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BALLISTICS OF THE COPERNICAN RAY SYSTEM

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Observations of the lunar surface are limited by the resolution in present telescopic methods. Few of the details can be seen by which an impact crater might be distinguished from a solitary maar volcanic crater. During the last few decades, much of the discussion on lunar crater origin has been concerned with the statistics of size, shape and distribution of the craters. By their very nature, the statistical arguments are inconclusive and do not lead to the determination of the origin of a single crater. The evidence which has been adduced for the impact origin of lunar craters is thus insufficient.

Many lunar craters are larger than terrestrial maar volcanos, and all of the major lunar craters are larger than any known volcanic crater. However, Wright[1] has pointed out that the low gravitational potential on the moon would result in a far wider distribution of volcanic ejecta on the moon than on the Earth. For the same magma, boiling would also begin at much greater depth on the moon. These factors might favor the development of larger maar craters on the moon than on the Earth, although the evidence of the chain craters suggests that the influence of these factors is not major.

Baldwin[2] has shown that the distribution of the depth as a function of the diameters of lunar craters is scattered around a curve extrapolated from data on craters which were produced by detonation of high explosives. The pertinence of this extrapolation is, at best, not clear. The shape and characteristics of a given crater are sensitive to the scaled depth of the charge or to the penetration of the meteorite. Most of the data on the depths of the lunar craters are from the visual measurements of Beer and Mädler[3] and Schmidt[4] during the nineteenth century. Some of these have large errors. The depth-diameter ratios of unscreened lunar craters show about the same broad scatter as ratios for unscreened terrestrial volcanic craters. This fact has been pointed out by Green and Poldervaart.[5] In the final analysis, we should not expect an especially close relation between the depth-diameter ratios of high-explosive craters and impact craters. Because a large amount of gas is produced, the cratering mechanics of high-explosive detonation are substantially different from those of high-velocity impact.

There is one major feature of lunar craters observable from the Earth, however, which may permit unambiguous discrimination of impact craters from volcanic craters. This feature is the distribution pattern of the ejecta. The ejecta from maar-type volcanos are almost invariably thrown out along high-angle trajectories, and shower down in a diffuse, more or less uniform, pattern around the crater. These trajectories are the result of entrainment of the fragments in the volcanic gas jets, which are predominantly vertical. The ejecta from large impact craters, on the other hand, are thrown out along both high and low trajectories.

The ejecta pattern around all known large impact craters, beyond the immediate vicinity of the rim, has been destroyed by erosion. Nevertheless the general nature of the pattern to be expected is revealed by the debris deposited around nuclear-explosion craters. The far-flung ejecta from nearly every shallow underground explosion crater, whether the explosion is nuclear or chemical, are laid down in distinct streaks or rays (Figure 1). The position and shape of the rays are governed, in turn, by the pattern in which the ground breaks up as it is engulfed by shock. From the ray pattern and the trajectories of the fragments that form the rays (the exterior ballistics), it is possible to reconstruct the fragmentation pattern of the ground (the interior ballistics of crater formation).

Many lunar craters are surrounded by a system of rays resembling the ejecta patterns around nuclear- and high-explosion craters. The ray pattern of Copernicus is especially suited for detailed analysis. Copernicus is favorably located near the center of the lunar disk; the ray system surrounding the crater is not only widespread but extends, in large part, over the dark and relatively smooth mare surface. Many of the fine details of the system can therefore be deciphered (Figure 2).

The crater itself is somewhat polygonal in outline, about 90 kilometers across and about 3,500 meters deep, measured from the crest of the rim to the floor.

