# LUNAR FIGURE AND LUNAR LIBRATION
# AS A CLUE TO LUNAR INTERIOR

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The study of geometrical and dynamical figure of the Moon is one of the important elements of the complex approach to investigation of our satellite. Correlation of visible limb and real relief, mass distribution in lunar body, relative position of center figure and center of mass, geometrical sizes and dynamical parameters - all these questions are connected with the study of lunar figure. Data concerning lunar relief give evidence of the processes happening and on the surface both in lunar interior at the different stages of lunar evolution: early volcanism epoch, the period of bombarding by large planetozimals, late volcanism stage, formation of lunar maria and craters. Series of works directed on the study of gravitational field of the Moon with the help of artificial lunar satellites significantly advances our knowledge about dynamical figure. This allowed to construct the more accurate theories of lunar rotation, to model the processes in deep interior of the Moon. The nearness of Moon to Earth allows to use all complex of scientific methods to its investigation. Traditional astronomical observations: astrophysical (albedo, spectral analysis), astrometrical data are combined with results obtained by geophysical and geochemical methods (seismic ranging by landing modules of spacecrafts), with laser ranging data and etc. Because of this the Moon always was, is being and will be the interesting object for the study and as the nearest natural cosmic laboratory. In this connection the programs of international space lunar experiments are very intensive and extensive. [23]

### KAZAN LUNAR INVESTIGATIONS

Ground-based astronomical observations fill their own place in the complex approach to investigation of the Moon. Although they have a less precision, the long series of ground-based observation are used for the study of long-period, secular variations of orbital and rotational parameters of the Moon. Interpretation of large-scale star-calibrated lunar photographs gives the possibility to obtain the data of the Moon's relief from the near side directly in the celestial system of coordinates.

*Heliometric and photographic observations* of the Moon were carried out in the Engelgardt's Astronomical Observatory (AOE) for the purpose: a) to study the lunar rotation ; b) to determine the selenodetic coordinates of lunar craters and c)to establish the uniform scale of ephemeris time. First in selenodesy *the catalogue of 264 crater selenocentric coordinates* was constructed by ``absolute method'', that is, relatively to star coordinate system. Dynamical range of topography of about 10km was discovered in the region of the Mare Oriental [21]. N.Rizvanov investigated the geometrical figure of lunar near side using the large-scale star-calibrated photographs [22]. He discovered that according his catalogue, the north of the parallel $+10^{o}$ *the relief of lunar surface is about 2.5 km lower* comparatively to generally accepted level determined by other ground-based observation of the Moon. This effect was conformed by analyses of lunar photographs obtained by ``Zond-6, -8''.

The work of Sh.Khabibullin ``Nonlinear theory of the physical libration of the Moon'' [4] has initiated theoretical investigation of lunar rotation in Kazan University. Prof. Khabibullin and his disciples have constructed the tables of LPhL for proceeding of libration observations with the aim to improve parameters of lunar dynamical figure, to reveal the free librations [5-10]. The attempt was made to consider the influence of internal structure on lunar rotation. On the basis of modern lunar motion tables the *analytical tables* of LPhL was constructed by Petrova [15,16]. Development of the theory is being continued by consideration of the complex stratigraphy of lunar interior. [2, 17 - 19].

**TOPOGRAPHY, ALTIMETRY AND GRAVITY MODEL FROM CLEMENTINE and LUNAR PROSPECTOR**

Towards the end of the 20th century our knowledge about the geometrical and dynamical figure of the Moon is significantly improved. The advance is achieved due to the development as the ground-based observations so the cosmic experiments, due to the application of Lunar Laser Ranging, of Lunar satellite Doppler data and, especially, of last cosmic experiments such as the Clementine-mission [28] and the Lunar Prospector [11].

Detailed maps of the lunar surface, an improved gravity model are obtained. The data have revealed some surprising features in the Lunar figure that distinguishes significantly from the Earth's one:

- the most pronounced topographic feature on the Moon is the South Pole-Aitken Basin as a largest and deepest impact basin in the solar system;
- distribution of elevations on the Moon determined by the Clementine deviates strongly from a normal distribution,
- suggesting that several geological processes have influenced the topography;
- the Clementine and the Lunar pospector missions provide data which strengthen the contrast between near and far sides: the geochemical dichotomy between the near and far-side; the farside crust is, an average, thicker (68 km) than on the near side (60 km), accounting for much of the offset in center-of-figure from the center-of-mass;
- the terrestrial hypsogarm is bimodal and reflects a marked difference between the oceanic and continental lithospheres, the lunar hypsogram, although not distinctly bimodal, clearly shows more structure than the simple normal distribution of altitudes that might be expected from a saturated cratered surface;
- new large mass concentrations (mascons) in the lunar crust, and especially, four mascons in the large farside basins are opened, this discovery rises the question of the formation and support mechanism of the mascons as uncompensated buried loads (excess mass) in basin.

