DISTRIBUTION OF LUNAR IMPACTS BY OBJECTS IN PARABOLIC LOW INCLINATION ORBITS

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Abstract. This paper presents a computer investigation extending to the case of parabolic orbits, an earlier investigation conducted by Barricelli and Metcalfe (1969) on lunar impacts by external low eccentricity satellites as a means to interpret the asymmetric distribution of lunar maria. Parabolic orbits can be approximated by two kinds of objects:

(1) High eccentricity external satellites may, near periapsis, approach the Moon with orbital velocity and other characteristics closely resembling those of a parabolic orbit.

(2) Asteroids and meteoroids approaching the Earth–Moon system with a low velocity may have moved in a nearly parabolic orbit when they reached the lunar distance from the Earth at the time when the impacts which carved the lunar maria took place.

The investigation gives, therefore, not only additional information relevant to the interpretation of the distribution of lunar maria by the satellite impacts hypothesis (in this case high eccentricity ones), but also information about the alternative hypothesis (Wood, 1973) that asteroid impacts rather than satellite impacts were involved.

1. Introduction

In a series of earlier papers Barricelli and Metcalfe (1969, 1975) and Metcalfe and Barricelli (1970), problems related to the distribution of lunar impacts by other (minor) Earth satellites have been studied. In particular the asymmetric distribution of the impacts which created the lunar mare basins has been interpreted on the assumption that they were impacts by earlier Earth satellites, Urey (1952, 1962), Gilbert (1893). In this paper the investigation has been extended to a study of lunar impacts by objects approaching the Earth–Moon system in parabolic orbits. The orbits we have investigated were contained in the same plane as the lunar obrit, but we have studied both prograde and retrograde orbits in order to obtain as much information as possible with limited resources about the impacts by this kind of objects.

Lunar impacts by objects approaching the Earth–Moon system in an approximately parabolic orbit are important on two accounts:

(1) Because the highly eccentric elliptical orbits some Earth satellites may have had would resemble parabolic orbits in the proximity of their periapsis, which is the part of the orbit in which a collision with the Moon has its highest probability (see Barricelli and Metcalfe, 1969).

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(2) Because objects approaching with low velocity, which have an enhanced probability of entering the Earth–Moon region (see below), would move in an approximately parabolic orbit with a focus on the barycenter of the Earth–Moon system, before entering the Moon's area.

The study is therefore of interest for the question of lunar impacts both by eccentric Earth satellites and by objects approaching the Earth–Moon system at a low relative velocity; meaning low relative to the orbital velocity v of the Moon which is given by

$$v = \sqrt{\frac{GM}{A}}; \tag{1}$$

M being the mass of the Earth, G, the gravitational constant, A, the semi-major axis of the lunar orbit. The present orbital velocity of the Moon is approximately $v = 1$ Km/sec. But in the past, when the Moon was closer to the Earth its orbital velocity may have been greater. All objects approaching the Earth–Moon system with a velocity u in orbits which, in the absence of Earth's gravitational field, would have carried them to a distance smaller than

$$R = A\sqrt{1 + \frac{2v^2}{u^2}} \tag{2}$$

will be focused by the gravitational field into the Earth–Moon region (meaning inside a sphere of radius A centered on the Earth, Barricelli 1973). According to Equation (2) the smaller u is relative to v, the larger is the radius R of the region of space in which material approaching with relative velocity u will be focused into the Earth–Moon region.

It is clear that asteroids and meteoroids with a low velocity relative to v will have a greatly enhanced probability of entering the Earth–Moon region.* Because of the low asymptotic velocity these objects will also approach the Earth–Moon system in orbits resembling parabolic orbits, the better the smaller their velocity.

We shall consider separately the two alternative interpretations of lunar impacts: the satellite impact alternative and the meteor impact alternative.