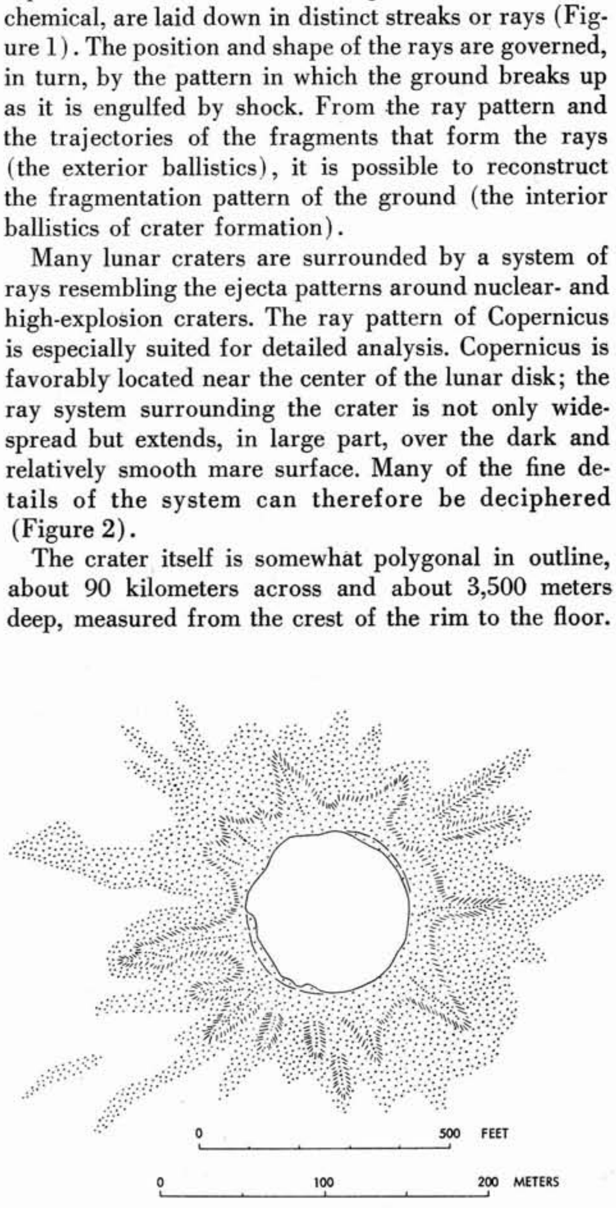


Figure 1. Ejection pattern at Teapot Ess nuclear explosion crater

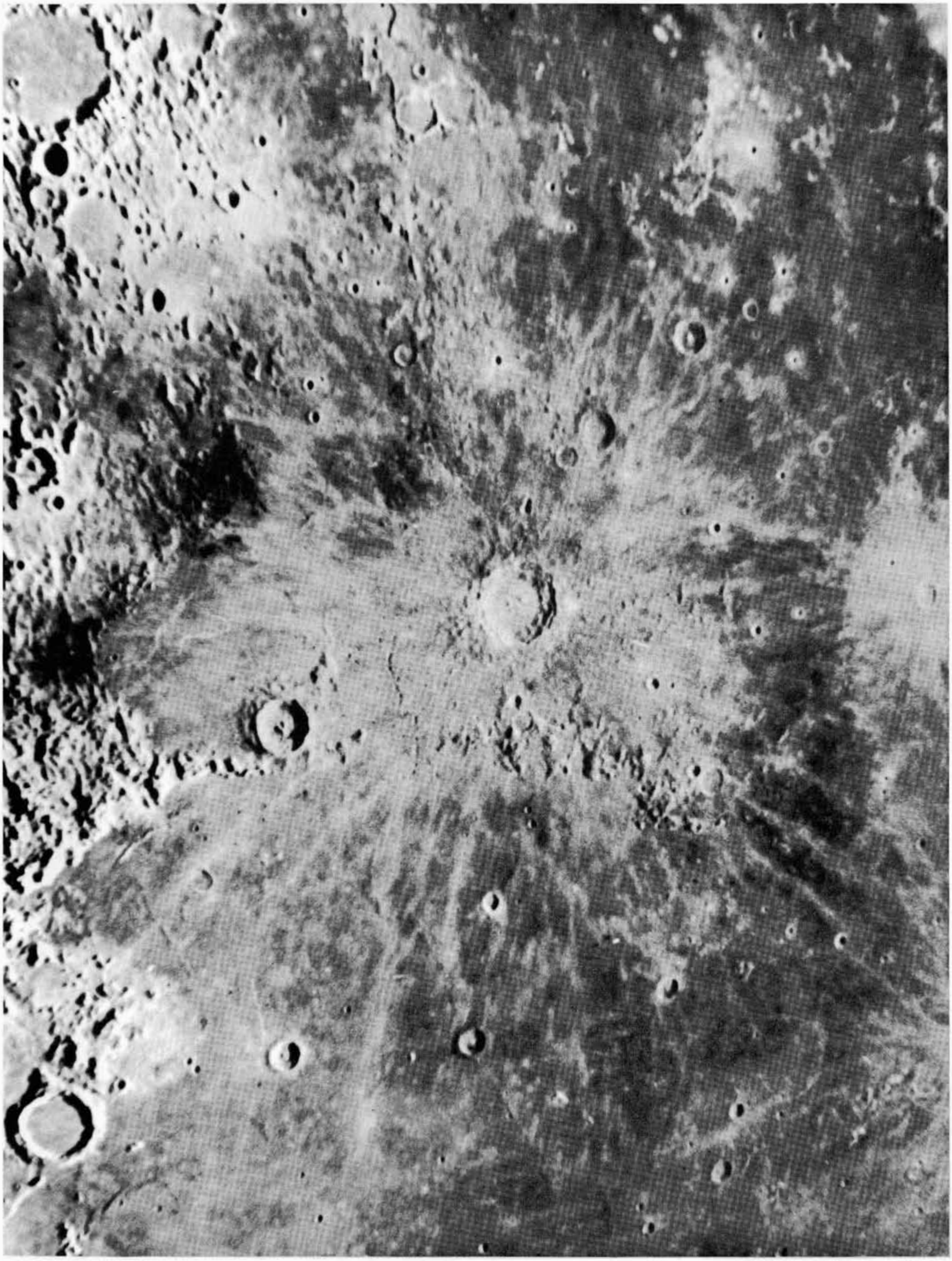


Figure 2. The region of Copernicus

The rim rises about 1,000 meters above the surrounding lunar surface. The interior walls of the crater comprise a series of terraces, scarps and irregular sloping surfaces that descend stepwise from the crest to the crater floor. The floor is a roughly circular area, of generally low relief, 50 kilometers in diameter. A few low sharp peaks rise above the floor near the center of the crater.

The outer slopes of the rim are a scaled-up version of the outer slopes of the rims of the Jangle U and Teapot Ess nuclear-explosion craters. To a lesser extent, the rim of Copernicus resembles the rim of Meteor Crater, Arizona. Rounded hills and ridges are combined in a distinctive hummocky array. This array consists of humps and swales without obvious alignment near the crest of the rim, and passes gradually outward into a system of elongate ridges and depressions with a vague radial alignment. The relief of the ridges gradually diminishes, until it is no longer discernable, at a distance of about 80 kilometers from the crest of the rim. Beyond that distance, the rim passes gradationally into the ray system.

The ray system, which extends over 500 kilometers from Copernicus, consists mainly of arcuate and loop-shaped streaks of highly reflective material on a generally dark part of the lunar surface. In reflectivity characteristics, the rays are essentially an extension of the crater rim and cannot be sharply delimited from it. The major arcs and loops can be locally resolved into *en échelon* feather-shaped elements, ranging from 15 to 50 kilometers in length, with the long axes of the elements approximately radially arranged with respect to the center of the crater.

The pattern of the ray system may be said to resemble the arrangement of iron filings in a dipole magnetic field in a plane containing the dipole. The 'dipole' axis of the Copernican rays trends northwest-southeast. Major arcuate rays curve away from the axis on either side and a large closed elliptical loop extends southwest toward Mösting. The ray system has a rough bilateral symmetry about a line coincident with the long axis of this loop, which is perpendicular to the dipole axis. Within the main loop extending toward Mösting are subsidiary loops. North of Copernicus are two so-called cross-rays. Both cross-rays consist of a series of vaguely defined loops, which are linked end-to-end. Near or along the dipole axis, either the rays tend to be confined and radially arranged with respect to Copernicus, or only individual feather-shaped ray elements are present.

Within the rays, and preponderantly near the concave or proximal margins of the major arcs and loops, are numerous elongate depressions or gouges in the lunar surface, ranging in length from the limit of telescopic resolution to about 8 kilometers. A peculiar feature of the gouges is their alignment, which is radial from Copernicus in some cases but is commonly at an angle to the radial direction. The alignment varies erratically from one gouge to the next. Visible depressions or gouges lie at the proximal ends of many ray elements, although there is not a one-to-one correspondence between gouges and distinguishable ray elements.

It is commonly stated in the literature that there is no determinable relief of the lunar surface associated with the rays. This is not strictly true. At very low angles of illumination the surface along the rays can be seen to be rough.[6] The roughness is due, at least in part, to the presence of the gouges and very low rims around the gouges.

The interpretation is adopted that lunar rays are thin layers of ejecta from the crater about which they are distributed. This interpretation dates back at least to the nineteenth century, and is probably older. The gouges are interpreted as secondary impact craters which were formed by individual large fragments or clusters of large fragments ejected from the principal crater. Distinct ray elements are interpreted as feather-like splashes of crushed rock derived chiefly from the impact of individual large fragments or clusters of fragments. Partial verification of these interpretations will be obtained if a full explanation of the ray pattern and associated gouges can be given in terms of the required ballistics.

In order to reduce the ballistic problem of the Copernican rays to a series of discrete points that can be treated mathematically, a compilation of 975 secondary impact craters (Figure 3) has been made. This is a conservative compilation and far from complete. The problem of compilation lies in finding the craters, many of which barely exceed the lower limit of resolution on good lunar photographs, and also in distinguishing secondary impact craters belonging to the ray system of Copernicus from other craters of about the same size that are common in this region. Three criteria were used to identify secondary impact craters, and no craters were included in the compilation that did not satisfy at least two of the criteria: (1) markedly elongate shape, (2) shallow depth compared to most small craters outside the ray system and (3) an extremely low rim or the absence of a visible rim. Most small craters in the region of Copernicus that fit these criteria occur in well-defined rays or ray elements. Nearly all such craters that do not lie in the Copernican rays appear to belong to another system of secondary impact craters around the major crater of Eratosthenes. The identification of the secondary impact craters is based mainly on Figure 2, a photograph taken by F. G. Pease at the Mt. Wilson Observatory. However, other photographs from Mt. Wilson and Lick Observatories were used as an additional check.

Two deficiencies in particular should be noted in the present compilation. First, there is a gap in the area around Eratosthenes where no secondary impact craters have been plotted. This gap is due not to the absence of craters but to the difficulty in distinguishing with certainty the secondary impact craters belonging to the Copernican ray system from craters produced by fragments ejected from Eratosthenes. Therefore,

