Lunar Mascons

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In 1968, Muller and Sjogren discovered large positive anomalies in the gravitational field of the Moon and introduced the concept of mascons as the sources of these anomalies. In our review, we shall attempt to summarize ideas set forth in the literature and related in some manner to lunar mascons.

Mascons are found on the visible side of the Moon and near the limb, with the majority of them being colocated with the major circular mare (Mare Imbrium, Mare Serenitatis, Mare Nectarius, Mare Crisium, and Mare Humorum). Existing methods of observation do not allow the detection of mascons on the back side of the Moon. However, the fact that there are no large circular mare on the back side allows one to suppose that there are no large mascons there.

The distribution of mascons in the body of the Moon and their structure cannot, in principle, be uniquely solved without the use of additional data and, therefore, has been extensively discussed in the literature. However, it is now understood that the anomalous masses are located in the outer layers of the Moon and are well described by disc-shaped models. The magnitudes of the anomalous masses can be estimated either by analysis of test bodies placed at various depths or by the theorem of Gauss. The largest mascons correspond to anomalous masses of approximately 20×10^{-6} times the mass of the Moon, or about 10^{21} g. If we assign the anomalous masses to the surface of the Moon, all the large mare have approximately the same excess mass per unit area—800 to 900 kg/cm^2. This would be equivalent to an additional layer of basalt 3 km thick, with a density of 3.0 g/cm^3. If a mascon were formed by material located at the surface with a density of 0.3 g/cm^3 greater than the density of the crust, the thickness of the layer of displacing material would have to be 30 km.

Mascons are located in topographical depressions related to geologically ancient formations. Insofar as the circular mare are genetically related to the impact of large bodies on the surface of the Moon, these same events played an important role in the formation of the mascons. The impact of these bodies and the filling of the circular mare were separated by considerable intervals of time, on the order of hundreds of millions of years. The possibility that the mascons were formed by the impacting bodies themselves seems at present improbable. Therefore, the origin of the mascons is related to the transport of matter within the Moon and, apparently, requires the following chain of events, independent of the specific mechanism of mascon formation.

In the early stage of its development, the Moon developed a thick crust with a density less than the density of the underlying mantle. Apparently during this era the outer layers of the Moon were sufficiently hot to be highly plastic and possibly in a state of near hydrostatic equilibrium. Impacts of large bodies on the surface of the Moon resulted in the formation of large craters at the locations of the future circular mare, which then became in some manner isostatically equilibrated. Following this, the Moon entered a comparatively quiet period during which formation of its lithosphere continued as a result of cooling of the outer layers. Apparently during this era the Moon acquired and retained an equilibrium shape. During this same era, the outer layers of the Moon acquired strength sufficient both to retain its shape and to support mascons. The formation of the lunar lithosphere was followed by the filling of the circular mare leading to the formation of the mascons.

Mascons represent the same kind of nonequilibrium feature on the Moon as does its figure, only on a smaller spacial scale. Apparently, the simultaneous theoretical study of the conditions of mascon formation and the figure of the Moon can reveal lunar dynamics during the epoch when the lunar lithosphere was formed. The lunar dynamics at this time are of fundamental scientific interest because they provide important boundary conditions for the formation of the Moon and the first stage of its existence.

The presence of mascons and the nonequilibrium figure (the latter is also reflected in the displacement of the geometric center of the Moon relative to the center of mass by up to several kilometers) leads to a displacement of the Moon's core from hydrostatic conditions and produces stresses on the order of 100 bars. This situation must be kept in mind when constructing various types of thermal histories for the Moon.

From the point of view of isostasy, there are two types of models for lunar mascons, nonisostatic and isostatic. A nonisostatic mascon corresponds to an actual excess of mass in the outer layer of the Moon. In the case of an isostatic mascon, the concentration of mass at the surface is compensated by a deficit of mass at a depth on the order of some hundreds of kilometers, leading to a density inversion. The isostatic model seems less satisfactory to us because it requires the existence of an area of reduced density at a considerable depth. Furthermore, this model strongly concentrates the stresses in the area between the two anomalous masses, increasing the maximum stresses in comparison to the nonisostatic models by five to ten times.

