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

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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). On 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 ≧ 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 ≧ 7 km.

These two crater samples, continental D ≧ 40 km and post-mare D ≧ 7 km, were sorted by $\eta$ in zones, the mean $\eta$ 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 km² 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

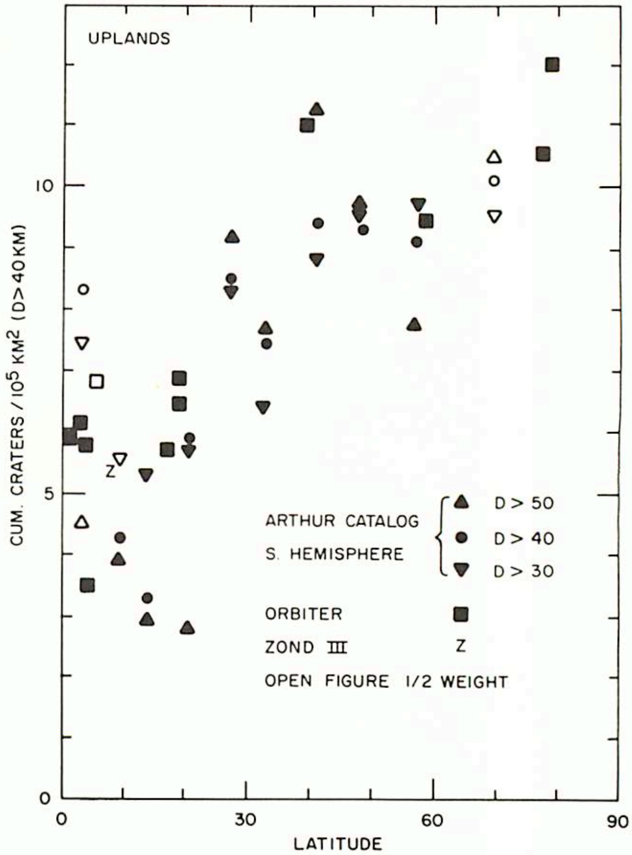


*Fig. 1* Crater density vs. latitude for craters of D > 40km (unless otherwise marked) on upland (i.e. "continental") surfaces. A pronounced polar concentration is found.

that the class 3 (damaged rims, generally pre-mare) is complete at diameters D ≧ 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 km² in continental areas as in maria, indicating that class-1 craters as a group date into pre-mare

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

time. Fig. 5 plots the class-1 latitude distribution for D $\geqq$ 10 km corrected in the following way to give the number of class-1 craters/km$^2$ 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 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.

*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.

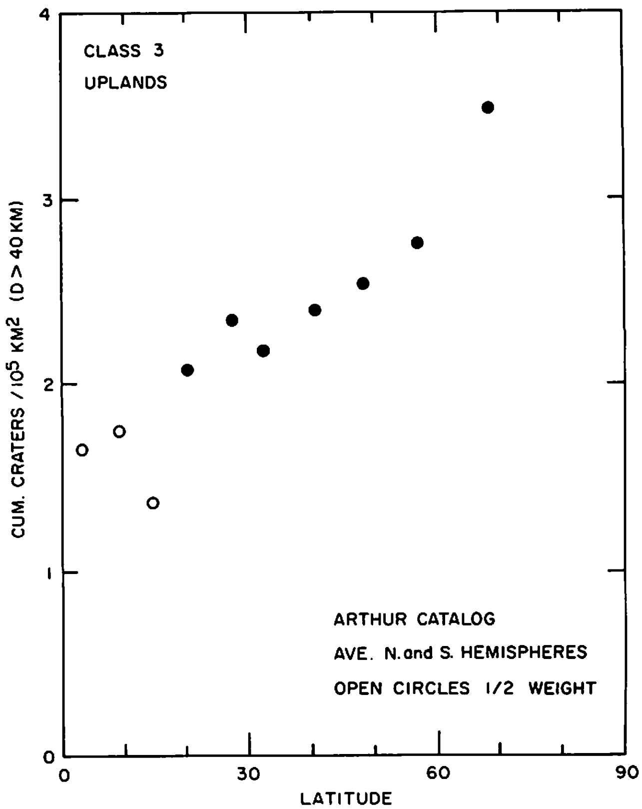


*Fig. 2* Crater density vs. latitude for Arthur catalog class 3 craters on upland surfaces.

