λ_0	50.12.22	52.03.07	54.12.21	59.01.28	67.04.10
65°	126°	94° (+ 7°)	214° (-32°)	135° (-14°)	179° (-30°)	296° (0°)
45	331	247 (-11)	5 (+34)	283 (+18)	327 (+35)	82 (-7)

* These are differential longitudes of the center of the hemisphere that gives the light curve maximum when it has the earth in its zenith, with respect to the longitude of the pole.

appreciable difference in phase angle between the two epochs, and a correction of -0.0010 was made to allow for the change in the light curve with phase (shown in Fig. 16).

Chang and Chang (1962) observed Vesta in 1958 and 1961 at the Purple Mountain Observatory. These observations came to my attention after completion of this paper. The 1961 observation should be combined with a light curve to be made at $+9.1$ phase in 1968 (see Sec. VI).

With Table VII, an important conclusion is reached, namely, that no consistency of the periods can be obtained for the other categories of Table VI: "single, retrograde," etc. None of these attempts succeeded.

The cycles in Table VII are computed with expressions (1) and (2), and the periods, therefore, are for the case of $\beta_0 = 90^\circ$. It is seen that the periods differ by amounts appreciably larger than the probable errors. Although the amplitudes of light curves observed at various longitudes differ only slightly, it is enough to indicate some deviation from $\beta_0 = 90^\circ$, namely with longitude of the pole near 130° or 310° . The analytical method of Cailliatte (1956), for the relation between light-curve amplitude and aspect, was used by Chang and Chang (1962), resulting in a longitude of the pole at 303° and the latitude at $+74^\circ$. The present method is independent of any assumptions regarding the shape of the asteroid and the relationship between amplitude and aspect. Whereas Table VII gives $\bar{P} = 0.222\ 588\ 68$ and $|\bar{\Delta}| = 0.000\ 000\ 19$, this residual is to be reduced to about $0.000\ 000\ 05$ by the proper choice of longitude and latitude of the pole. Provided that sufficient observations are available, at the proper phase angles (see Sec. VI), the present method appears to be more precise, and it definitely resolves whether Vesta's light curve has one or two maxima.

Table VIII gives the last three significant decimals of the period computed for various trial values of λ_0 and β_0 . The calculations are for the four intervals of Table VII, followed by columns for the weighted mean period and the weighted mean residual. The weights are with the reciprocals of the squares of the probable errors in the last column of Table VII.

A minimum value of $|\bar{\Delta}|$ is readily found in Table VIII, namely for $\beta_0 = 65^\circ$ and $\lambda_0 = 126^\circ$. There still is, however, a second possibility. Incidentally, if the latitude of observation had not been taken into account, there would have been no $\pm 180^\circ$ resolution for the

longitude of the pole. The second possibility is seen in Table VIII near $\beta_0 = 45^\circ$ and $\lambda_0 = 331^\circ$.

Table IX shows what regions are observed on Vesta at the various epochs, for the above two possible combinations of ecliptic latitude and longitude of the pole. The "longitude on Vesta" starts from the meridian through the ecliptic longitude of the pole, and it increases in the same direction as the ecliptic longitude. With direct rotation, one observes, in a light curve, decreasing Vesta longitudes. Positive and negative Vesta latitudes are in the same direction as those in the ecliptic reference frame. It is seen in Table IX that the first solution, with $\beta_0 = 65^\circ$, gives less aspect variation because the observations are somewhat closer to the Vesta ecliptic. This effect is, however, less strong than might have been expected from the large latitude difference of the two solutions; the reason for this lies in the 7° inclination of Vesta's orbit.

The values of $|\bar{\Delta}|$ in Table VIII should be considered with some reservation; they are modified if, for instance, the relative weights of the periods are adopted differently. However, the first possibility, with $\beta_0 = 65^\circ$, appears more likely because of the internal consistency of the 1958/59 observations when expressions (5) and (6) are applied (lower part of Table VI). When $\beta_0 = 45^\circ$ and $\lambda_0 = 331^\circ$ are applied instead, the consistency is less than the probable error of $\pm 0.000\ 001$ allows, with the following values in the second column of Table VI: $\bar{P}_{sid} = 0.222\ 583$, $\bar{P}_{sid,iner} = 0.222\ 589$, and $\bar{P}_{sid,decr} = 0.222\ 582$.