2. The Satellite Impact Alternative

The case of satellite impacts with low eccentricity has already been presented (Barricelli and Metcalfe, 1969, 1975). In the same publications evidence was presented that the probability of colliding with the Moon was low for satellites with a high inclination, and approached a maximum value for low inclination external satellites at the time when the gradually expanding lunar orbit approached their periapses. We shall now present the results of a comparable investigation carried out for objects in parabolic orbits and inclin-

* By the same token collisions with the Earth are expected to be greatly enhanced for objects with a low asymptotic velocity relative to $\sqrt{(GM/R_E)} \approx 8$ Km/sec (where R_E is the radius of the Earth). This enhancement should be detectable for meteors in asteroidal orbits, but not so easily for objects in cometary orbits because of the much greater eccentricity and inclinations of these orbits which would seldom give asymptotic velocities below 8 km/sec.

ation equal to zero used to simulate satellites with high eccentricity and low inclination. We found it unnecessary to use various low inclinations other than 0° relative to the lunar orbit since we did not expect to obtain much relevant information in addition to that obtained in earlier experiments (Barricelli and Metcalfe, 1969, 1975).

The Moon is assumed to have had a bound rotation to the Earth at the time when the impacts occurred, but not necessarily with the same face towards the Earth, which is facing the Earth today.

It is well-known that the probability of an impact is greatest for those objects whose velocity relative to the Moon is low in its proximity. Such satellites would be moving in a prograde direction in or near the plane of the lunar orbit and would have a perigee or apogee close to the lunar orbit. As long as we are dealing with satellite impacts, we may disregard orbits with perigees inside the orbit of the Moon, and also orbits with apogees close to the Moon. In fact it is well-known that the Moon has once in the past been very close to the Earth and near the Roche limit. No sizeable satellite could have been formed or could have survived for a long time inside the Roche limit. The Moon can, therefore, only have collided with external satellites – meaning with satellites whose perigees were outside the orbit of the Moon – in its journey from the Roche limit to its present orbit.

A large portion of the satellite impacts is assumed to have occurred between the Roche limit (at a distance of 2.89 R_E from the Earth's center) and a distance of 10 R_E from the Earth, R_E being the radius of the Earth. In fact, in all the other satellite systems, except Neptune, the radial distribution density of moons is largest below 10 planetary radii. We have, therefore, selected an Earth–Moon distance of 38 400 km (which is one tenth of the Moon's present distance from the Earth and about 6 R_E) for our investigation.

A convenient way to represent the results of an investigation of satellite and meteor impacts on the Moon as well as other results of the investigation is to plot the results on a "fixed Earth–Moon perigee chart" like those presented in Figures 1, 3 and 4. In the fixed Earth–Moon chart both the Earth and the Moon are assigned a fixed position in a reference frame which is assumed to rotate together with the Earth–Moon system. For simplicity the Earth–Moon distance is assumed to be constant. The perigees of incoming satellites are designated by one of the symbols ○, +, – and ● in the respective positions they would have occupied (pre-interaction perigee positions) if the mass of the Moon had been equal to zero, and the mass of the Earth had been increased by an amount equal to the mass of the Moon (for further details cf. Barricelli and Metcalfe, 1969).

For each pre-interaction perigee position, the orbit which would have been the result of interaction with the Moon was calculated. If within two revolutions of the Moon the interaction resulted in a collision with the Moon on the side facing the Earth, the perigee position was marked with the sign, +. If the result was a collision on the far side, the sign, –, was used to mark the perigee position. An open ring, ○, was used in the cases in which the interaction resulted either in a collision with the Earth or in a new orbit easily distinguishable from the pre-interaction orbit in a drawing the size of Figure 1. A filled ring, ●, was used in those cases in which none of the above described events was observed within two revolutions of the Moon.