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

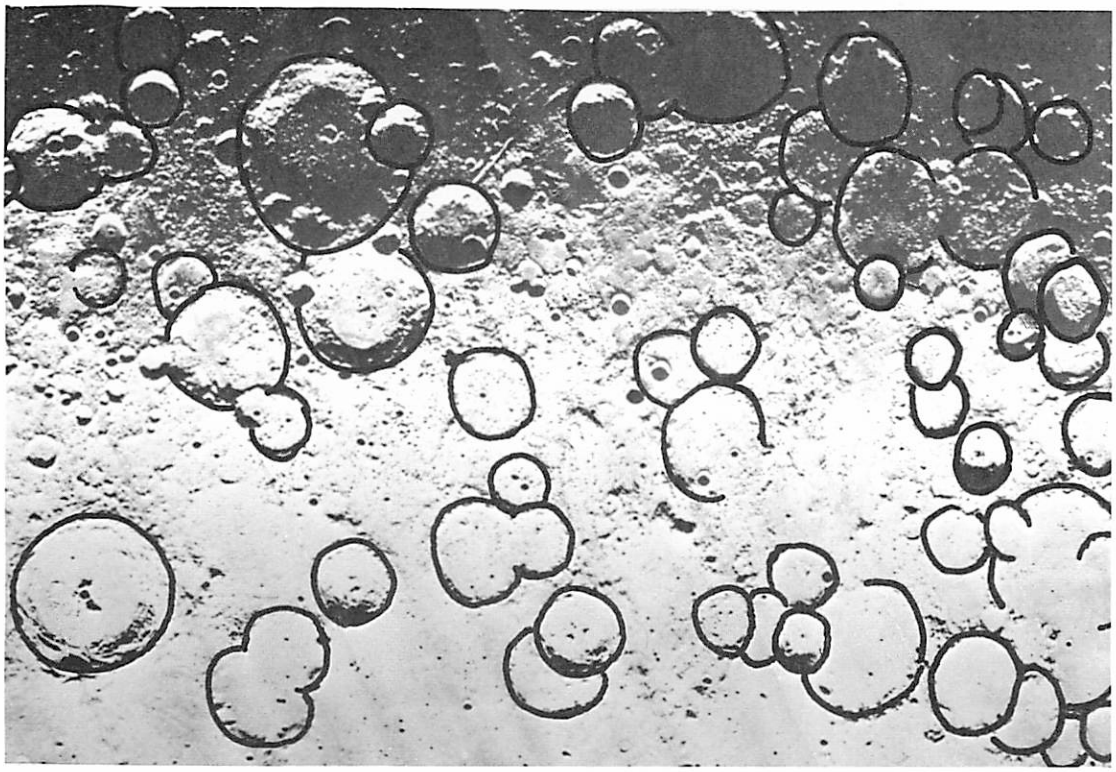

*Fig. 4* North polar region (pole at lower right). Orbiter IV Frame M-190. Scale is same as Fig. 3. Craters of D > 40km number 59, giving a polar/equatorial density ratio of 1.7 for these two areas (Figs. 3 and 4).