The following values and their estimated probable errors are adopted. For the ecliptic latitude of the

TABLE X. Computed epochs and residuals.

Obs. date 1958/59 UT	Computed UT	Observed minus final solution	Computed other trial
2 Nov.	11 ^b 19 ^m 5	+4 ^m 0	+5 ^m 3
5 Nov.	14 07.1	+2.3	+3.2
11 Dec.	4 56.0	+2.5	+3.0
19 Jan.	9 08.1	+0.1	+1.3
24 Jan.	6 38.5	-4.9	-4.4
26 Jan.	1 22.3	-1.2	-0.8
28 Jan.	6 47.00	...	...
31 Jan.	9 33.5	+0.5	-0.1
5 Feb.	7 04.9	+2.3	+1.9
20 Feb.	10 21.0	+1.1	+1.0
25 Feb.	7 53.9	+1.8	+2.5
6 May	5 41.4	+4.0	+3.5
10 May	5 52.6	+0.5	-0.2

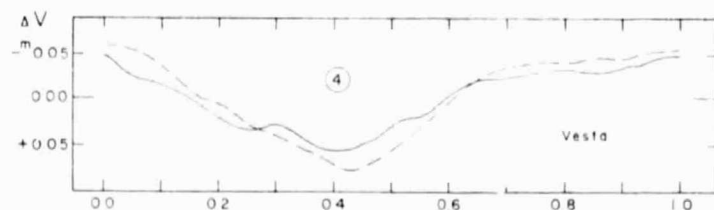


FIG. 16. The change in shape of the light curve with change of orbital phase. The solid line is as observed near opposition, and the broken line is for about 24° phase angle.

pole,

$$\beta_0 = 65^\circ \pm 4^\circ. \quad (5)$$

The longitude of the pole,

$$\lambda_0 = 126^\circ \pm 5^\circ. \quad (6)$$

The true or sidereal period of rotation is

$$0^d 222\ 588\ 71, \text{ which is } 5^h 20^m 31^s 665 (\pm 0^s 003). \quad (7)$$

Table X gives an application of expressions (1)–(7), namely to compute the epoch of maximum light for the various light-curve observations in 1958/59. In the third column the differences, observed minus computed, of the epochs in Table IV are listed. The residuals are surprisingly high as compared to the probable error of $\pm 0^m 5$ in Table IV, which was based on the consistency of the fitting of light curves. Solutions were tried with a different period, with the phase corrections omitted, etc.; but very little difference is thereby made in these residuals. One of the other trials

is shown with residuals in the fourth column; it was for $\beta_0 = 90^\circ$ and period $0^d 222\ 608$. The conclusion is made from Table X that the actual precision of fitting short light curves is of the order of 1 or 2 min, rather than $\pm 0^m 5$. Superimposed on the scatter is a systematic effect due to the change in shape of the light curve with phase.

5. Phase Functions

Figure 16 shows how the shape of the light curve changes with phase. The "Mean V" levels of Table I were used to construct the light curves of Fig. 16. "Mean V" had been obtained from superposition of the light curves using the computed times of maximum with the residuals of the fourth column of Table X. (The final solution gave the residuals of the third column, but the differences seem trivial for the determination of "Mean V" and the work was not redone.) The solid line in Fig. 16 is for 28 January 1959, and the dashed line for 2 and 5 November 1958, and 6 May