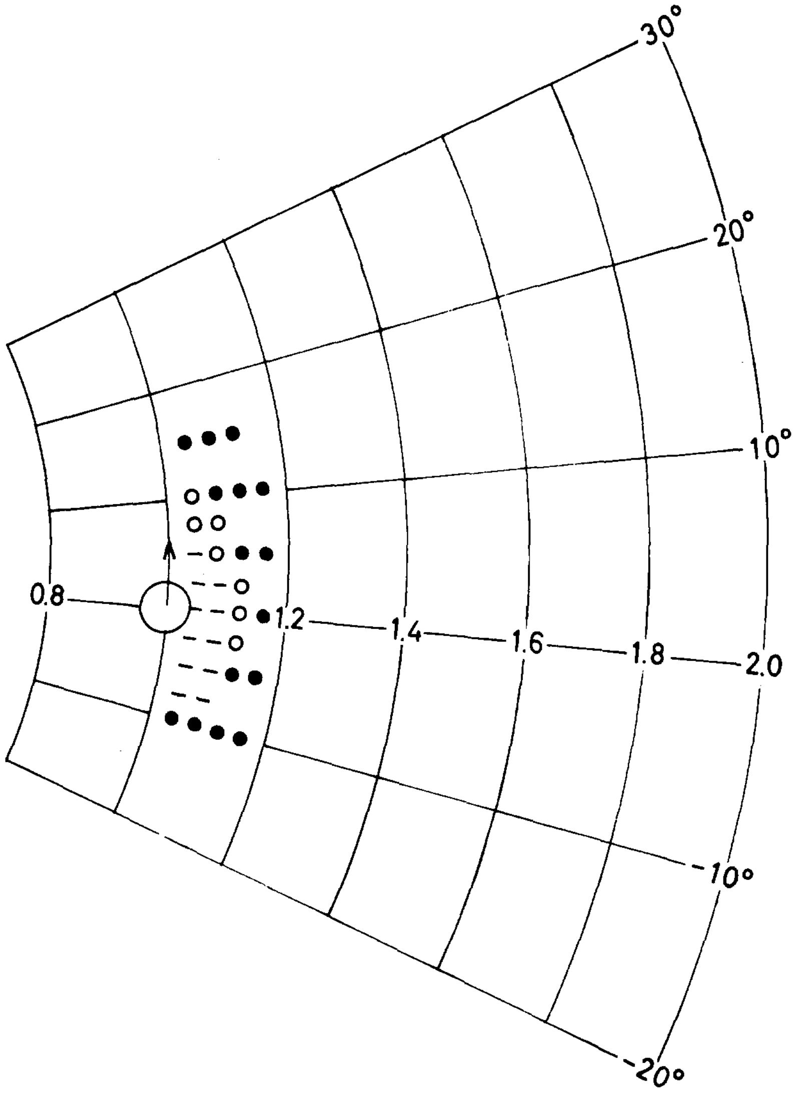

Fig. 1. Satellite interaction perigee chart. The reference system used is fixed to the Earth and the Moon, which is assumed to be moving in a circular orbit with constant velocity (theoretical case without perturbations). Summary of interaction types by satellites with different pre-interaction perigee positions relative to the Moon. The pre-interaction perigee position is marked by one of the signs +, —, ○, •; +, collision with the Moon on the Earth side; —, collision with the Moon on the far side; ○, heavy interaction without collision with the Moon; •, no heavy interaction.

The probability that a satellite which has acquired an orbit substantailly different from the original one (open rings) should subsequently collide with the Moon in a later interaction is considered low (cf. Barricelli and Metcalfe, 1969) compared with the probability of other developments such as a collision with the Earth, or escape into space.