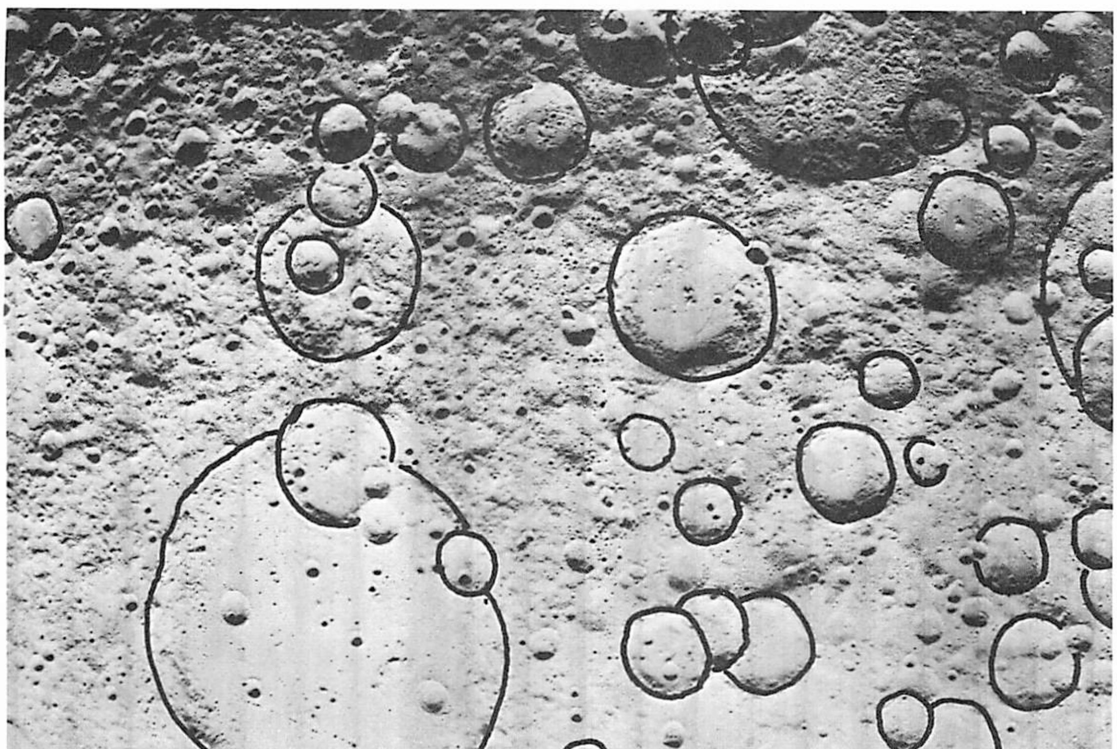

*Fig. 3* Equatorial region on moon's far side, centered on lunar equator. Orbiter I Frame 116, with craters of D > 40km outlined. Centers of 35 such craters are included in this area.

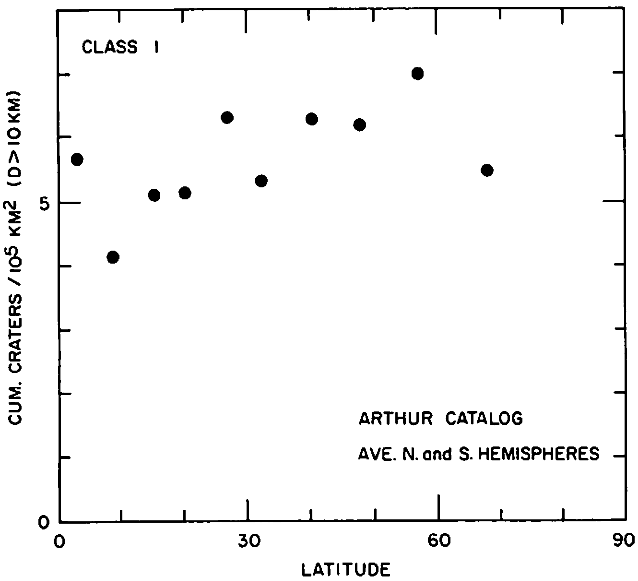


*Fig. 5* Crater density vs. latitude for Arthur catalog class 1 craters. The density values are corrected to equal the values found on *upward,* not mare, surfaces (see text). Only a marginal polar concentration is detected.

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.

