THE IMPACT-THEORY INTERPRETATION OF THE DISTRIBUTION OF MARIA ON THE LUNAR SURFACE

RALPH METCALFE and N. A. BARRICELLI*
Dept. of Mathematics, MIT Cambridge, Mass., U.S.A.

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Abstract. The satellite impact interpretation of the surface distribution of lunar maria is presented according to Barricelli and Metcalfe (1969). It is emphasized that the formation of molten rock (lava) which, according to the Apollo 11 findings, seems to have been the origin of the material of which maria are composed, can be the result of heat developed by the impacts which created the respective maria (Gilbert 1893) and does not necessarily imply a volcanic or internal origin of this material.

The distribution of mascons and some of its possible interpretations are discussed.

1. The Surface Distribution of Maria

The asymmetric distribution of lunar maria is one of the most significant characteristics of the Moon's surface which has recently been revealed by spacecraft photography. It has been noted that many current theories which attempt to explain the formation of Earth side maria such as Imbrium, Serenitatis, and Crisium are unable to explain the absence of large size maria on the far side (Kopal, 1966). However, the hypothesis that the large maria were created by the impact of small Earth satellites upon the lunar surface yields predictions consistent both with the features of the observed maria and with their actual distribution on the Moon. The basic hypothesis, that many of the lunar maria are primarily regions of solidified lava originally produced by the impacting of early Earth satellites, was first proposed by Gilbert (1893) and later supported by Darney (1933), Urey (1952, 1962), and many others.

Because of tidal effects, the distance between the Moon and the Earth has been steadily increasing. Earlier, perhaps some four billion years ago, the Moon may have been much closer to the Earth than it is today. Any other Earth satellites which were present at this time may have been eliminated from the Earth-Moon system, as the Moon spiraled out, by colliding with the Earth or Moon, or by escaping into space. Collision with the Moon, resulting from the increasing diameter of the Moon's orbit, is actually the most likely possibility for a satellite moving around the Earth in roughly the same direction as the Moon itself (Barricelli and Metcalfe, 1969).

2. Lava-Formation by the Heat Produced in Satellite Impacts

To analyze the possible formation of some of the lunar surface features it is essential to distinguish between satellite impacts and meteor impacts. The former are due to

* Present address: Oslo Universitet, Dept. of Mathematics, Blindern, Norway.