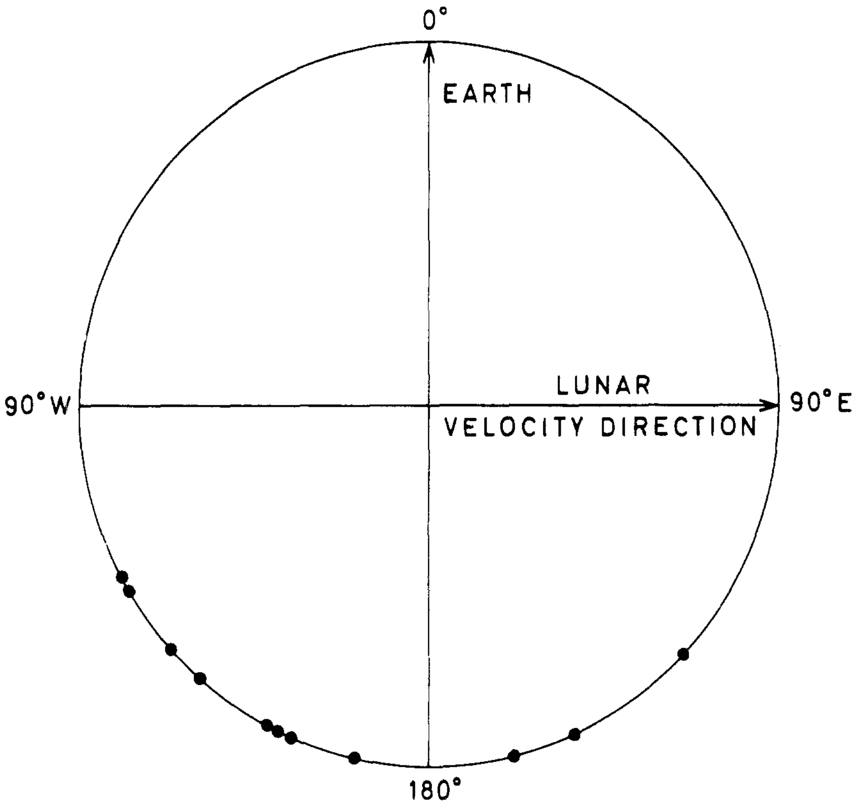

Fig. 2. Equatorial crosssection of the Moon. Impacts by highly eccentric (parabolic) satellites defined in Figure 1, are marked by filled rings •.

We found it therefore sufficient to restrict our investigation to the study of lunar impacts by satellites external to the orbit of the Moon.

The chart of perigees given in Figure 1 shows that there is a region of "heavy interactions" between the Moon and the satellite, leading to one of the three types of events described by the symbols +, − and o. This region may be called a "heavy interaction window" containing among others the pre-interaction perigee positions leading to impacts on the Moon. We find 11 impacts on the far side (− signs), at the time when the impacts took place and 7 heavy interactions leading to other developments (o marks).

When we compare these data with earlier results, we find that the heavy interaction window presented in Figure 1 is much (more than 5 times) smaller than the similar window determined for low eccentricity external satellites (see for example Barricelli and Metcalfe, 1975, Figure 2). This is no surprise, since a prograde satellite approaching the Moon at its perigee from a nearly parabolic orbit would have a higher speed relative to the Moon, than a satellite approaching its perigee from a low eccentricity elliptical orbit.

However the distribution of satellite impacts on the lunar equator (the only place

