Problem of lunar mascons: An alternative approach

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Abstract. The origin of lunar mascons is discussed on the base of results of the orbital experimental exploration of the Moon by the Gravity Recovery and Interior Laboratory and the Lunar Reconnaissance Orbiter missions. We lead the discussion on the basis of representations of Galactocentric paradigm which links processes in the Solar System and on its planets with the Galaxy influences. The article describes a new approach to the interpretation of the crater data, which takes into account the quasi-periodic bombardments of the Moon by galactic comets. We present a preliminary evaluation of the age of mascons as well as of craters and mares on the Moon based on this approach.

1. Introduction

Mascons are major formations in the crust of the Moon, causing specific gravitational anomalies. Over the past half a century much effort was spent on the investigation of their nature [1]. The pioneer measurements of the Soviet automatic station “Luna-10” revealed anomalies of the gravitational field of the Moon [2]. The study of these anomalies by automatic stations “Lunar Orbiter” led in 1968 to the discovery of mascons [3]. In 1998–1999 according to the measurements data of the automatic orbital station “Lunar Prospector” it was found that most mascons are located under the extensive lunar mares having rounded shape. It should be noted that currently mascons were found not only on the Moon but also on Mars and on Mercury [4].

The origin of mascons is connected with falls of large cosmic bodies forming a giant craters filled with basalts—lunar mares, under which there is a mass of matter of enlarged density. The authors of [5] on the basis of a detailed gravimetric lunar exploration by mission GRAIL (the Gravity Recovery and Interior Laboratory) and laser altimetry data LOLA (the Lunar Orbiter Laser Altimeter) proposed a model of mascons formation as the result of lifting up of a large masses of heavier subcrustal mantle material. However, the same authors concluded [6], that mascons cannot be explained by the fall of cosmic bodies with the diameter distribution is the same as for bodies of modern asteroid belt. Thus the problem of mascons origin on the Moon cannot be considered solved.

In this paper to explain the mascons origin we involve representation of Galactocentric paradigm [7], which is well proven at the solving of broad range of problems in cosmogony, geology and comparative planetary science. This approach allows us to justify the fundamental conclusion that mascons arise not from the falls of interplanetary bodies (asteroids and comets of the Solar System), as is commonly believed, but as a result of cyclical bombardments of the Moon and the terrestrial planets by high-velocity galactic comets.
2. Galaxycentric paradigm

Galaxycentric paradigm is based on the recently discovered astrophysical phenomenon—jet ejection of a gas-dust matter from the center of spiral galaxies [8]. In accordance with the representations Galaxycentric paradigm in the process of movement of the Sun on galactic orbit, all the objects of the Solar System quasi-periodically undergo intense bombardments by comets of galactic origin. These comets arise in condensation zones of gas-dust matter (star-forming) in the Galaxy spiral branches and appear in the Solar System only during the periods, when the Sun is in jet streams of substance and the branches of the Galaxy [7].

The falls of galactic comets onto the Earth and other planets happen as relatively short “cometary showers” of the duration of 2–5 million years, which are repeated in 19–37 million years. Due to the inclination of the ecliptic to the galactic plane at an angle of 62°, at the Sun orbital motion in the Galaxy, galactic comets in 150 million years alternately bombard predominantly the southern or northern hemisphere of planets [9].

During single cometary shower ∼ 10⁴–10⁷ of galactic comets can fall onto the surface of the Earth. The last cometary bombardment of “medium” intensity took place in the time interval from 5 to 0.6 million years ago. Galactic comets moved relative to the Sun at a speed of about 450 km/s, nuclei of comets consisted primarily of water ice with density ≈ 1 g/cm³, they had a diameter of 0.1–3.5 km, mass of 10¹²–10¹⁷ g, and the energy of 10²⁰–10²⁵ J. The size distribution of galactic comets is exponential, the density of cometary falls was of ≈ 5 comets of all sizes on area 100 × 100 km², and comets themselves mostly bombarded the southern hemisphere of all planets.