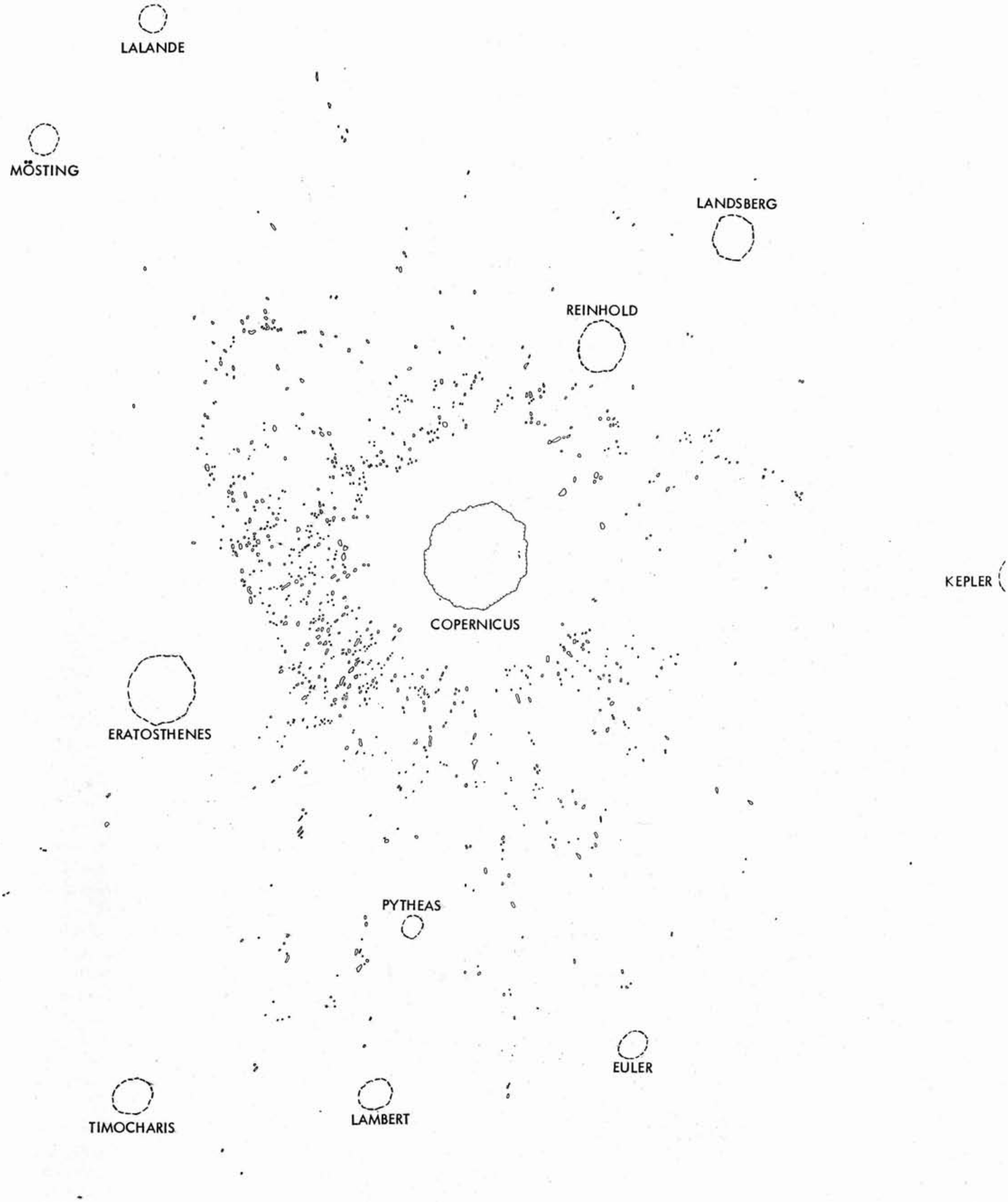


Figure 3. Secondary impact craters in the Copernican ray system

all craters in the area around Eratosthenes have been omitted. The second deficiency is a relative incompleteness of the compilation on the east side of Copernicus as revealed by the much lower areal density of craters on the east. This defect is due to the fact that in the principal photographs used for the compilation the terminator lay to the west of Copernicus, and the small secondary impact craters can be distinguished with much higher confidence on the side nearest the terminator.

Ranges of all secondary impact craters plotted in Figure 3 were measured from the Mt. Wilson photographs. The distance measured was from the tip of the centermost peak on the floor of Copernicus, which is almost precisely at the center of the circular crater floor, to the nearest point on the rim of each secondary impact crater. These measurements are strictly preliminary and have significant systematic proportional errors in certain directions. The purpose of making the measurements was simply to find the general nature of the fragmentation pattern that controlled the Copernican rays.

The frequency distribution of the secondary impact craters as a function of range shows a sharp mode about 100 kilometers from the center of Copernicus (Figure 4). At greater distances, the frequency drops off rapidly but the histogram reveals several subordinate maxima. Toward the outer extremity of the ray system, the frequency drops gradually to zero. From the modal distance toward Copernicus, the frequency drops off very rapidly. This is because toward the main crater the gouges in the pre-existing lunar surface tend to be covered up or smothered under an increasingly thick deposit of the material which makes up the crater rim. The smothering effect begins about 80 kilometers from the edge of the crater, and from this point inward there is essentially a continuous blanket of ejecta.

The problem at hand is to reduce the trajectories of the fragments, or clusters of fragments, which have formed the secondary impact craters and to solve for the original position of these fragments within the crater. We wish to know if the special pattern of the ray system of Copernicus can be related to a fairly simple pattern of breakup of the rocks within the area of the crater and whether this interior ballistic pattern reflects any of the visible structural features of the lunar crust in the region of Copernicus. If such a relationship can be found it will strengthen not only the ballistic interpretation of the rays but also the general cratering theory upon which the numerical computations are based.

To find the trajectories for individual fragments ejected from Copernicus, we require a theory of cratering that gives the relation between ejection velocities and angle of elevation of ejection. A series of approximations and idealization of the cratering problem will be used to obtain a relation in closed algebraic form.

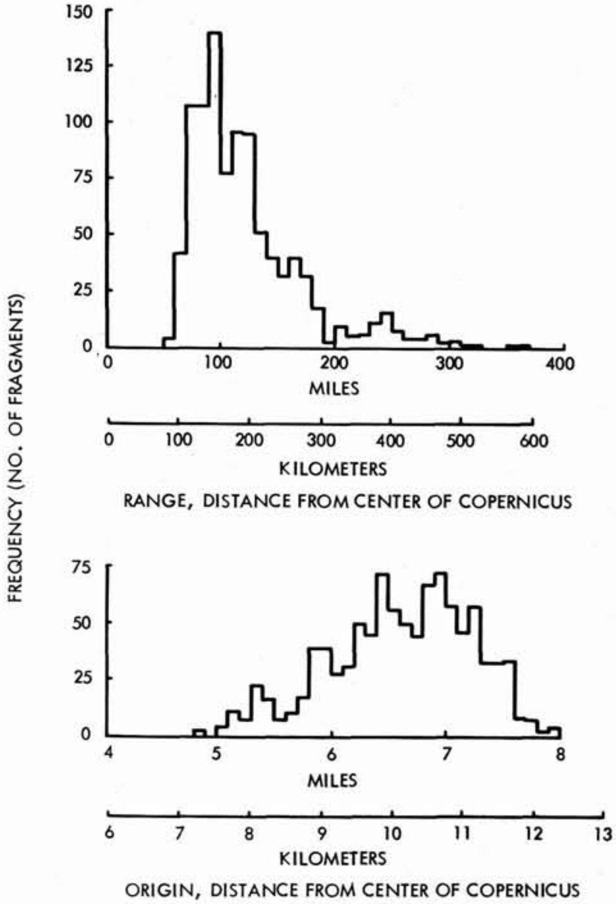


Figure 4. Frequency distribution of secondary impact crater-forming fragments by range and by calculated original position in Copernicus

First, the shock generated by impact will be treated as having an apparent origin at a point some distance below the surface which corresponds to the center of gravity of the energy delivered during penetration of the meteorite. This approximation becomes seriously in error within a narrow cone with an axis coincident with the penetration path. However, at angles to the probable penetration path, which may help to explain the observable features of the Copernican rays, the approximation is held to be valid within the limits of variation introduced by inhomogeneities of the lunar surface. The exterior ballistics can then be expressed in terms of the geometric parameters shown in Figure 5.