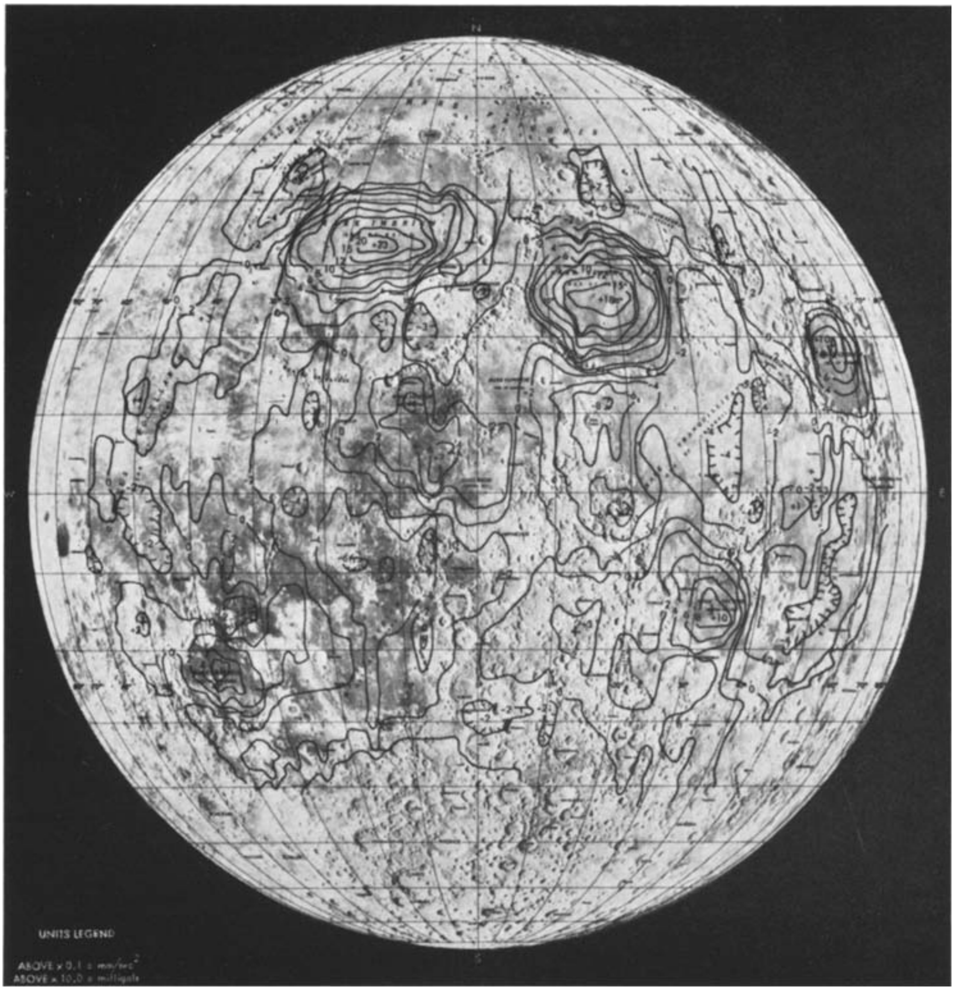

Fig. 1. Map of gravitational anomalies identifying the positions of mass concentrations beneath the lunar surface.

collisions involving objects in orbit around the Earth, while the latter are due to collisions involving objects which are not Earth satellites, such as meteors and comets. The energy generated in a satellite impact is primarily created through the acceleration of the impacting object by the Moon's gravitational field. So the collision velocity of a satellite impact is usually close to the lunar escape velocity, 2.4 km/sec. On the other hand, the meteor impact velocity, which can vary substantially, tends to be one order of magnitude greater than the lunar escape velocity. The energy generated during a *meteor impact* is often sufficient to vaporize a substantial portion of the material involved in the collision, causing an explosion and creating a saucer-shaped crater similar to the large meteor craters on Earth (Marshall, 1943). On the other hand, although the energy and temperatures generated during a *satellite impact* are usually sufficient to melt part of the material involved in the collision, they are insufficient to vaporize a significant quantity of the material. Thus, lunar surface structures caused by satellite impacts tend to present a dark, smooth, horizontal surface indicating the production of large amounts of lava, while those caused by meteor impacts give evidence of a violent explosion in which most of the material was vaporized, leaving behind comparatively much less lava.

An important factor in the production of lava during the satellite impact is the size of the colliding satellite. Unless the satellite is above a certain critical size, there will not be sufficient time during the actual impact for the mechanical energy to be converted into heat before much of the energy is dispersed through physical displacement of the material involved. Thus, only craters above a certain minimum size should be expected to exhibit the dark, smooth surface characteristic of features created by satellite impacts, unless flooding by external lava has occurred. The craters Kruger and Billy are probably representative of the smallest possible satellite impact craters presenting the dark, smooth surface indicating the production of substantial quantities of lava during collision. Although most lunar craters have the appearance of meteor craters, such structures as Ptolemaeus, Archimedes, Plato and the Maria Imbrium, Crisium, and Serenitatis appear to have been caused by satellite impacts.

3. Interpretation of the Distribution of the Maria

Since the Moon has been spiraling steadily away from the Earth, most satellite collisions with the Moon would involve satellites whose orbits were external to the orbit of the Moon. Under such conditions, it has been shown that collisions between the Moon and small external satellites traveling in the same direction and in roughly the same orbital plane as the Moon would primarily take place on the far side of the Moon (Barricelli and Metcalfe, 1969). Thus, if the present Earth side of the Moon were actually the far side of the Moon at the time during which most satellite impacts were occurring, the asymmetric distribution of maria would be explained.