3. The interaction of the galactic comets with planets

At speed of galactic comets ≈ 450 km/s the mechanism of their interaction with terrestrial planets is different [10,11] from that for interplanetary bodies [12], falling on the planets with a speed on the order of magnitude smaller. In this case the impact process is accompanied by the formation of narrowcasting hypersonic shock wave that can penetrate deep into the lithosphere causing strong heating of rocks at a depth of about 300 km.

The high density of the galactic comets falls in the periods of bombardments leads also to formation of the large lenses of strongly heated and partially molten asthenosphere substance in the lithosphere. The formation of such lenses on our planet in conditions of a “thick” lithosphere (on mainlands) causes a significant lifting of the continents surface and in conditions of a “thin” lithosphere (in oceans) leads to the outpouring large amounts of basaltic magma on ocean floor [13]. In the time intervals between cometary bombardments the substance of lenses cools, and relaxation processes in the lithosphere is largely level the effects on the surface.

The described mechanism of interaction of galactic comets with planets applies to all terrestrial planets, including the Moon. It is found [10] that, depending on the combination of a number of conditions the galactic comets can create on these planets the following types of the impact structures: craters, diatremes, lava sheets, volcanoes, dome-shaped uplifts of surface, as well as coronae and montes (on Venus). The main factors that influence forming of these structures on planets are:

(i) density of gas shell;
(ii) thickness of planet lithosphere;
(iii) composition and degree of heating of lithosphere rocks;
(iv) frequency of galactic comets fallings.

4. New approach to interpreting the cratering data

According to Galaxycentric paradigm, impact structures on planets are formed due to the falls of two different populations of parental cosmic bodies:
(i) asteroids and comets of the Solar System;
(ii) high-speed galactic comets.

The former are characterized by the backward square size distribution, and the second—exponential. Herewith the sizes of arising shock structures will be distributed by the same law, that the falling cosmic bodies.

This circumstance allows [7] to discern easily impact structures created by cosmic bodies of different origin, by analyzing their distributions on diameters \( D \) on the charts in a special double logarithmic coordinate system, in the form of so-called R-function [12], and also on the chart in semilog coordinate system in the form of the cumulative number structures \( N(D) \) with a diameter greater \( D \). As a result the structures created by falls of asteroids and comets of the Solar System on the R-chart will have the form of straight line parallel to the X-axis. Whereas the structures created by the galactic comets give on the chart in semilogarithmic coordinates the distribution of \( N(D) \) in the form of a sloping straight line.

On the basis of these very simple considerations we may analyze the distribution of craters, seas and mascons on the Moon as well as the terrestrial planets in terms of their possible origin.

5. Actual data and their discussion

The subject of our analysis and discussion are the graphs in figures 1–6. Figure 1 shows the R-distribution of large craters on upland (continental) and lowered (marine) areas of the surface of the Moon, Mars and Mercury on data [14]. According to our interpretation, the craters in marine areas of the surface of the Moon and Mars are of asteroid origin. The density of “marine” craters is on 1–2 orders of magnitude lower than “upland” craters which have the size distribution of a different type.

Cumulative \( N(D) \) distributions of upland craters on the Moon, Mercury and Mars are shown in a semilogarithmic coordinate system in figure 2 [9]. These plots show that the vast majority of craters with a diameter \( D = 10–160 \) km on continents of the Moon, Mercury and Mars are created by the galactic comets. On the atmosphereless Moon and Mercury the graphs of \( N(D) \) are almost identical. The density of the largest craters on the Mars is lower due to the ablation of nuclei galactic comets in the martian atmosphere [7]. Herewith the continental parts of surface the Moon, Mercury and Mars are completely saturated by craters with a diameter \( D \geq 10 \) km. Maximal saturation by such cratered surfaces of the Moon, Mercury and Mars is almost identical and equal to \( \approx 100 \) craters on square \( 10^6 \) km\(^2\) [8].

