Japan Geoscience Union Meeting 2012
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PPS04-01 Room:102B Time:May 25 09:00-09:30

Mercury's moment of inertia from spin and gravity data

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Rotation studies coupled with gravity measurements provide powerful probes of planetary interiors (e.g., Munk and MacDonald 1960, Peale 1976, Lambeck 1980, Wahr 1988, Dickey et al 1994). Peale (1976) has shown that measurements of Mercury's obliquity and amplitude of longitude librations, together with a knowledge of the second-degree coefficients of the gravity field, can illuminate the size and state of the core.

Over the past ten years we have used the Goldstone Solar System Radar (GSSR) in conjunction with the Green Bank Telescope (GBT) to characterize the spin state and interior of Mercury. We implemented a technique (Holin et al, 1988, 1992) that provides instantaneous spin rate measurements with 10 ppm fractional precision and spin axis orientation at the arcsecond level. On the basis of measurements at 21 distinct epochs between 2002 and 2006, we found observational evidence that Mercury closely follows a Cassini state and that it exhibits forced librations in longitude, as predicted by theory. The amplitude of the librations indicates that the mantle of Mercury is decoupled from a molten outer core (Margot et al 2007). A long-period (~12 year) libration signature may be present in the data.

Analysis of the radio science signal from the MESSENGER spacecraft (Solomon et al, 2001) has provided measurements of the low-degree gravitational harmonics with a precision of better than 1% (Smith et al, 2012). The combination of spin and gravity data permits a determination of the polar moment of inertia of the entire planet and that of the outer librating shell. The moments can be used with interior models (Hauck et al, 2004, 2007) to arrive at an estimate of the core size. The core size error budget indicates that the precision of the ground-based estimates of obliquity and librations will ultimately dictate the quality of the core size determination, as well as the attendant inferences regarding the interior structure, thermal evolution, and magnetic field generation of the planet.

Spin measurements obtained since 2006 are being used to (1) refine the determination of the obliquity and of the libration amplitude; (2) confirm the presence or absence of a long-period libration component; (3) quantify deviations of the pole from the strict Cassini state. Departures from the expected spin orientation can provide information about core properties and dynamics. Such an offset in the spin orientation of the Moon has been used to quantify dissipation in the lunar interior, with both dissipation due to solid-body tides and dissipation at a liquid core/solid body boundary playing a role (Yoder 1981, Williams et al 2001).

Keywords: Mercury, interior, gravity, spin

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Some preliminary estimates of the possibility of determining the Lunar physical libration in the project ILOM

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A brief description of targets and problems of the future Japanese project ILOM (In situ Lunar Orientation Measurement), which is planned to be realized as one of kinds of observations of lunar rotation at the second stage of SELENE-2 mission, is given in the report. One of the important elements of the project is placing of a small optical telescope on the lunar surface with the purpose to detect the lunar physical libration with high accuracy 0.001 arc sec. Computer simulation of the future observation is being done with the purpose of their optimization: effective placement of measuring system on the lunar surface and formation of scheduling of observations for monitoring the physical libration of the Moon. The results of the first stage of the simulation are presented in the paper. At this stage the tracks for the selected stars are constructed and analyzed, their sensitivity to the internal characteristics of the lunar body, in the first place, to the selenopotential coefficients, is tested.

Analyses of simulated stellar tracks observable from the lunar surface (in a polar zone) revealed a difference from daily parallels of stars in comparison with ground based observations. During one "lunar day" equal to 27.3 terrestrial days, a star moves along a spiral. In dependence on the longitude of the star, these spi-rals can be untwisted or twisted. In the latter case a star can describe a loop in the sky of the Moon during the observation period. The reason of such unusual astrometry phenomenon is combination of the slow rotation of the Moon as compared with the Earth and the fast precession motion of the lunar pole (in comparison with precession motion of a terrestrial pole).

Due to physical libration the shifts of all tracks will be observed towards direction opposite the Earth. The tracks are sensitive to gravity model of the Moon and are different even for the most accurate modern gravity field models LP150Q and SGM100h.

In the current report we present formulation of the inverse problem of the lunar libration and the application of gradient method for solution of this problem. It is shown that longitudinal libration can not be revealed from observations of polar stars. It is shown, that measuring inaccuracy E in selenographic coordinates x and y causes the inaccuracy in libration angles less than sqrt(2)*E. Residuals in comparing libration angles of inclination (rho) and node (I*sigma) calculated for two kinds of lunar body model (deformable and rigid Moon) are analyzed. FFT applied on the residuals spectra reveals several periodical components which are sensitive to the Love number k2 Identification of the components with origin harmonics in analytical series of libration is carried out, what can be useful for the future spectral analyses.