From the Rankine-Hugoniot conditions, we have the following relations across the shock front. For the conservation of mass

$$U\rho_o = (U - \mu)\rho \tag{1}$$

For the conservation of momentum

$$P = \rho_o U \mu \tag{2}$$

For the conservation of energy

$$e = \frac{P}{2}\left(\frac{1}{\rho_o} - \frac{1}{\rho}\right) \quad (3)$$

where

U = shock velocity

ρ_o = initial density of lunar crust

μ = particle velocity behind the shock front

ρ = density behind the shock front

P = pressure increment across the shock front

e = internal energy increment across the shock front

Combining Equations 1, 2 and 3, we have

$$e = \frac{\mu^2}{2} \quad (4)$$

An approximation, employed successfully by Griggs,[7] to predict shock arrival times in the Jangle U underground explosion in the region of strong shock results in

$$E = 2eM \quad (5)$$

where E is the total shock energy and M is the mass engulfed by shock. This approximation can be derived if we assume that the energy is uniformly distributed in the material behind the shock. Such a distribution is impossible, but the relation gives a fair approximation for the rates of decay of energy, pressure, and shock and particle velocities for shock propagation in rock. From this, a cube root scaling law for the crater diameters may be evolved. E can be written as

$$E = \frac{mv^2}{2} \quad (6)$$

where m is the mass of the meteorite or impacting bolide and v is its velocity. Combining Equations 4, 5 and 6, we have

$$\frac{v^2}{\mu^2} = \frac{2M}{m} \quad (7)$$

Partly for algebraic simplicity, M will be taken as

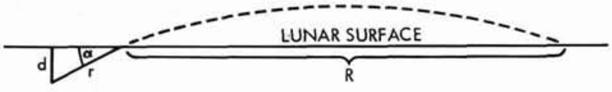
$$M = \frac{4}{3}\pi r^3 \rho_r \quad (8)$$

where ρ_r is the initial density of the lunar crustal material. This relation preserves cube root scaling and will minimize the estimate of v. We also may write

$$m = \frac{4}{3}\pi x^3 \rho_m \quad (9)$$

where x is the radius of the bolide, ρ_m is its density and, from Figure 5,

$$r = \frac{d}{\sin a} \quad (10)$$



d = depth of apparent origin of shock

r = slant radius from apparent origin of shock to surface

a = angle of slant radius to the horizontal

R = range of trajectory of ejected fragment

Figure 5. Geometric relations of ballistic parameters

If we combine Equations 7 through 10, the result is

$$v = \mu\sqrt{\frac{2\rho_r}{\rho_m}}\,\frac{1}{\sin^{3/2} a}\left(\frac{d}{x}\right)^{3/2} \quad (11)$$

For an elastic wave, the particle velocity for a point on the surface would be $2\mu \sin a$, but the velocity of a large fragment ejected by shock from a rock surface will be close to μ. This simply means that the kinetic energy imparted by the rarefaction wave reflected from the ground surface is minor, and that the angle of ejection of a fragment from the horizontal lunar surface would be close to a. These relations are consistent with experimental results which have been obtained for large underground explosions.

In order to evaluate Equation 11 numerically, we must make some assumptions about $\frac{\rho_r}{\rho_m}$ and $\frac{d}{x}$, and a relationship between μ and a is required. Some minimum requirements of this accessory relationship can be drawn from the ray system of Copernicus.

From Equations 4, 5 and 8, we have

$$\mu = \sqrt{\frac{3E}{4\pi \rho_r r^3}} \quad (12)$$

For a first approximation, let us ignore radial variation in the lunar gravitational potential and the departure of the lunar surface from a sphere. We shall employ the simple classical ballistic formula

$$R = \frac{\mu^2 \sin 2a}{g} \quad (13)$$

where g is the gravitational acceleration at the surface of the moon (167 centimeters per square second). Substituting Equations 10 and 12 into 13, we have

$$R = \frac{3E \sin^3 a \sin 2a}{4\pi \rho_r d^3 g}$$

where

$$\frac{3E}{4\pi \rho_r d^3 g} = K \text{ (a constant)}$$

The greatest distance that the Copernican rays can be traced is a little more than 500 kilometers. To set a minimum value for v, let us suppose that this distance actually represents the greatest range of fragments. (This supposition is demonstrably false, but will be examined later in more detail.) With this supposition, there are two possible trajectories for any range less than the maximum, one for ejection angles higher than that for the maximum range and one for lower ejection angles. For the maximum range, we have

$$\frac{dR}{d\alpha} = K(\cos \alpha\, 4 \sin^3 \alpha \cos \alpha - \sin^4 \alpha \sin \alpha) = 0 \quad (15)$$

$$\cos \alpha_{max} = \sqrt{\frac{1}{5}}$$

$$\alpha_{max} = 63^\circ\, 26' \quad (16)$$

Substituting the value of α obtained in Equation 16, and 500 kilometers for R in Equation 13, we have

$$\mu = \frac{167 \cdot 5 \times 10^7}{0.80}\ cm/sec. = 1.02\ km/sec. \quad (17)$$

We are now able to evaluate minimum values of v from Equation 11. For Meteor Crater, Arizona, a value for $\frac{d}{x}$ of 8 to 10 was found, if $\frac{\rho_r}{\rho_m}$ equals $\frac{1}{3}$ and v equals 15 kilometers per second.[8] For the lunar surface and likely compositions of the impacting bolide, values of $\frac{\rho_r}{\rho_m}$ between $\frac{1}{2}$ and 1 are more probable. For these higher ratios of the densities, lower values of $\frac{d}{x}$ may be anticipated for the same impact velocities. Let us adopt two sets of values for numerical evaluation:

$$\frac{\rho_r}{\rho_m} = \frac{1}{2}, \quad \frac{d}{x} = 4$$

and

$$\frac{\rho_r}{\rho_m} = 1, \quad \frac{d}{x} = 2$$

For the velocities derived from Equation 11, these sets of values are realistic for the case of Copernicus. Substituting the first set into Equation 11, we obtain

$$v = \frac{1.2 \cdot 8}{0.846} = 9.6\ km/sec. \quad (18)$$

For the second set, we obtain

$$v = \frac{1.02 \cdot 1.414 \cdot 2.83}{0.846} = 4.8\ km/sec. \quad (19)$$

An interesting point about these results is that the cratering and ballistic theory presented here leads to the conclusion that the bolide which formed Copernicus was probably an independent member of the solar system and *not* a planetesimal or moonlet orbiting the Earth.[6a] The value of 4.8 kilometers per second for the impact velocity, obtained in Equation 19, is a minimum.

It may be noted from Equation 14 that the range, as defined, can be set independently of the total energy E and the size of the crater, if the linear dimensions of the shock scale as the cube root of the energy. Thus we would expect the trajectories from small craters formed by small bolides to be almost as long as those from large craters formed by large bolides, if the impact velocities are similar. However, there is a rough correlation between size of crater and length of observable rays on the moon. This can be interpreted to mean that the rays are visible only out to the point where the density of ejected material is so sparse that it can no longer be photographed. The smaller craters would have shorter observable rays because the quantity of ejected debris is less. Upon close examination, we will find that the rays fade out gradually. There is rarely any suggestion of increase in ray density near the end, such as would be predicted by the maximum-range hypothesis. Thus the Copernican rays are formed only by material ejected at low angles; the material ejected at high angles went into escape trajectories.

From Equation 14, the total range R_T of a fragment from the epicenter of the shock may be written as

$$R_T = K \sin^3 \alpha \sin 2\alpha + \frac{d}{\tan \alpha} \quad (20)$$

From the form of Equation 20, it may be seen that the total range, as defined, must pass through a minimum. For a large crater, this minimum will be slightly less than the radius of the initial crater produced by ejection of material. At decreasing angles of α (sufficiently low that the total range starts to rise because of rapid increase of the second term), pieces will no longer be thrown out of the crater but will be displaced only a short distance laterally. A series of thrust sheets may be formed at angles of α where the total range passes through the minimum. In a large crater, the final radius of the crater is increased by slumping.