Returning to the analysis of figure 1, it should be noted that the structures with a diameter \( D \geq 160 \) km have also been formed by falls of galactic comets because their size distributions are an obvious consequence of representation of the exponential dependence in the R-coordinate system. It should also be noted that in figure 1, these shock structures are named as “upland craters”, although in reality the authors [15] classified them as “marine basins” or more simply—“mares”.

Figure 3 shows the relation of central gravitational anomaly Bouguer with the diameter of lunar craters [15]. The authors declare that this relation is built for only continental Moon craters. However starting with \( D \geq 200 \) km, they are not craters, but the marine lava basins containing mascons. So, the positive gravity anomaly Bouguer is observed only in such basins. With the increase of basin size the anomaly is also growing.

Positive gravity anomaly in mascon basins indicates that there is a large mass of material under the bottom basin, heavier than the material of lunar crust. This substance, according to the authors [5,6,15] represents the intrusion of mantle material that rises to the Moon surface due to impact of a large cosmic body. The study of such incursions has shown (see figure 4 [6]), that there is almost a linear relationship between an intrusion diameter and the mascon marine basins, if to judge about the basin size on the diameter of inner topographic ring of all shock
Figure 1. R-distribution of large craters on upland (continental) and lowered (marine) areas of surface the Moon, Mars and Mercury [14].

Figure 2. Cumulative $N(D)$ distributions of upland craters on the Moon, Mercury and Mars in a semilogarithmic coordinate system [7].
Figure 3. Amplitude of the central gravitational Bouguer anomaly versus $D$ for craters formed in the lunar upland. Yellow line shows the approximation of the measurement data of the proposed model [15].

Figure 4. Diameter of the central positive Bouguer anomaly versus diameter of the peak ring or inner topographic ring. Red and Black icons marked the lunar basins of various types. The dotted line—the ratio of 1 : 1 [6].
Figure 5. Cumulative size-frequency distributions for complex craters and basins according [6].

Figure 6. Cumulative $N(D)$ distributions of coronae (1) and montes (2) on Venus [10].

structure. In the large basins the lava that streamed on the surface forms a range of rings of larger diameter. Then the structure size is defined as the diameter of the main ring of marine basin (see figure 5).
Based on this concept the authors [6] have constructed cumulative $N(D)$ distributions of the mascon basins, which were different for the visible and the back Moon side. It turned out that on the near lunar side there are present more large basins $D \geq 350$ km, while on the reverse side there are more of basins a smaller size. The authors explain different basins size of the visible and the far side of the Moon by different thickness of lunar crust on both Moon sides as well as by differences in temperature and porosity of lunar rocks.

In figure 5 in semilogarithmic coordinate system we present data [6] approximating cumulative $N(D)$ mascon distributions by an exponential functions (dashed lines). Black diamonds and red squares belong to the basins on the near and far side of the Moon, respectively. The solid line shows the average dependence. The area of possible errors in the averaging is shaded. We draw attention to the fact that the transition from distribution of craters on the continents to the mascon basins is not a monotonous. So, if the number of craters with a diameter $D \geq 160$ km is $N_{cr}(160) \leq 1$ on area of $10^6$ km$^2$ (see figure 2), whereas the number of mascon basins of the same diameter $N_{mb}(160) \approx 2$ on area of $10^6$ km$^2$ (see figure 5).

According to our findings [10, 11] single upland craters arise in areas of “thick” lithosphere as a result of the falls of separate galactic comets, while mares are formed by magma which was poured on the surface from asthenospheric lenses, which form in areas “thin” lithosphere at a very high density of cometary falls.

There is another factor that needs to be taken into account when interpreting the data in figure 5. Let us explain it using the data in figure 6 [10], where cumulative $N(D)$ distribution of corons and montes on the Venus is shown. It should be noted that corons are called big tectonomagmatic round elevations surrounded by the ring of concentric ridges, while montes are large mountains (mountain structures). We believe [10] that they both are objects of one nature, which arose as the result of several past cometary bombardments of the Venus, and today are at different stages of evolution. Montes appeared first but now due to the relaxation processes were transformed into corons.