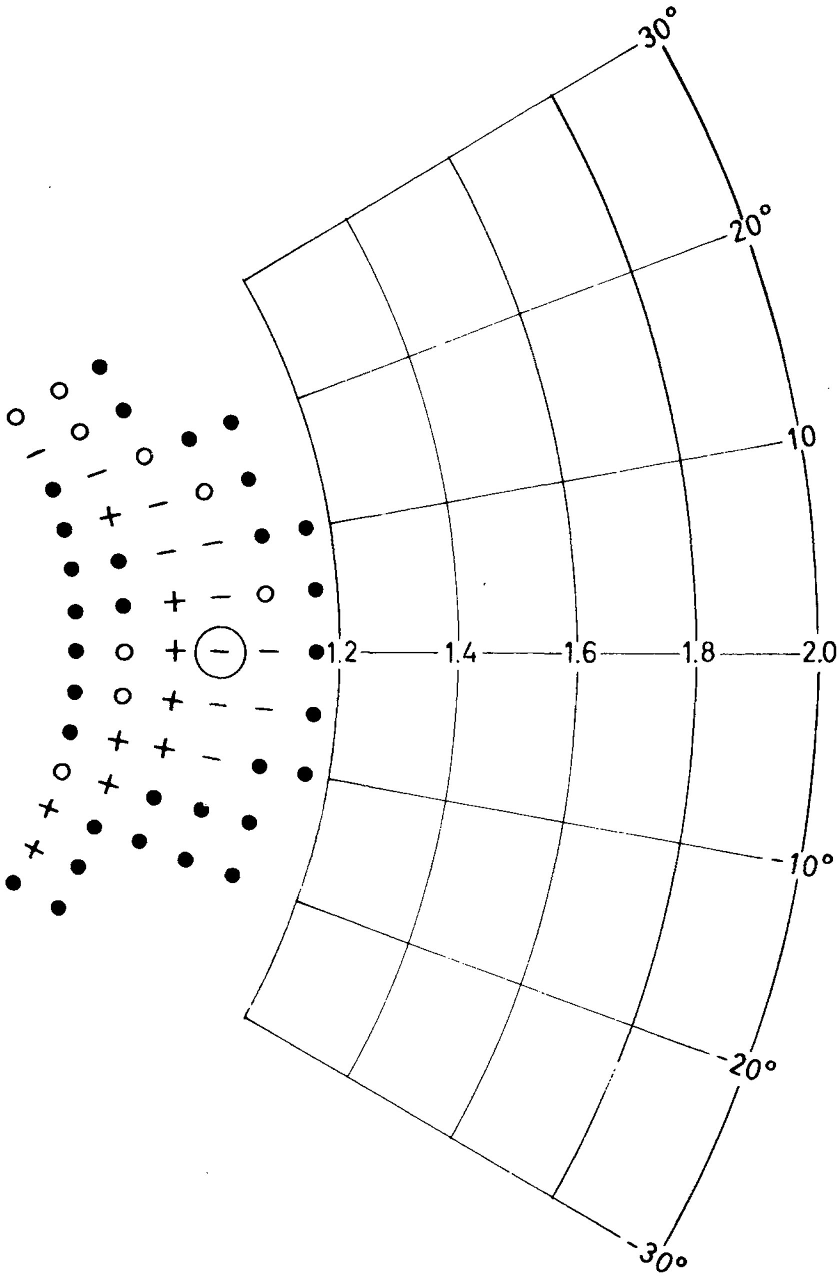

Fig. 3. Interaction perigee chart for asteroids entering with a prograde inclination 0° orbit. See Figure 1 for symbols used.

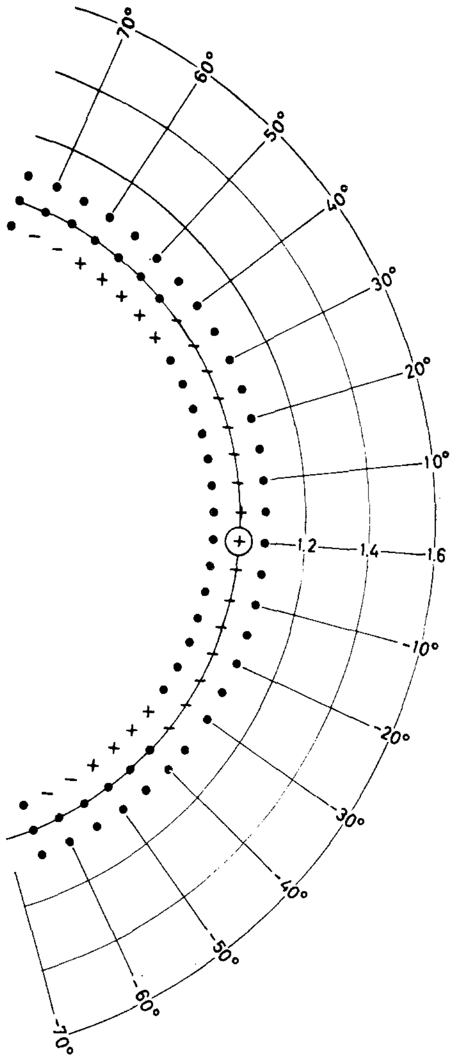

Fig. 4. Interaction perigee chart for asteroids entering with a retrograde inclination 180° orbit.

where satellites of inclination zero can hit the Moon), which is presented in Figure 2, does not show a drastic difference from the distribution obtained with low eccentricity satellites of inclination equal to zero (which is shown by the equatorial impacts presented in the Barricelli and Metcalfe 1975 paper on Figure 1). All of the 11 impacts registered in Figures 1 and 2 were on the far side of the Moon at the time they occurred. In the earlier low satellite eccentricity experiments 21 out of 24 equatorial impacts were on the far side. The difference is statistically not significant, nor is the lunar surface distribution of the impacts presented in the respective figures.