From Equation 12, we may write

$$\mu_2^2 = \frac{\sin^3 \alpha^2}{\sin^3 \alpha_1} \mu_1^2 \quad (21)$$

Thus, if d and any pair of values for μ and α are specified, we may draw a curve for R_T. By successive approximation, it may be found that an ejection velocity of 0.4 kilometers per second for an ejection angle of 12 degrees will lead to the formation of a crater of the lateral dimensions of Copernicus. This assumes that the center of gravity of the energy released is at a depth of 3.2 kilometers. The crater is taken as having been enlarged by slumping 25 kilometers, the cumulative width of the terraces on the crater walls. From Equation 11, the impact velocity is found to be 17 kilometers per second. At this velocity, the center of gravity of the released energy is located at a distance below the surface which is about equal to the linear dimensions of the bolide. This assumes that the bolide is composed of the same material as the lunar surface (calculated from methods given by Shoemaker[8]). For a value of $\frac{d}{x}$ equal to 2 and a density of 3 for the impacting bolide, the kinetic energy is found to be 1.8×10^9 kilotons TNT equivalent, or 7.5×10^{28} ergs. This may be compared with 1.2 kilotons for the Jangle U experiment; the cube root of the ratio of the energies is $1.1_4 \times 10^3$. As the ratio of the diameters of the two craters is 1.1×10^3, the cratering theory employed gives good agreement with the empirical cube root scaling law for the diameters of nuclear craters.[9] It should be noted that the scaled depth for the Jangle U is slightly greater than that calculated for Copernicus.

The precise equation for the range of the trajectory on a spherical body can be written in the form

$$\phi = tan^{-1} \frac{\mu^2 \sin \alpha \cos \alpha}{lg - \mu^2 \cos^2 \alpha} \qquad (22)$$

where ϕ is half the angular distance of travel along the surface and l is the radius of the sphere.[10] For ranges up to 100 kilometers, or about 3 degrees on the lunar surface, the error of Equation 13 is small.

Given μ equal to 0.4 kilometers per second at a 12-degree ejection angle, the ejection velocity for all ejection angles may be specified from Equation 20 (Figure 6). From Equation 22 and the tangent of α, the range of individual fragments initially at the surface may then be expressed as a function of the distance of these fragments from the epicenter of the shock (Figure 7).

Fragments ejected at angles ranging from about 6 to 14 degrees form the continuous ejecta blanket mantling the rim of Copernicus. The ejected fragments follow a series of overarching trajectories, as required to form the inverted stratigraphy of the rim at Meteor Crater, Arizona. Fragments ejected at angles ranging from about 14 to 22 degrees form the secondary impact craters (the gouges) and the rays (Figure 8). Between ejection angles of 22 and 43 degrees, the smaller volume of material ejected is so widely scattered over the surface of the moon that it is lost. Above 43 degrees, the fragments are ejected into escape trajectories.

The actual formation of rays depends upon a departure from the idealized cratering model. Fragments are not ejected precisely along the radii from the apparent shock origin but are thrown out in distinct clusters or clots. The shape and orientation of these clots, as they are first formed in the crater, can be found by using the theoretical trajectories to replace the fragments in the approximate original positions.

In order to plot positions within Copernicus for the approximate original loci of the fragments that produced the secondary impact craters, the provisional hypothesis is made that each secondary impact crater was formed by one main fragment, and that all of the fragments came from a near-surface layer. From Figure 7 it can be seen that all of the fragments are then transposed back into Copernicus along radii from the central point, which is taken as the shock epicenter. In the provisional transposition, all of the fragments are found to originate from a circular belt around the shock epicenter (Figure 9) with an inside radius just under 8 kilometers (5 miles) and an outside diameter of 13 kilometers (8 miles). The farthest thrown fragments are derived from the inner margin of the belt.

The large loop-shaped ray extending toward Mösting is found to have originated from a linear cluster of fragments within Copernicus about 7 kilometers long. The trend of this cluster is essentially parallel with the dipole axis of the whole ray system. It is also parallel with a northeast trending linear system of prominent ridges in the Carpathian Mountains (Figure 2) and with the dominant trend of linear topographic features in the general vicinity of Copernicus. These ridges and linear features are structural elements of the lunar crust that, at least in part, clearly predate the formation of Copernicus. The fragmentation pattern thus appears to have been influenced by pre-existing lines of weakness; individual clots of fragments evidently pulled apart along faults and fractures already present in the lunar crust. The linear cluster of fragments that formed the loop-shaped ray toward Mösting is interpreted as a pre-existing structural block that maintained its identity momentarily as it was engulfed by shock. In this way, the major features of the ray pattern on the dipole axis and the axis of symmetry are controlled by the dominant structural grain of the lunar crust in the vicinity of Copernicus.

Subordinate structural trends also influenced the ray pattern. A prominent arcuate ray curves around just north of Hortensius. This ray is derived from a linear

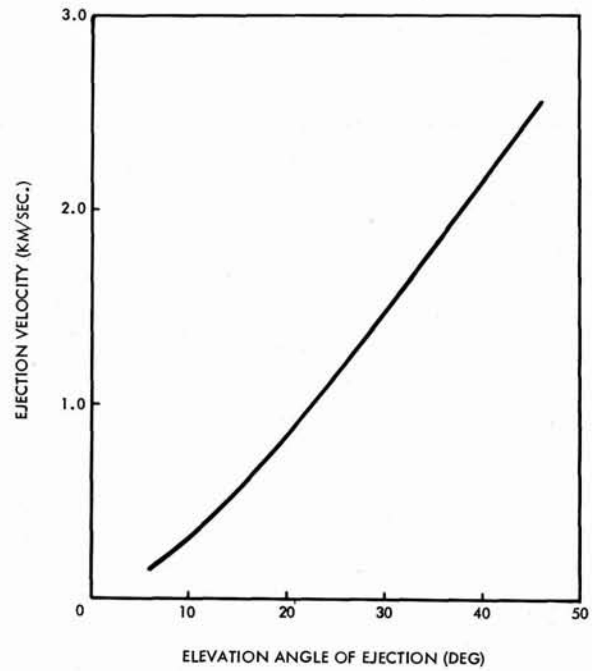


Figure 6. Ejection velocity as a function of elevation angle of ejection from Copernicus

cluster of fragments parallel with a subordinate set of north-northwest trending linear features, north of Copernicus, and a north-northwest trending set of terraces on the eastern crater wall. Other linear clusters, also present in the interior ballistic pattern, are parallel with other linear structures in the crater wall and the region around Copernicus.

The significance of these results is that a simple genetic relationship between the main features of the Copernican ray pattern and other observable features of the lunar crust is found by use of the idealized theory of cratering. The theory accounts quantitatively for both the crater dimensions and the distribution of ejecta. The transposition of rays into linear fragment clusters, however, is not a sensitive test of precision of the computed trajectories. The main features of the interior ballistic pattern would not be significantly changed by minor modification of the relationship between elevation angle and ejection velocity, which was derived from a series of approximations.