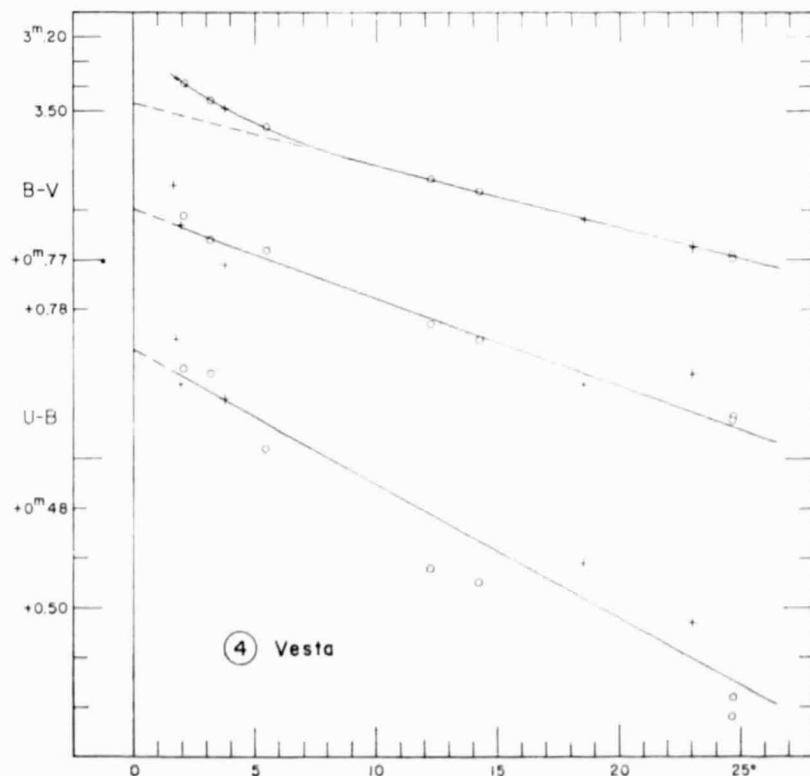


FIG. 17. Phase functions of Vesta. *Abscissas*, the orbital phase angle in degrees. *Ordinates*, top curve, the observed magnitudes (*V* on the *UBV* system) reduced to unit distances from the sun and earth; middle curve, the *B-V* colors; bottom curve, the *U-B* colors. Crosses are for observations made before and circles for after opposition.

TABLE XI. Magnitude-phase relations for Vesta, 1958/59.

Phase	V	B-V	U-B	V corr.	B corr.	U corr.
1.5	3.340	+0.758	+0.452	+0.126	+0.131	+0.127
2.0	3.382	.762	.454	+ .084	+ .085	+ .080
3.0	3.444	.766	.456	+ .022	+ .018	+ .010
4.0	3.499	.769	.459	- .033	- .039	- .050
5.0	3.542	.770	.462	- .076	- .084	- .097
6.0	3.589	.772	.464	- .123	- .132	- .148
7.0	3.630	.773	.467	- .164	- .174	- .193
8.0	3.669	+0.774	+0.470	-0.203	-0.214	-0.236

For larger phase angles, use 0.0255 mag/deg for V, 0.0264 (B), and 0.0291 (U).

1959. The amplitude changed from 0.104 mag at opposition to 0.137 mag near 24° phase. The change between November and January, and between January and May, is more than 20° in phase and only a few degrees in longitude. The conclusion is therefore made that the changes in shape are due to a change in phase rather than in aspect. A similar conclusion was reached for 20 Massalia, where there was a change in amplitude from 0.17 to 0.23 mag as the phase changed from 9° to 20° (Gehrels 1956). No difference in shape could be detected between -23° phase (November 1958) and +25° phase (May 1959), but this conclusion is based on poor evidence as the light curves were short, and May 10 may have had some trouble (see Sec. I).

Figure 17 gives, at the top, the mean brightness of each light curve as a function of the orbital phase. The "Mean V" values were used after reduction to magnitudes at unit distances from sun and earth (Table I). It is seen in Fig. 17 that the phase function is the same before as after opposition. The precision of each point is ± 0.002 mag. (p.e.) which is about the width of the drawn line. At small phases the brightness increases nonlinearly ("opposition effect"). Extrapolation of the straight line gives the absolute magnitude,

$$g_V = 3.466. \quad (8)$$

Figure 17 also shows the average colors for each night (Table I) as a function of orbital phase. It is seen that the B-V relation is the same before and after opposition, but that there is an appreciable difference in the U-B results. The scatter of the points with respect to the mean U-B line in Fig. 17 is ± 0.0045 (p.e.), which is nearly three times the internal probable error of the determinations (± 0.0017 mag) so that the effect probably is real. The scale of ordinates for B-V and U-B is 20 times that of the upper curve; 0.002 mag now is about the size of the symbols. It is also seen in Fig. 17 that there may exist an opposition effect in the color-phase relations. The most marked effect, however, is a reddening with phase. Ignoring the nonlinearity near zero phase,

$$B-V = 0.760 + 0.0018|\alpha|, \quad (9)$$

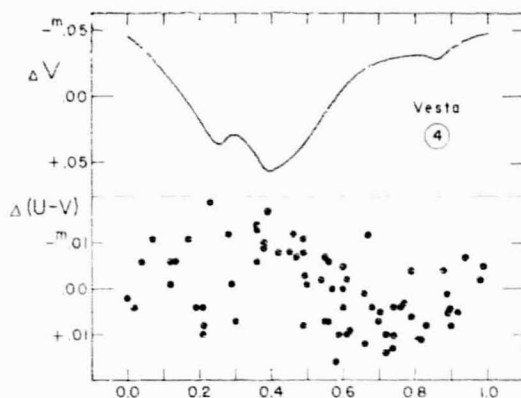


FIG. 18. Color changes over the surface of Vesta. Abscissas, the rotational phase. The top curve is a sketch of the light curve. A dot shows the individual color observation (U-V) minus the nightly mean.