Although conditions on the Moon and Venus can hardly be called similar, there is a certain commonality in the mechanisms of formation mascons, montes and corons by galactic comets. We see this commonality in similarities in the size of large impact structures on the Moon and Venus, as well as the parameters of $N(D)$ distribution (see figures 5 and 6).

The data in figures 5 and 6 show that along with heating of rocks by galactic comets, two other processes are involved in the formation of the relief of modern planets—the cooling of lithosphere rocks and the tectonic relaxation of surface in time intervals between cometary bombardments. Results actions of these processes obviously depend largely on the formation time of craters, mares and mascons.

6. Problem of dating the age of impact structures on the Moon
The only way to determine age of these structures on the Moon is the approach [16–18], consisting in a joint analysis of the isotopic ages of lunar rock samples taken by American astronauts from the six places landing of spacecrafts “Apollo-11, 12, 14–17” as well as of the three descent places of Soviet automatic stations “Luna-16, 20, 24” and the study of distribution diameters of large impact craters on the sites of rocks sampling, according data remote sensing using lunar orbital stations. On sensing data, researchers build cumulative size-frequency distribution of the craters with a diameter of $D \geq 1$ km or $\geq 10$ km, which is approximated by some polynomial of the 11 order. After that, temporary corrections are entered in the polynomial, they take into account the results of isotopic dating of samples of lunar rocks. This approach is used at construction of the stratigraphic scale of geological time the Moon as a whole [16–21], as well as for determining the time formation of individual lunar craters, mares and plans [22–25].

It should be noted, however, that this method of determining age of main landscape structures on the lunar surface is based on three assumptions [20, 21]:
(i) upland craters with diameters $D \geq 1$ km created resulted from bombing the lunar surface by meteorites, which have the diameter distribution on the same law as objects modern asteroid belt;

(ii) main meteorite bombardment took place 4–3 billion years ago, and since then intensity of the fallings of larger cosmic bodies at the Moon has been relatively stable and meets the modern era;

(iii) isotopic age of the lunar rocks samples delivered on the Earth correspond to the time of formation of impact structures on the Moon surface.

However all three these assumptions based on ideas seemingly correct half-a-century ago, as well as the appropriate them method of dating the lunar surface today do not have the necessary empirical grounds.

We propose a more adequate approach to interpretation of the cratering data based on representations of Galaxycentric paradigm [7]. This approach takes into account:

(i) moments of cometary bombardments;

(ii) orientation of the axis-rotation Moon relative to the Galaxy plane in the periods of cometary bombardments;

(iii) processes of tectonic relaxation, which level off the Moon surface during the time between the cometary bombardments.

Firstly, in contrast to the craters with diameter $D \leq 10$ km the vast majority of craters with diameter $D \geq 10$ km (see [7]), as well as mascons and mare on the Moon as shown in this paper are created by falls of galactic comets, and not by asteroids and comets of the Solar System.

Secondly, the falls of galactic comets on the planets have character of relatively short ($\approx 2–5$ million years) very intense cometary showers that are cycled through 19–37 million years. At this, galactic comet through 150 million years alternately bombard principally either the southern or the northern hemisphere of planets [9].

Thirdly, on the surface areas exposed to the cometary bombardments, along with the formation of craters there occurs a strong non-uniform heating of the rocks of the lithosphere [10, 11]. In areas with a “thick” lithosphere this heating causes a significant lifting of the planet surface but on areas of a “thin” lithosphere it leads to the outpouring of a large number magmatic melts to the surface [13].

Fourthly during the time between cometary bombardments, heated rocks get cool that causes leveling and flattening the surface of planets [7, 9].