Urey (1962) has pointed out that the Imbrium impact was probably the most recent of the large satellite impacts. Gilbert (1893) notes that the asymmetry of the lava formation in the Imbrium impact area and the characteristics of the surrounding surface features could be accounted for if the satellite whose impact created Mare Imbrium had approached at a small angle to the horizontal from a northwesterly direction. Many of the scars and craters in the region southeast of the Apennines may have been created by fragments blasted out during the Imbrium collision. Such a collision could impart enough angular momentum to the Moon to bring it out of its bound rotation to the Earth and spin it about its axis (Barricelli and Metcalfe, 1969). After the gravitational action of the Earth had succeeded in damping the spinning of the Moon and re-establishing a bound rotation with the same side of the Moon always facing the Earth, the near and far sides could have been reversed. Because of the ellipsoidal symmetry of the Moon, the original far side and the original near side would have about an equal probability of finally facing the Earth when the bound rotation was re-established. Thus we would expect that the present near side of the Moon should contain most of the satellite impacts, if it were actually the far side at the time most of the satellite impacts were occurring.

In addition to being located primarily on one side of the Moon, most impact Maria are concentrated in the region between latitude 30° South and 50° North. Such a distribution would be expected if most of the impacting satellites originally had orbits which were in approximately the same plane as the Moon's orbit. In other satellite systems, such as those of Jupiter and Saturn, the innermost moons are usually in orbits close to the equatorial plane of the mother planet, while the external moons are in orbits with larger inclinations to the equatorial plane. If a similar situation existed for the early Earth satellites, the oldest satellite impacts on the Moon should have been closest to the Moon's equator, whereas the more recent impacts could often occur at higher latitudes. This is in general agreement with observations, since the lava regions around Oceanus Procellarum have been greatly altered by later events, indicating that these are older than such higher latitude lava formations as the Maria Imbrium and Serenitatis.

4. The Mascons

Recent work by Muller and Sjogren (1968) has indicated the presence of mass concentrations (mascons) distributed beneath the surface of the Moon. Most of the mascons appear to be located under the centers of maria (Fig. 1). If the satellites which collided with the Moon had heavy iron-nickel cores, it would be expected that the heavier material in the core would sink to the bottom of the lava pool, forming a mascon. A slightly puzzling aspect of the mascon distribution is the absence of mascons in the Oceanus Procellarum, Mare Tranquillitatis, and Mare Foecunditatis regions. While there is no assurance that all satellites colliding with the Moon would have iron-nickel cores – a fact which in itself could explain the absence of mascons in several of the maria – another possible interpretation of the observed mascon distribution can be based on the following considerations:

Robert Jastrow, at Columbia University, Paul Gast, at Lamont Geological Observatory and Robert Phinney at Princeton have suggested, on the basis of recent evidence from the Apollo 11 mission, that the Moon may, like the Earth, possess a molten core. At an earlier time in history, the quantity and distribution of the molten material in the Moon's interior could have been very different from the present. For example, in the early history of the Moon's formation a collision with an unusually large object could have melted or partially melted a large portion of material in the Oceanus Procellarum and other equatorial areas of the Moon. For a long period mascons in this area (particularly the heaviest ones) may have sunk deeply into the Moon's interior thus becoming unobservable from orbiting satellites. Impacts which occurred in other areas, such as Imbrium, Serenitatis, and Crisium, may have left iron-nickel cores which were simply embedded at much smaller depths under the lunar surface and appear today as mascons. Gottlieb (1969) suggests that the Serenitatis mascon is buried at a depth of 150 km. This also gives an indication of the depth range of the lava pools created by major impacting satellites. If Gottlieb's estimate is correct, such lava pools are much deeper than was earlier believed, and the time required to cool off and solidify lava pools of this size could amount to many hundred thousands of years (see Urey, 1952 and 1962).

However, the evidence hitherto presented in support of the hypothesis that the Moon has a molten core is by no means conclusive. One of the main arguments held in support of a molten core and a possible vulcanic origin of maria, namely the igneous characteristics of the lunar rocks collected by the Apollo 11 astronauts is evidently ignoring the fact that the satellite impact theory also implies that the maria must be composed of solidified lava, originated by impact heat. Evidence that the maria have been molten cannot, therefore, give a decision in favour of one or the other theory unless the nature and origin (impact heat or internal origin) of lunar lava can be established.

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