We propose that mascons in the thick (up to 100km) lunar continental crust might be produced by convective processes in the upper mantle of the Moon at the early stage of its thermal evolution}. Processes of mascon formation are apparently analogous to those in the Earth [4,17]: the top of the plume rising from core-mantle boundary (CMB) was conserved in the thick lunar crust. The analogous model of convective evolution of the lunar mantle is proposed by [12]: the partial melting occurs in the upper mantle as a consequence of hot upwelling plumes generated by instabilities of the hot core-mantle thermal boundary layer.

**LUNAR LASER RANGING**

Contributions from LLR includes the three-orders-of -magnitude improvement in accuracy in the lunar ephemeris, a several- orders-of-magnitude improvement in the measurement of the variations in the Moon's rotation, and the verification of the principle of equivalence for massive bodies with unprecedented accuracy.

The data set considered by [13,14] consists of more than 9900 normal points ranges spanning the period between 1969 and 1995. The analysis of LLR data provides a wealth of information concerning the dynamical figure and internal structure of the Moon. Presently the most accurate estimate of the lunar moment of inertia is obtained from combining the determinations of moment of inertia differences γ and β from the LLR solution and the lunar gravity field coefficients $J_2$=[C- (B+A)/2]/MR$^2$] and $C_{22}$=[(B-A)/4MR$^2$] obtained from analysis of lunar satellite data and LLR. The resulting polar moment from this combination is C=(0.3935±0.0011)MR$^2$ [1]. The same value, obtained later by [24], is 0.3929±0.0009MR$^2$.

An interpretation of polar moment gives [1] in terms of a 60-km-thick lunar crust with density of 2.75 g/cm$^3$ a constant density ρ of the lunar upper mantle, a lower mantle with contrast in Δρ relative to the upper mantle, and a variable-radius iron core with density of 7g/cm$^3$.The maximum core size is in the range of 220 to 350~km.

An improved gravity model from the Lunar Prospector gives the improved normalized polar moment of inertia C/MR$^2$=0.3932±0.0002 that is consistent with an iron core with a radius of 220 to 450km. If the maximum radius of the core is 450 km as derived from seismic and magnetic data, then the core is probably Fe or Fe-rich, although an FeS core is not excluded by the data and models [11].

The inferred from LLR data core radius [26] has a limit of 352 km for iron and up to 374 km if sulfur presented.

**LUNAR PHYSICAL LIBRATION**

The study of geometrical and dynamical figure of the Moon is impossible without the observations of rotational motion of the Moon and, consequently, without the development of the lunar rotation theory.

The observations of the fine effects in the lunar rotation by the LLR analyses allow also to inference into the lunar interior, because the rotation is influenced by solid-body tides and interaction at a liquid-core/solid-mantle boundary. For example, the dissipation in the Moon causes a small 0."26 advance in the lunar rotation axis. According to [27] this offset, a unique signature of dissipation, is observed as a small, meter-sized, monthly variation. From additional LLR data and an improved gravity field from Lunar Prospector Williams et al [26] have found four such dissipation terms, that can be explained with the combined effects of tide plus core (2/3 of the 0.26" term comes from a monthly tidal Q of 37 and 1/3 comes from the core.

Theoretical solution of libration equations [18] for two-layer Moon (rigid mantle-liquid core) gives two modes of free lunar libration in the case of polar motion: a Chandler-like wobble with a period $P_{CW}$=74.06 yr (when expressed in the rotating lunar frame), and a Free Core Nutation with a period $P_{FCN}$=144.73 yr (when expressed in the inertial frame).

The FCN detection of the Moon and its period will allow [24]:

a) to decide on the physical nature of the lunar core – it is possible only for the liquid core;

b) to determine core radius and its flattening;

c) to determine density jump at the CMB and CMB flattening.

**CONCLUSION**

All these discoveries require to take a new view of the evolution of the Moon, its origin and thermal history, to develop the experimental and theoretical investigations of our satellite.

In the light of the presented observed and theoretical data concerning the lunar figure, we attempted to propose a different line of attack on some local problems.

– The detailed analyses of hypsometric maps obtained by Clementine will allow to answer the question: is there 2.5 km lowering of the relief on the near side to the North from the +10 degrees parallel of latitude as against the generally accepted one?

– Results of the seismic observations by Japanese mission, LUNAR-A are expected to provide key data on the size of the lunar core and its physical properties. The heat flow measurements will also provide important data on thermal structure and concentrations of heat-generating elements in the Moon. These data will help to test our hypothesis about the origin of mascons discovered by Clementine in the thick continental crust of lunar far side.

– We propose to develop the theory of physical libration through consideration of visco-elastic proprieties of lunar body and core mantle differential rotation to adequately describe the observational data.

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