and

$$U-B = 0.448 + 0.0027|\alpha|, \quad (10)$$

where α expresses the orbital phase angle in degrees.

Table XI shows the detailed phase relations in Visible, Blue, and Ultraviolet light. The B values were obtained with a least-squares solution of the observations at phases larger than 3° which gives $B-V = 0.763 + 0.0016|\alpha|$, and by drawing a small opposition effect through the points at smaller phase angles. The drawn lines of Fig. 17 were used for the V and U-B values.

The last three columns of Table XI give the corrections to absolute magnitude for comparison with the corrections generally adopted for the asteroids (Gehrels 1967).

Figure 18 shows a sketch of the light curve of Vesta and at the same time the differences in color, U-V, from the mean. For each individual transfer—there were at least three transfers made during a light-curve run—the difference from the mean color for the night is plotted. Zero and 1.0 rotational phases are at maximum light (the epoch shown with a vertical line at 6^h47^m UT in Fig. 7). It is seen in Fig. 18 that the darker side of Vesta also is slightly bluer.

6. Concluding Remarks

Vesta appears to be a nearly spherical object with nonuniform reflectivity and color over the surface. The normal reflectivities are computed by Haupt (1958) to be of the order of 52% on one side and 45% on the other. With such high reflectivity Vesta differs appreciably from the common asteroids, that have on the average about 7% reflectivity (G. P. Kuiper, personal communication). Vesta's light curve has one maximum and one minimum, but this statement has only relative merit. The feature sketched in Fig. 18 near 0.87 rotational phase, for instance, might be called a secondary minimum. The significant conclusion is that Vesta is

nearly spherical whereas most asteroids are not. Is Vesta perhaps an escaped satellite?

The opposition effect, the color being consistently redder than that of sunlight, and the reddening with phase, are phenomena of a porous surface texture with dimensions in the micron-millimeter range. The effects on Vesta are similar to those observed on the moon; some interpretations have been discussed by Gehrels, Owings, and Coffeen (1964) for the lunar surface. The cause of the porous microtexture perhaps lies in bombardment by the solar wind and subsequent tunneling and sputtering. Theoretical work appears urgently needed.

The difference between $U-B$ before opposition and after opposition (Fig. 17), if real, is not understood.

The determination of longitude and latitude of the pole can be checked and considerably improved by obtaining three light curves during the next opposition. A light curve at $+3.1$ phase (November 1968) will allow comparison with the observations of 1952, 1954, and 1959. A light curve at $+9.1$ phase will match the one of Chang and Chang (1962) made on 7 December 1961. A light curve at $+18.0$ phase will be ideal for comparison with the 1950 observation, especially because the aspect will be nearly the same in 1968 as it was in 1950. It is important to have the phase angles close to those mentioned so as to minimize the uncertainties in the phase correction of expression (2).

The uncertainty of the phase correction did not appreciably affect the present determination of longitude and latitude of the pole because of the selection of the epochs compared in Table VII. That expression (2) is close to the truth was found in the work for Table VI: with only the f correction the first entry in Table VI is $P_{sid} = 0^d.222\ 606$.

The long light curve of 28 January appeared essential

for the solutions of period and phase relations. At large phase angle, it would have been better to have longer light curves; especially the one of 10 May 1959 is marginal. Precise timing, using WWV signals for calibration, is essential in this work. In the future for bright objects, it will be better always to plot the mean of two integrations rather than four, in order to show fine details of the shape of the light curve. A better attempt should have been made to find comparison stars of the same color as that of the asteroid. The desirability of having two comparison stars during the night has to be weighted against the difficulty of finding two conveniently nearby stars. Extension of the wavelength range of the observations into the infrared may be found useful (see Fig. 3 of Haupt 1958).

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