The provisional hypothesis states that all the secondary impact crater-forming fragments were derived from a near-surface layer. Material derived from deep positions, close to the origin of the shock, will be ejected at the same angles as fragments close to the surface. The near-surface fragments are farthest from the shock origin along any given slant radius and experience the lowest peak shock pressure. Therefore, it is reasonable to expect that the largest fragments have come from near the surface. The question is whether any fragments, or cluster of fragments, large enough to form secondary impact craters may have originated at significant depth beneath the surface. The frequency distribution of the secondary impact crater-forming

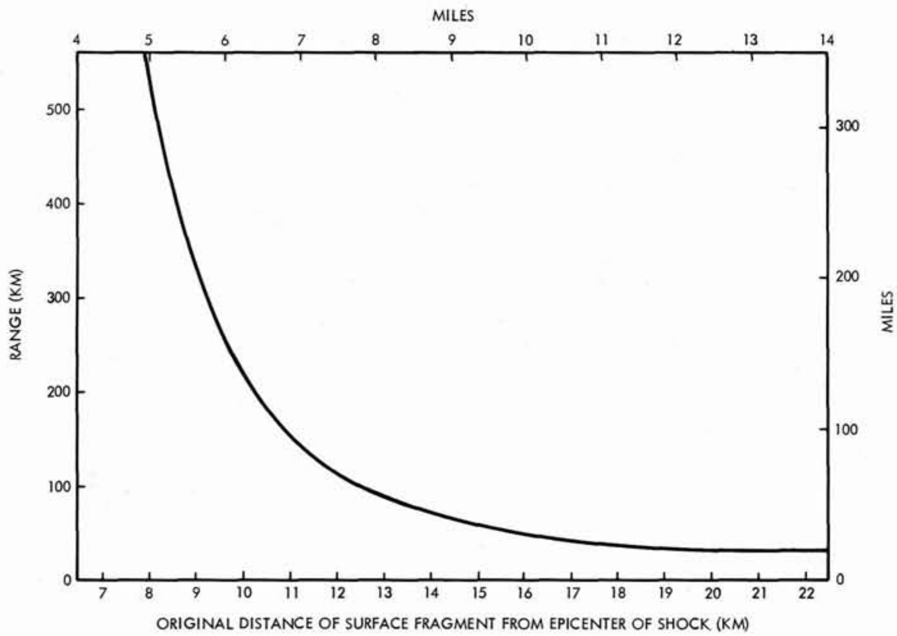


Figure 7. Range of fragments as a function of original position in Copernicus

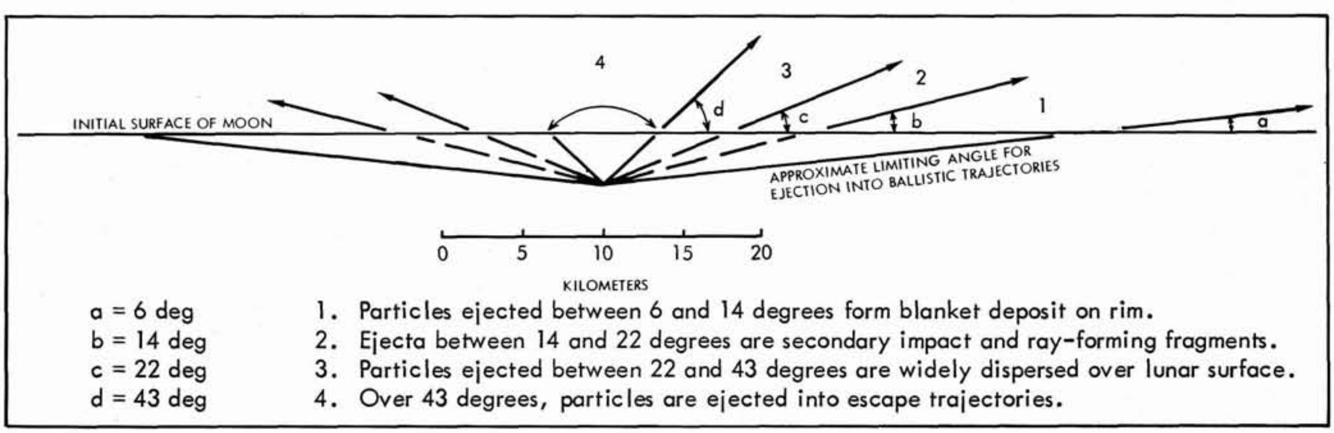


Figure 8. Provenance of fragments ejected from Copernicus

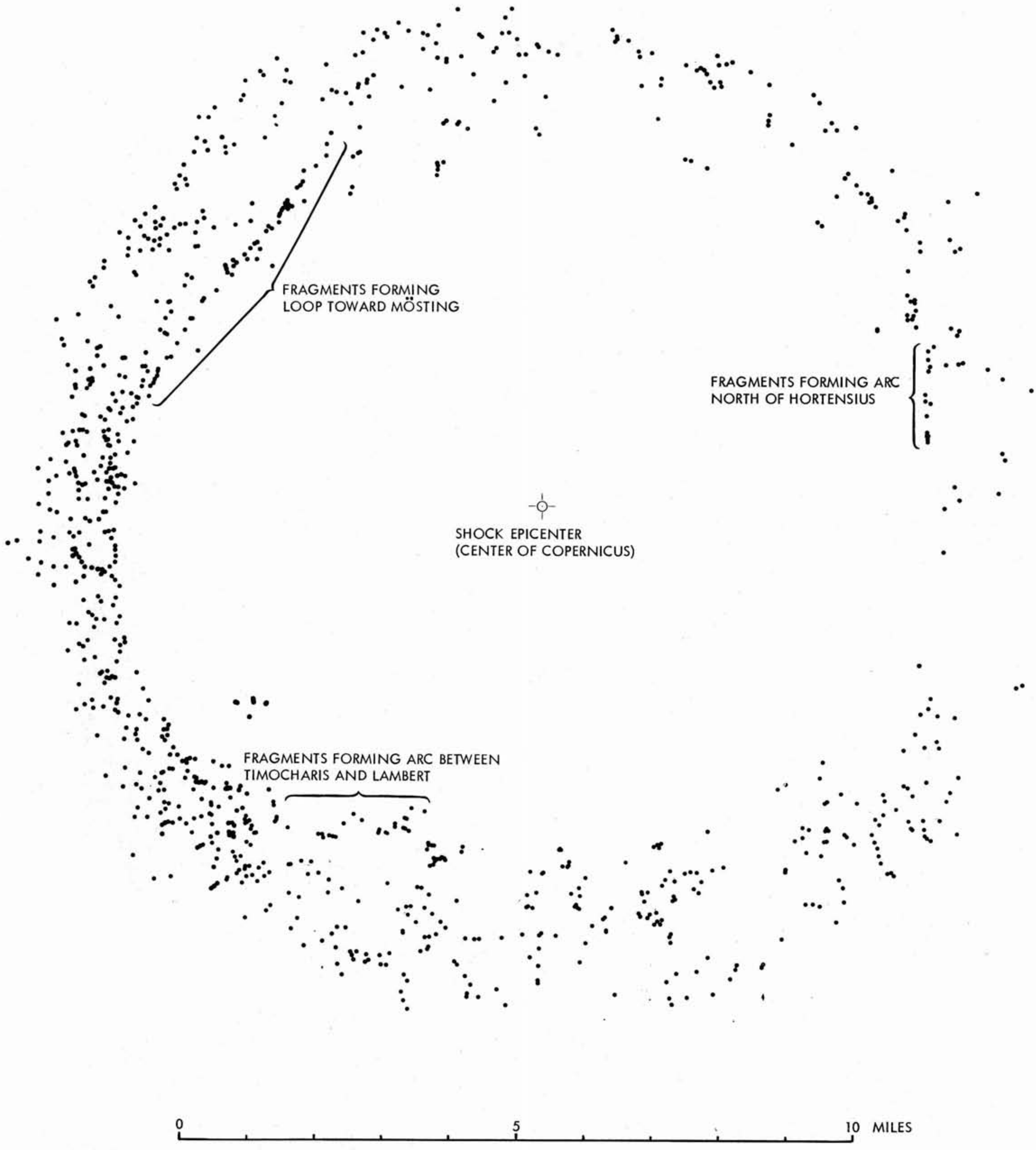


Figure 9. Provenance of fragments which formed secondary impact craters in the Copernican ray system

fragments in the reconstructed internal ballistic pattern provides some evidence bearing on this question.

The radial frequency distribution of fragments, after transposition into the crater, shows a series of pronounced maxima and minima that correspond to maxima and minima in the original range frequency distribution of the secondary impact craters (Figure 4). This distribution has been divided into three sectors around Copernicus (Figure 10), and the individual maxima may then be identified with major rays or belts of secondary impact craters. In nearly all cases, it was found that a maximum in one sector coincides closely in radial position with a maximum in one of the other sectors. Such a coincidence suggests that the interior fragmentation pattern has elements of concentric symmetry around the shock epicenter. A concentric pattern would be found if the lunar crust were layered and clusters of fragments were formed by the separation or pulling apart of layers. This implies that clusters which are separated radially in the fragmentation pattern as plotted in Figure 9 may actually have been separated vertically in the crater.