Fifthly, the age of the lunar surface is not associated with an isotopic age of formation of the Moon rocks, samples of which have been delivered to Earth after space flights. Our studies show [26, 27], that the modern lunar landscape was largely determined by the last comet bombardment, which took place from 5 to 0.6 million years ago. At this time the density of cometary fallings was so high that a large part of the Moon surface was completely saturated with craters with a diameter $D \geq 10$ km. Since formation of such craters is due to the rocks ejection from a depth of $\approx 3$ km and more, the isotopic age of lunar rocks tells us about the time of solidification of their material, but not about lunar landscape formation time.

And finally sixthly during the last cometary bombardment galactic comets brought to the Moon a lot of water which is present in the lunar rocks and, in particular, forms the tongues of glaciers slipped from walls and central peaks of larger cometary craters now [28, 29].

Thus the standard method of time determination of impact structures origin on the Moon cannot be considered adequate, and the age estimation of these structures credible.
7. The time of tectonic relaxation of lunar surface
This factor needs special consideration. The fact is that due to the large angle of inclination of the ecliptic to the Galaxy plane, galactic comet through the time of \( \approx 150 \) million years alternately bombard either the southern or the northern hemispheres of planets and the Moon. Therefore when in one lunar hemisphere galactic comets form craters, seas and mascons, in the other hemisphere the relaxation processes may align the landscape of surface.

The facts show that if in the Jurassic period (200–150 million years ago), galactic comets are mainly bombed the northern hemisphere of terrestrial planets, in the Cenozoic they bombed mainly the southern hemisphere [9]. The Moon in this regard is no exception.

In [8] provides a method for evaluating the landscape formation time on the surface of the terrestrial planets, taking into account the tectonic relaxation processes in the lithosphere, which is based on the analysis of the distribution of the asteroid craters with diameters \( D \gtrsim 10 \) km. This method assumes that the interplanetary asteroids creating these craters have back-quadratic distribution on diameters and at this their concentration in the near-Earth space during the Phanerozoic changed slightly. The major idea is that the larger interplanetary bodies are, the less frequently they fall on the planets. Starting with a certain diameter of asteroids \( d^* \) their falls will become so rare that during the time \( (T) \) between such events, the processes relaxation have time to level craters from previous falls of bodies of such size.

To estimate of the size of such bodies is offered the formula [7]: \( d^* = 3.5 \left( \frac{T}{2.9} \right)^{1/3} \), where: body diameter \( d \) is expressed in kilometers, and time \( (T) \) in million years.

Knowing the dependence of crater diameter \( D \) on the diameter of interplanetary body \( d \), using this formula we can roughly determine the age of the cratering surface. Figure 7 shows an example of determination by this method the age of the cratering surface northern polar region of Mars, devoid of craters from galactic comets. The calculation showed that time-formation of this area of marine hemisphere Mars lies in range from 34.8 to 68 million years [8]. Thus the landscape of this area Mars surface well could be formed in the Cenozoic.

This approach based on an analysis of the distribution of the asteroid craters with a diameter \( D \gtrsim 10 \) km can also be used to estimate the time of formation of marine basins of the Moon. It should be noted that craters of asteroid origin are easily distinguished from the craters created by galactic comets by virtue of their morphology and other features [7].

Asteroid craters with diameter \( D \sim 1 \) km and less cannot be used for estimation of lunar surface age because their vast majority has a secondary origin and their formation rate cannot be counted.

8. Evaluation time-formation of relief lunar surface
Using the data (presented in figures 1–5) as well as the results of [7,9–11] let us now discuss the question of the time-formation on the Moon of large craters, mares and mascons on the Moon, guided by the above representations.

8.1. Age of craters
We will distinguish the “upland” craters located on the elevated areas of the lunar surface, and “marine” craters present in mare basins (see figure 1).

Immediately, we note that almost all upland craters with a diameter of \( 10 \leq D \leq 160 \) km are formed by falls of single galactic comets (see figure 2). The lower boundary of this range is due to 100% saturation of the Moon surface continents by the craters with \( D \geq 10 \) km [7], which “erase” all craters are smaller size. While time the upper limit of the range is defined by the fact that the structures of larger diameter are classified not as craters, but as a “mare basins”.