The presence of circular mare on one side of the Moon indicates that during their formation this side was physically isolated. It was assumed at one time that this was related to the fact that collisions of the Moon with large bodies occurred on one side of the Moon with greater probability. This was physically explained by the Moon's being in synchronous rotation and in the process of tidal evolution of its orbit when it caught up with smaller satellites of the Earth, which preferentially struck one of the lunar hemispheres and created the circular mare.

Presently, the impression is growing that the presence of circular mare and mascons on one side of the Moon is related not to an asymmetry of collisional processes, but rather to asymmetry of the lunar crust. It is thought that the thickness of the crust on the back side of the Moon is distinctly greater than it is on the visible side. The impact of large bodies on the visible side of the Moon significantly weakened the thin crust there and caused subsequent lava flows; whereas, with the thicker crust of the back side of the Moon, lava did not reach the surface.

So far, one cannot provide a unique interpretation for the mechanism of formation of lunar mascons. According to one point of view, the mascons are the remainders of bodies which struck the surface of the Moon and formed the circular mare. We have already noted that this is improbable. Although the impact mechanism of a large body with the surface of the Moon is insufficiently clear, there is no doubt that in a high-velocity impact the mass ejected from the crater is many times greater than the mass of the impacting body. The mascon of Mare Orientale is clearly connected with a high velocity impact, in which case the primary body would hardly remain in the crater.

There are several different hypotheses explaining the formation of the mascons by the transport of material in the Moon. Hypotheses related to local mass transfer require that there be a shortage of mass in the vicinity of the mascons and, consequently, a negative gravitational anomaly. The mascon of Mare Orientale is actually surrounded by a ring of negative anomalies. The question of the actual existence of such anomalies around other mascons has not yet been definitely answered. In hypotheses related to global transport of material in the Moon, the mass deficit is distributed over a great portion of the body of the Moon and does not lead to negative anomalies.

In one hypothesis of local mass transfer, a mascon is formed by denser matter rising from the mantle into the impact depressions in the lunar crust until an isostatic equilibrium is achieved, followed by subsequent filling of the remaining topographic depression with lava. In this case, the anomalous mass is created by the plug intruding into the crust from the mantle, and the mascon is located at the base of the crust. In other such hypotheses, the mascon is created by filling of the depressions with lava which is denser than the material of the crust. Some hypotheses attempt to explain the mascons by processes of chemical differentiation, without utilizing the concept of impact origin for the circular mare; however, these hypotheses seem as yet insufficiently developed.

In hypotheses related to global transport of material in the Moon, a source of excess pressure must be found which is capable of forcing the dense matter of the lunar interior into the impact-weakened areas of the crust beyond the limits of isostatic compensation. The excess pressure might be created by cooling and thermal compression of the outer parts of the Moon, which were heated by impacts during the final stages of its formation. This process would apparently lead to a global system of faults in the lunar crust. The excess pressure might also be created by expansion of the central areas of the Moon during the early stages of lunar history. During the time of formation of the mascons, the Moon was significantly closer to the Earth, and it is not ruled out that tidal stresses in the body of the Moon made a significant contribution to the expulsion of matter from the lunar interior into the lunar crust.

The problem of lunar mascons brings up a number of questions which still require an answer. A key unknown is the detailed structure of the lunar crust. This information might significantly narrow the range of uncertainty in our understanding of mascons. The history of formation of the lunar lithosphere and the history of stresses in it are insufficiently developed. We do not know the mechanism of formation of the noncircular lunar mare or their subsequent evolution. It is not fully understood why the flowing of lava into these mare did not result in the formation of mascons. It is not clear whether mascons subsided during the course of subsequent lunar history.

For a better clarification of the structure of the lunar mascons and selection among various mechanisms for their formation, it would be interesting to perform a series of experiments on the surface of the Moon. Since the mascons are ancient formations and the regions where they are located should be characterized by stable heat flow, it would be interesting to measure the heat flow and compare it with the heat flow in other areas of the lunar surface. It would also be desirable to perform detailed gravimetric surveying in several different regions of a circular mare. Gravimetric surveying on the lunar surface itself would help, in particular, to answer the questions of the negative anomalies around mascons. Finally, it would be worthwhile to perform deep electromagnetic soundings and to obtain a detailed seismic profile in the region of a circular mare.

We see that the problem of lunar mascons is related to the most important questions of the structure and evolution of the Moon. The remaining uncertainties show clearly that further and more detailed studies of the Moon by spacecraft are needed.