Some features of the ray pattern seem easiest to explain by a combination of vertical and horizontal separation of fragment clusters. For example, the very long ray trending north between Timocharis and Lambert is intersected or joined by two east-west trending cross-rays. One of these crosses north of Pytheas, and the other runs immediately north of Turner. The greatest density of visible secondary impact craters along the north-south ray occurs near the intersections. Such relations could be explained as follows: The north-trending ray was formed by an elongate cluster of fragments with the approximate shape and orientation shown in Figure 9. However, one end of the cluster originally lay at a deeper level in the lunar crust than the other, and more than two separable layers were included in the cluster. The uneven distribution of secondary impact craters along the ray would be due to the tendency of the fragments of each layer to hang together momentarily on ejection. This interpretation implies that the fragments of the Turner cross-ray are derived from a different layer than those of the Pytheas cross-ray.

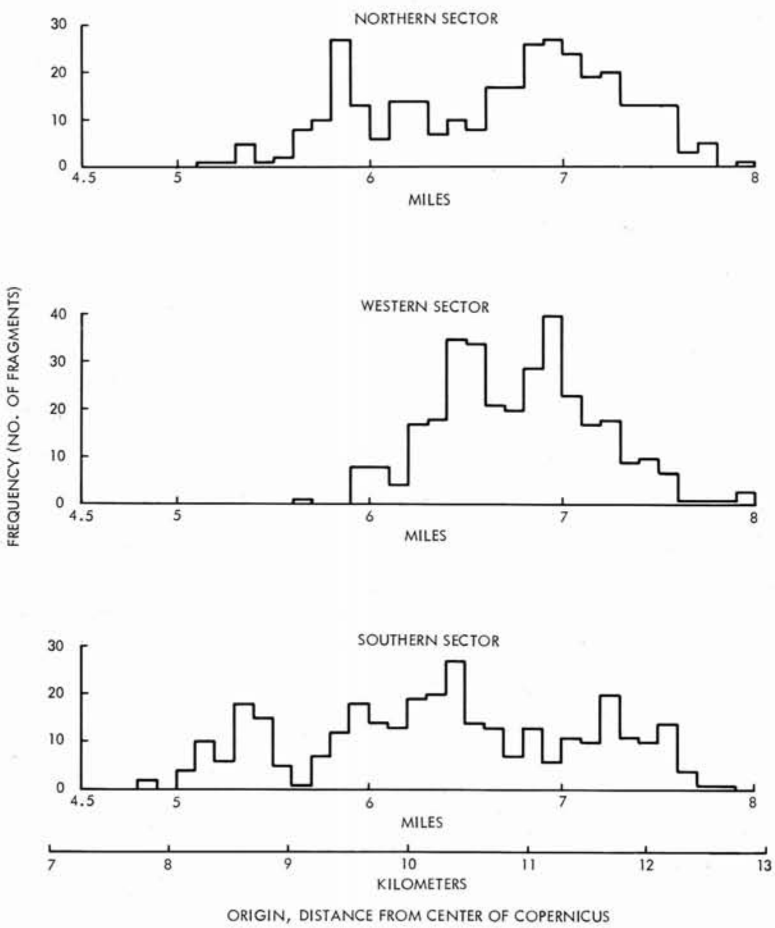


Figure 10. Frequency distribution (by sectors) of secondary impact crater-forming fragments according to calculated original position in Copernicus

From this interpretation, it is not immediately evident which of the two cross-rays would represent the deeper layer. The shock propagation theory suggests that, along a given slant radius, the upper layer should have the higher ejection velocity. If this be the case, the Pytheas cross-ray must represent the higher layer. On the other hand, empirical evidence from high-explosive cratering experiments suggests that, along certain slant radii, fragments from the deeper layer would travel farther.[11] The data from these experiments may not be applicable because the fragments are ejected more by the impulse derived from expansion of the explosion gases than by the shock.

Keeping in mind these different factors that may influence fragmentation, we may examine the question of the actual size of the fragments that formed the secondary impact craters. At least 975 fragments are derived from an annular segment of the lunar crust with an area of about 330 square kilometers and an unknown depth. If the fragments are assumed to be of equidimensional shape and all derived from one layer, the maximum mean diameter of the fragments would be about 600 meters. If the depth from which the large fragments are derived was about three times the mean diameter of the fragments, the maximum mean diameter would be closer to one kilometer. Probably very few, if any, of the fragments that formed the secondary impact craters were as much as one kilometer across. First, a mean diameter of a little less than one kilometer would require that essentially all of the material ejected at ray-forming angles (Figure 8) were large fragments. However, empirical data on the size-frequency distribution of fragments produced by shock show that about 50 percent of the material will be more than an order of magnitude smaller than the maximum size. Secondly, there is a much larger number of secondary impact craters in the visible size range than has actually been compiled. A better guide to the actual size of the fragments may be provided by the length of the cluster of fragments that was ejected toward Mösting to form the loop-shaped ray. At least 50 fragments were derived from a cluster which was only 7 kilometers long. The mean diameter of the fragments which formed the visible secondary impact craters in this loop was probably in the range of 100 to 200 meters.

These results have an immediate bearing on the origin of the secondary impact craters of elongate shape. Many of these craters are oriented at angles to the radial direction from Copernicus and thus cannot be attributed simply to plowing or skidding of a low-angle missile on the lunar surface. Arbitrarily oriented craters could be formed by arbitrarily oriented elongate fragments, but the length required for the fragments is too great. Some of the secondary impact craters are more than 5 kilometers long. All of the markedly elongate craters are, therefore, probably compound craters formed by the impact of two or more fragments travelling close together. All gradations can be found, especially along the inner margin of the ray system, between short chains of secondary impact craters and compound craters in which the partially merged components can still be recognized. The formation of these chains and compound craters is simply a lesser manifestation of the phenomenon of fragment clustering which is responsible for the broad-scale pattern of the rays. Ejection of fragments from large primary impact craters thus provides another mechanism, in addition to volcanism, by which chains of small craters could have been formed on the lunar surface.

D. Alter: I think that part of your hypothesis is certainly true. However, the oversystems which take in, not one, but a number of craters would be difficult to explain by an impact ejectamenta hypothesis. For example, consider the great rays that go from Tycho and link up with the Stevinus-Furnerius system. One of these rays stops at a cross-ray that comes from Stevinus. Then there is the great oversystem that takes in Copernicus, Kepler, Olbers and Aristarchus. I believe that those extremely bright craters, such as Copernicus, were formed by asteroids. However, the craters around them seem to be 'blowhole' craters along faults connected with the great explosion.

There's another point I'd like to mention. I haven't been able to see the lack of symmetry of those little craters. Except for places where two of them seem to have come together, most of them appear to be round. If they appear lopsided it is because the material which was ejected from the 'blowhole' crater was carried away by wind from the great explosion. The temporary atmosphere caused by gases escaping from Copernicus, or other large craters, would carry the discharge from the little craters in an almost radial direction. I think that this is the most satisfactory explanation.

F. E. Bronner: I don't think that you are really disagreeing in the elongate appearance of these craterlets. What you have said is essentially the same explanation which Dr. Shoemaker has already given us. Each elongate craterlet is, in effect, a number of them coalescing. Isn't this correct?

E. M. Shoemaker: That is right. I think that they are, almost invariably, multiple features. I agree that many lunar craters which form chains are 'blowhole' craters. Our problem is distinguishing them from craters of primary or secondary impact. We won't be able to solve this, of course, until we get better resolution in our photographs or until we can get up there and pound our pick on them.