Existing facts allow to suppose [7,26–29] that most of the upland craters on the Moon are the result of the last cometary bombardment on the border of the Neogene and Quaternary (5–0.6 million years ago), and to a less extent in the two or three previous bombardments at the
Figure 7. Differential density of major craters in Northern polar area of Mars [7]: Mugs—fact data; solid line—theoretical distribution of craters at $T \rightarrow \infty$.

Figure 8. Distribution of the lunar mascons along latitude belts, constructed by us according to [6]. Legend: red line—“young” basins, blue line—“old” basins.
borders Oligocene-Miocene, Paleocene-Eocene and also Cretaceous and Paleogene. Therefore upland craters and a mountain landscape created by them appear to have the Cenozoic age, i.e. not older than 65 million years.

8.2. Age of mariner basins
Lunar mares have on average the same age as “upland craters”. The main difference between them is that mare basins with a diameter $D \geq 160$ km are formed as a result of falls of not one but many galactic comets. The summation of their effects may cause a strong heating of deep-seated rocks, which contributes to the lift to the surface of denser mantle rocks and also leads to an abundant outpouring at the surface of basaltic magmas on the surface which can spread over a very large area.

Another difference is that the mares are formed at the end of comet bombardment or after their completion. This is evidenced by the low density marine craters and their size distribution (see figure 1). The data in figure 1 show that asteroids involved in the formation of marine craters with $D \geq 10$ km. However it is impossible to believe that asteroids create all marine craters are impossible since the R-function of marine craters lightly increases with $D$ growth. This growth indicates also the presence of craters created by galactic comets.

8.3. Age of mascons
The authors of [6] on the basis of a joint analysis of the GRAIL and LOLA data revealed a total of 181 mascon structures on the Moon, subdividing them into six groups:

(i) 37 “upland” craters of intermediate diameters of 160–200 km, part of them has positive Bouguer anomalies, and others have not;
(ii) 16 peak-ring basins;
(iii) 29 basins with one topographical ring without inner structure;
(iv) 11 multi-ring basins;
(v) 17 depressions represented by strongly degraded basins without precise topographical features of impact effects;
(vi) 71 unsystematized structures.

In the present study we have shown that mascons, as well as large lunar craters and mares are created by the falls of galactic comets during periods of cometary bombardments. Therefore the age of mascons can be judged from the formation time of large craters and mares on the Moon, using for this purpose the data (see figure 1). However, mascons are found not only under Moon mares, but also on the elevated areas of the lunar surface, where mascons have no apparent connection with craters. We explain the origin of these “upland mascons” by their formation under bottom of marine basins that arose earlier, but by now ceased their existence.

Since in the Cenozoic (last 65 million years) galactic comets mostly bombed the southern hemisphere of the Moon, we should expect here more young mascons. While in the northern hemisphere old mascons should prevail. In figure 8 we show the latitudinal distributions for 29 basins with a topographic ring without internal structure which we consider “young”, as well as 71 unsystematized structures, which we consider “old”. It is clearly seen that the young basins really dominate in the southern hemisphere of the Moon, while the number of old structures in the northern hemisphere is more.

9. Conclusions
(i) A new approach to the interpretation of cratering data, which takes into account a bombing the Moon by galactic comets, substantiates.
(ii) Using the results of the study mascons, systematized in [6] we got the preliminary estimates of the average age of the craters, mares and mascons on the Moon, which is significantly less than was considered earlier.

(iii) High-precision measurements of the gravitational field of the Moon in the GRAIL experiment indicate that a significant part of the energy of cosmic body is spent on heating the lunar mantle rocks. Since the mascons cannot be explained by the fall of the Solar System bodies, the discussed alternative approach, consisting in heating of the mantle rocks by galactic comets using Lavrent’ev model [11, 30], allows us to solve the problem of mascons origin.

(iv) The results of this article prove the need to transition in cosmogony and comparative planetology to the representations of Galaxycentric paradigm [7, 31].

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