As far as these data can tell, the asymmetric distribution of maria on the Moon can probably be interpreted just as well by high eccentricity satellite impacts as by low eccentricity satellite impacts or by a mixture of both. In order to decide between the two one would need other arguments or a much larger number of high eccentricity satellite impacts. In both cases one needs the assumption that the far side of the Moon and the side facing the Earth have been interchanged by a major impact (probably the impact which created the Mare Imbrium, see Barricelli and Metcalfe, 1969).

3. The Asteroid Impact Alternative

So far we have applied to the satellites with highly eccentric (nearly parabolic) orbits the same method used in the early study (Barricelli and Metcalfe, 1969). However the method can also be applied in an investigation of impacts by objects moving in parabolic pre-interaction orbits, which are the orbits of slow meteoroids and asteroids entering the Earth's gravitational field from space. Also in these cases it is convenient to represent the results in a fixed Earth–Moon perigee chart. This has been done in Figure 3 for prograde orbits and in Figure 4 for retrograde orbits complanar with the Earth–Moon system. Of course in this case not only perigee positions outside the orbit of the Moon but also perigee positions inside the orbit of the Moon have been marked in the chart. Pre-interaction perigee positions outside the orbit of the Moon have been restricted to the number required in order to make them comparable with those inside the orbit of the Moon, by using a common mask distance (compare Figure 3 with Figure 1 where a higher density of perigee positions was used in order to obtain a significant number of the impacts). In Figure 5 presenting an equatorial crosssection of the lunar impacts obtained with prograde orbits (registered in Figure 3) are marked with filled rings, •, and impacts obtained with retrograde orbits (registered in Figure 4) are marked with open rings, o. We observe that prograde asteroids strike the Moon prevalently but not exclusively on the trailing edge whereas the retrograde asteroids strike the Moon exclusively on the leading edge. The last type of impact is more strongly represented, and the result is an excess of impacts on the leading edge when both open and filled rings are included. Particularly the central portion of the leading edge around 90°E, from approximately 85°E to approximately 105°E, receives a relatively high density of impacts. Despite the fact that in this study only asteroid orbits complanar to the orbit of the Moon are considered, when we take into account that retrograde orbits in Table I and Figure 5 do not include all perigee distances used in the prograde ones, the result roughly agrees with the data obtained by Wood (presented by Page, 1973) indicating that the density of impacts by asteroids in a portion of the leading edge may approach a value 4 times greater than the density of impacts on the opposite side of the Moon. In Table I the impact longitudes are recorded as a function of the pre-interaction perigee positions.

The impact velocities are given in Table II for those objects whose pre-interaction perigee positions were aligned with the Moon, including 3 prograde and one retrograde orbit (see Table I). For the last one the impact velocity is close to the sum of the orbital