For the case I presented, the impact velocity of the asteroid would be about 17 kilometers per second (Equation 11). In my opinion, this means that Copernicus could have been formed at any time in geologic history. It was certainly formed later than most of the surrounding features, except perhaps for the little dark halo craters.

I am a little disappointed that I was not able to persuade you that the alignment of the gouges has a complete explanation in the interior ballistics, the way in which the rock breaks up. The alignments are the result of the linear directions in the fragmentation patterns behind the shock front.

R. E. Page: I don't quite agree that the velocity of the ejected material would be high enough to cause a crater as large as Copernicus.

E. M. Shoemaker: The velocity at which a fragment hits the surface would be about the same as the ejection velocity which I have computed. It would be about 0.4 kilometers per second for the range of rays from Copernicus. The question is: How large a crater would be formed from a given sized fragment travelling at about one kilometer per second? A chunk of ordinary rock travelling at that velocity would merely splash when it hit the lunar surface; it would make a gouge something like that from a drop of water. Suppose a fragment which is 500 feet in diameter makes a gouge that is one mile across — large enough to photograph. This gouge would be 10 times as large as the fragment. These are about the dimensions we are dealing with. I think that, in most cases, the elongateness is caused not by a single fragment but by a cluster of fragments.

R. E. Page: Do you think that the far sides of these craters would be piled higher than the sides toward Copernicus?

E. M. Shoemaker: I think that would depend entirely upon the arrangement of the cluster. Various combinations of fragments in a cluster could result in almost any arrangement on the rim. If it were a single fragment, the side away from Corpernicus would be piled higher. The rims of these craters are often so low that it is difficult to be sure.

L. Giamboni: Approximately a third of these feather-like splashes near Corpernicus are aligned so that they point toward the center of the crater. Another third, or more, are aligned to point toward the eastern rim, but comparatively few of them point south or west of the crater. So there is a statistical bias of these splashes to one side of Copernicus. The splashes around Tycho are also biased to the east. The statistics are somewhat proportionate and are not, in any sense, random. Perhaps these alignments may be explained in terms of Coriolis forces and in terms of rotation, so that the times of flight would have to be somewhat longer than those indicated by your calculations.

E. M. Shoemaker: I don't think I could define the axis of the feather-shaped elements from Copernicus closely enough to reach such a conclusion. I hold deep reservations about our ability, at this time, to orient these elements. In the case of Tycho, I have an explanation which is completely different from yours. I think that the large rays from Tycho, which you discussed most extensively in your paper,[10] are closely analogous to the large rays of Copernicus, which do not radiate from the center of the crater. They are arc-shaped and, in some cases, very nearly straight. They can point to various parts of the rim, or not toward the crater at all. Only if the material split into radial, pie-shaped fragments, with each 'piece of pie' ejected to form a ray, would the ray be radial.

J. Green: Photographs of bomb craters show radial structures and do not show, to my satisfaction, tangential rays. On the other hand, calderas are commonly bounded by tangential fractures. If Copernicus was volcanic, as its internal central volcano-like structures indicate, a tangential ray pattern produced by internal processes would be a logical feature to expect. How do you explain the lack of relief of these rays if they are all throw-out debris of most of the volume of Copernicus?

E. M. Shoemaker: It would be very difficult to explain a ray that did show relief. Suppose each one of these fragments was about 150 to 300 meters in diameter. If they were splashed out over hundreds of square kilometers on the lunar surface, we would quickly see why there isn't much relief in the rays. The result would be a very thin layer of fine debris.

J. Green: I'd like to bring out a point concerning the gouges that were shown. Some "on-ray" gouges are parallel with the rays; others are not. In Figure 2 there is an *en échelon* pattern of three features in a direction which is not radial to Copernicus but at an angle to it. The explanation you gave was that some clusters of fragments travelled in a line to produce a gouge that was not radial. How can one accept three such clusters impacting so as to produce three parallel lines on a ray? If this were the result of fracturing (i.e., if the rays were tectonic in origin) and if there were a slight differential movement on one side of the fracture with respect to the other, a series of tension fractures would be formed in the orientation shown. These fractures could localize volcanic activity on the rays. It is difficult for me to think of a train of ejectamenta producing a gouge which has all of the appearances of a tension fracture formed by differential movement along a zone of weakness.

E. M. Shoemaker: You will also find that other gouges are "splayfoot" across the rays. I like these because they fit my hypothesis, and especially because they are on the side of the arc toward the crater. It is generally true that these gouges are at the proximal ends of the elements in the cross-rays. However, I think we need to see this in more detail before we can call it a tension feature. The only thing I am convinced of is that we can see an elongate groovè in these places.

J. Green: What are the statistics of having ejecta form three *en échelon* grooves in such a series as is shown here?

E. M. Shoemaker: This is not random at all. The point is that the clustering of the fragments is related to the interior ballistics of the crater, which are, in turn, governed by fracture patterns in the lunar crust.

C. W. Tombaugh: For a long time I was an adherent of the ejecta hypothesis *in toto,* but now I am not. For the short rays, this hypothesis may well be applicable. However, I don't think it can account for the long rays of some of the bright ray systems.

We might test this hypothesis on another planet, such as Mars, which has an atmosphere. In the oasis-canal system of Mars, many of the canals are tangent to the oasis, which we might consider the equivalent of the rim of an impact crater. However, it would be difficult to find dust particles travelling over hundreds of miles on Mars because its atmosphere would impede such an ejection of fragments.

If a mass of loose fragments is ejected, each particle will retain its azimuth direction. As they travel long distances they should become fanned out, but they do not. A wide range of velocities, or angles of impact, would be required to have the ejecta dribble down ever so perfectly over hundreds of miles to form long rays —especially like some of the rays from Olbers. To have them so tightly confined in azimuth seems to me inconsistent with your model.

J. Green: I would like to read an excerpt from Jules Verne who, incidentally, was an excellent selenographer. He, of course, did not believe that the rays are external in origin. This is what he has written about the rays: "What was the origin of these sparkling rays, which shone on the planes as well as on the reliefs, at whatever height they may be? All started from a common center, the crater of Tycho. . . . Herschel attributed their brilliancy to currents of lava congealed by the cold; an opinion, however, which has not been generally adopted. Other astronomers have seen in these inexplicable rays a kind of moraines, rows of erratic blocks, which had been thrown up at the period of Tycho's formation. 'And why not?' asked Nicholl of Barbicane, who was relating and rejecting these different opinions. 'Because the regularity of these luminous lines, and the violence necessary to carry volcanic matter to such distance, is inexplicable.' . . . 'Indeed,' continued Michel, 'it is enough to say that it is a vast star [pattern], similar to that produced by a ball or a stone thrown at a square of glass.' 'Well,' replied Barbicane, smiling. 'And what hand would be powerful enough to throw a ball to give such a shock as that?' 'The hand is not necessary,' answered Nicholl, not at all confounded, 'and as to the stone, let us suppose it to be a comet.' 'Ah! those much-abused comets!' exclaimed Barbicane. 'My brave Michel, your explanation is not bad; but your comet is useless. The shock which produced that rent must have come from the inside of the star [pattern]. A violent contraction of the lunar crust, while cooling, might suffice to imprint this gigantic star.' 'A contraction! something like a lunar stomach-ache,' said Michel Ardan. 'Besides,' added Barbicane, 'this opinion is that of an English savant, Nasmyth, and it seems to me to sufficiently explain the radiation of these mountains.' 'That Nasmyth was no fool!' replied Michel."*

This gives us the viewpoint of the other camp, that the rays are not ejection debris—they are not fractures produced by the impacting of a meteor. However, they could be fracture patterns produced by the same generally operative processes that have localized calderas on Earth.

**From* The Omnibus—Jules Verne, *"Round the Moon," J. B. Lippincott Co., Garden City, N. Y., ch. XVIII, pp. 786-787.*

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