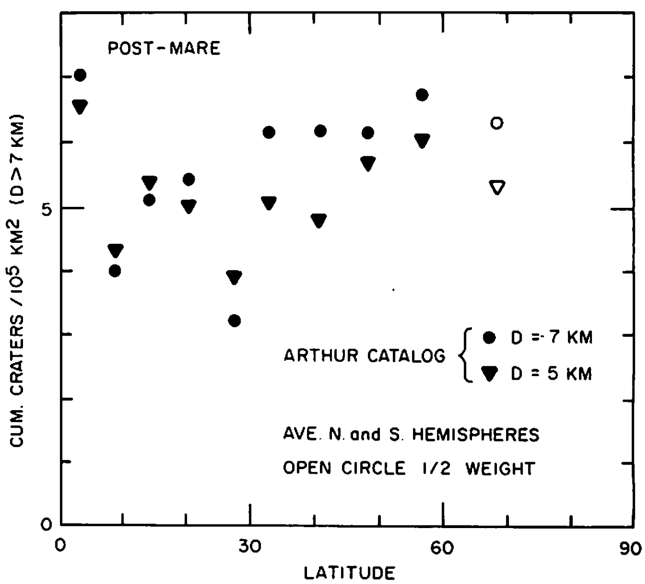


*Fig. 6* Crater density vs. latitude for post-mare craters. The density values are corrected for D $>$ 7km, although two diameter ranges are plotted.

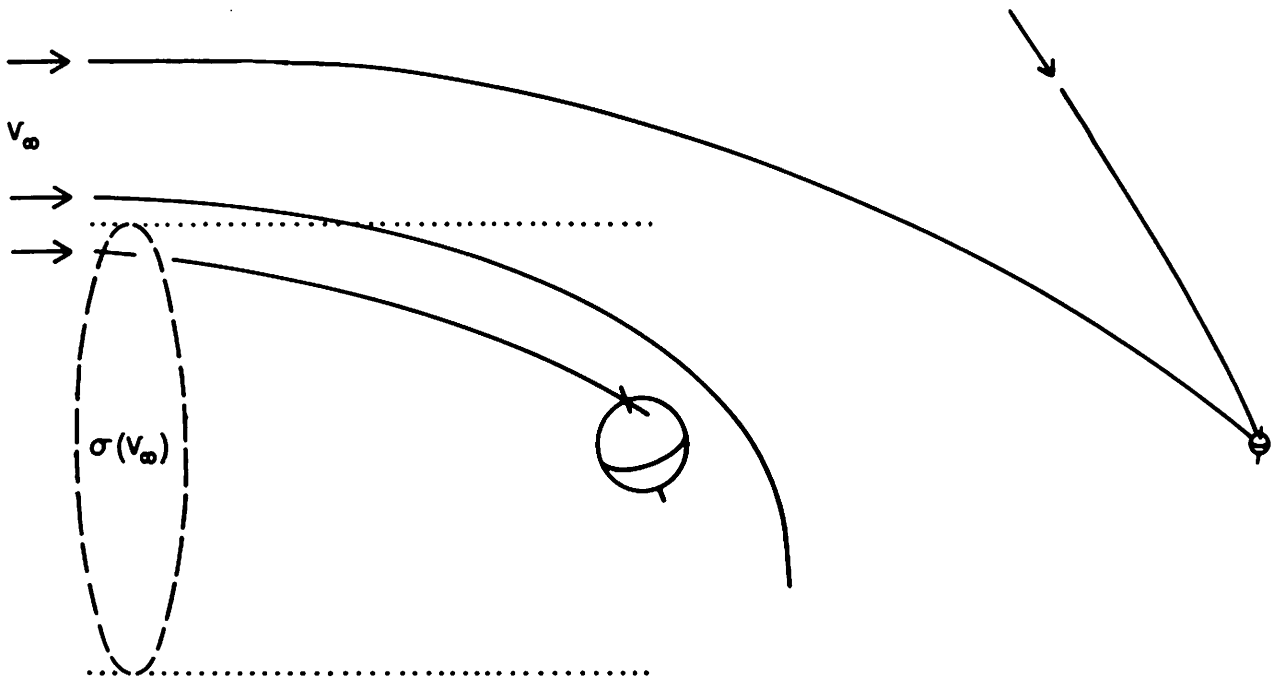


*Fig. 7* Schematic diagram of possible dynamical explanation of polar concentration of old craters. Low-inclination planetesimals approaching the earth-moon system with velocity $V_\infty$ strike the moon preferentially at high latitudes because of shielding by the earth's gravitational cross section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

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