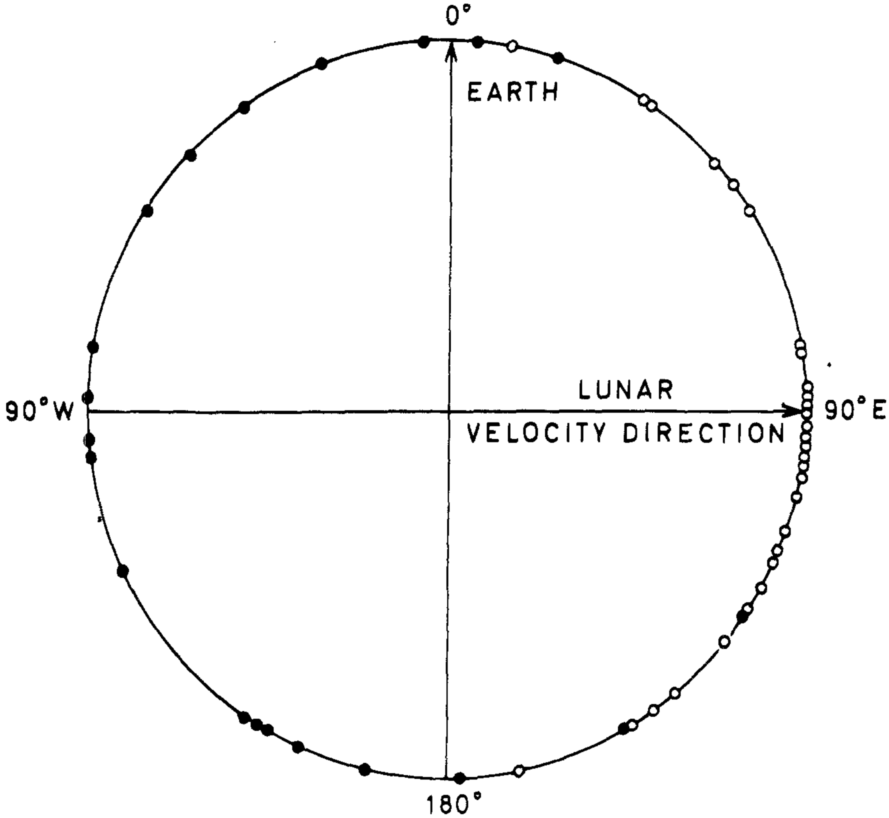

Fig. 5. Equatorial crossection of the Moon, impacts by prograde asteroids are marked by filled rings •. Impacts by retrograde asteroids are marked by open rings ○.

velocity of the Moon (3.1 km/sec) and the orbital velocity of the object colliding head on with it (4.4 km/sec) augmented by an increment due to the lunar gravitation. For the 3 prograde objects the impact velocities are comparable to or slightly higher than the lunar escape velocity (2.4 km/sec).

The impact velocities would become greater if the parabolic orbits were replaced by hyperbolic orbits with an asymptotic velocity typical of asteroidal velocities relative to the Earth. But the excess of impacts on the leading edge compared with the trailing edge of the Moon would hardly be greater. On the contrary it may be slightly lower, because asteroids entering with a greater speed would be less influenced by the lunar direction of movement. The same applies, for the same reason, for asteroids with parabolic orbits whose pre-interaction perigee positions are closer to the Earth than those considered in this study (which are recorded in Figures 3 and 4).

TABLE I

Impacts by objects in parabolic orbits complanar with lunar orbit as a function of pre-interaction perigee position on the fixed Earth–Moon perigee chart. Sign (+), near-side impact, (—) far-side impact

Degrees W (Moon = 0)	Geocentric distance (Moon = 1)	Impact longitude	Sign
A. Prograde orbits			
+ 2.5°	1.08	158° E	—
0°	–	170° W	—
— 2.5°	–	156° W	—
— 5°	–	159° W	—
— 7.5°	–	135° E	—
+ 5°	1.04	168° E	—
+ 2.5°	–	156° W	—
0°	–	135° W	—
— 2.5°	–	122° W	—
— 5°	–	120° W	—
— 7.5°	–	140° W	—
+ 10°	1.00	150° W	—
+ 5°	–	95° W	—
0°	–	98° W	—
— 5°	–	147° W	—
— 10°	–	125° E	—
+ 15°	0.92	153° E	—
+ 10°	–	118° W	—
+ 5°	–	35° W	+
0°	–	6° E	+
— 5°	–	21° W	+
— 10°	–	61° W	+
+ 20°	0.84	177° E	—
+ 15°	–	87° W	+
— 10°	–	18° E	+
— 15°	–	46° W	+
+ 25°	0.76	152° W	—
— 20°	–	4° E	+
— 25°	–	77° W.	+
B. Retrograde orbits			
+ 40°	1.00	~ 170° E	—
+ 35°	–	~ 140° E	—
+ 30°	–	~ 115° E	—
+ 25°	–	~ 105° E	—
+ 20°	–	~ 100° E	—
+ 15°	–	~ 95° E	—
+ 10°	–	~ 90° E	—
+ 5°	–	~ 90° E	+
0°	–	~ 90° E	+
— 5°	–	~ 90° E	—
— 10°	–	~ 95° E	—
— 15°	–	~ 100° E	—
— 20°	–	~ 110° E	—
— 25°	–	~ 120° E	—
— 30°	–	~ 130° E	—

Table I (*Continued*)

Degrees W (Moon = 0)	Geocentric distance (Moon = 1)	Impact longitude	Sign
– 35°	–	~ 145°E	–
+ 70°	0.92	150°E	–
+ 65°	–	115°E	–
+ 60°	–	98°E	–
+ 55°	–	77°E	+
+ 50°	–	50°E	+
+ 45°	–	30°E	+
+ 40°	–	10°E	+
– 35°	–	30°E	+
– 40°	–	45°E	+
– 45°	–	55°E	+
– 50°	–	75°E	+
– 55°	–	90°E	–
– 60°	–	125°E	–

TABLE II

Examples of impact velocities for a few indicated pre-interaction perigee positions

	Prograde orbits			Retrograde orbit
Degrees W (Moon = 0)	0°	0°	0°	0°
Geocentric distance (Moon = 1)	0.92	1.00	1.08	1.00
Impact velocity (Km/sec)	2.49	2.70	2.07	8.87

4. The Distribution of Maria

The excess of lunar maria on the face visible from the Earth is not the only prominent feature of their surface distribution. Another important feature is their latitudinal distribution showing an enhanced frequency of maria at low latitudes compared with high latitudes. Any impact interpretation of lunar maria must account for their latitudinal distribution as well as their prevalence on the face visible from the Earth. The only impact interpretation which seems able to account for this sort of latitudinal distribution is based on the assumption that most impacting objects were moving in low inclination orbits relative to the plan of the lunar orbit before impact. In the preceding paper (see Barricelli and Metcalfe, 1975; Figure 1) it was found that for an interpretation of the lunar maria distribution by Earth satellites of low eccentricity their orbital inclinations would have to be prevalently around the 2° range for the adopted Earth–Moon distance at the time of impacts (and, of course smaller for greater Earth–Moon distances). The inclination required is not necessarily the same for parabolic orbits but is expected to be in the same range. Our investigation of orbits with inclination equal to 0° is therefore expected also for this reason to yield information pertinent to the study of the impacts which created the lunar maria. There is however another aspect of this low inclination feature, namely the following: for Earth satellites it is no problem to assume inclinations in this range. Most satellite systems include groups of moons with inclinations around one or two degrees relative to the planet's equator, and of course also relative to each other. For objects coming in from space, however, this poses a major problem. In order to achieve an average inclination of only two degrees relative to the lunar orbit, not only the inclination of the lunar orbit relative to the ecliptic would have to be not greater than two degrees, but the inclination of the incoming asteroids relative to the ecliptic would have to be several hundred times smaller or less than 0.01°. This last requirement is quite unacceptable and it certainly does not fit the present distribution of orbital inclinations of asteroids. When we add to this the evidence presented in Figure 5 and by Page (1973), we find that the interpretation of the asymmetric distribution of lunar maria based on the excess of impacts on the leading edge of the Moon does not show a good fit with observation. The satellite impact interpretation presented in Figures 1 and 2 for high eccentricity orbits and in the preceeding papers by Barricelli and Metcalfe (1969 and 1975) for low eccentricity orbits, seems on the other hand to fit the observation fairly well as far as the distribution of maria is concerned. The results presented in these papers strongly support the notion that if the asymmetric distribution of lunar maria is to be ascribed to an asymmetric distribution of impacts, the impacts will have to be from Earth satellites, not from asteroids.

This has major consequences which to some extent simplify the interpretation of the shapes and properties of lunar maria, and will be discussed in a subsequent paper (Barricelli and Thorbjörnsen, in preparation).

The results presented above show that the method used in this paper and described in the preceding papers (Barricelli and Metcalfe, 1969 and 1975) can give, in an economical way in terms of machine time and execution, much important information about the distribution of lunar impacts, not only by Earth satellites, but by asteroids and meteoroids. The method can be extended to hyperbolic orbits and orbits with different inclinations, possibly including also other perigee distances, if needed.

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