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Keywords: Lunar physical libration, simulation, ILOM

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VLBI mission proposed for SELENE-2 and its contribution to constrain the lunar internal structure

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Internal structure and composition of the Moon provide important clue and constraints on theories for how the Moon formed and evolved. The Apollo seismic network has contributed to the internal structure modeling. Efforts have been made to detect the lunar core from the noisy Apollo data (e.g., [1],[2]), but there is scant information about the structure below the deepest moonquakes at about 1000 km depth. On the other hand, there have been geodetic studies to infer the deep structure of the Moon. For example, LLR (Lunar Laser Ranging) data analyses detected a displacement of the lunar pole of rotation, indicating that dissipation is acting on the rotation arising from a fluid core [3]. Bayesian inversion using geodetic data (such as mass, moments of inertia, tidal Love numbers k2 and h2, and quality factor Q) also suggests a fluid core and partial melt in the lower mantle region [4]. Further improvements in determining the second-degree gravity coefficients (which will lead to better estimates of moments of inertia) and the Love number k2 will help us to better constrain the lunar internal structure.

Differential VLBI (Very Long Baseline Interferometry) technique, which was used in the Japanese lunar exploration mission SELENE (Sept. 2007 - June 2009), is expected to contribute to better determining the second-degree potential Love number k2 and low-degree gravity coefficients. In SELENE, the VLBI radio sources (called VRAD) were on board the two sub-satellites, Rstar and Vstar. The differential VLBI data, when both the radio sources were within the beam-width of the ground antennas, were of particular importance because they are highly accurate with atmospheric and ionospheric disturbances almost cancelled out by the simultaneous observation. Such tracking data, i.e. "same-beam differential VLBI data" were useful for precision orbit determination [5] and also used to develop an improved lunar gravity field model SGM100i [6].

SELENE will be followed by the future lunar mission SELENE-2 which will carry both a lander and an orbiter. We propose to put the VRAD-type radio sources on these spacecraft in order to accurately estimate k2 and the low-degree gravity coefficients. By using the same-beam VLBI tracking technique, these parameters will be retrieved through precision orbit determination of the orbiter with respect to the lander which serves as a reference. The VLBI mission with the radio sources is currently one of the mission candidates for SELENE-2.

We have conducted a preliminary simulation study on the anticipated k2 accuracy. With the assumed mission duration of about 3 months (84 days) and the arc length of 14 days, the k2 accuracy is estimated to be better than 1 %, where the uncertainty is evaluated as 10 times the formal error considering the errors in the non-conservative force modeling and in the lander position.

Through forward model calculation, we will show that the k2 error as small as 1 % is sensitive enough to the change in the liquid core radius of about +/-40 km. We will also show that the k2 accuracy has sensitivity to possible partial melt layer and contribute to narrow the range of the plausible internal structure models. Although k2 by itself can not distinguish the effect of core size from that of partial melt layer, it is expected that the combination with other geophysical data such as seismic data as well as geochemical data will establish a realistic lunar interior model.

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Keywords: Moon, gravity field, tidal Love number, internal structure, VLBI, SELENE-2

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Comparison of changes in Earth rotation with temperature changes in the recent century

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Chandler wobble is the resonant motion of the Earth pole, which was discovered more than a century ago. It is supposed that atmospheric and oceanic processes supply energy for it. To reveal the sources of the Chandler excitation and their spatiotemporal behavior, we study atmospheric angular momentum (AAM) geographical maps since 1948 yr, by applying multichannel singular spectrum analysis (MSSA, [1]) and Panteleev filtering in the Chandler frequency band.

We also try to find explanations for similarities between the curves of Earth rotation changes and global mean temperature anomalies. The latter, besides the global worming "hockey stick", shows about 20-year period variability. In [2] presence of a 18.6-year amplitude modulation in the Chandler excitation was revealed. In [3] it was shown that the Moon tide could play an important role in the weather variability and atmospheric circulation.

This joint study is an attempt, to draw attention to these interesting facts and to obtain pro and contra of the hypothesis of the existence of a common factor, that influences both Earth rotation changes and climate variability.

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Keywords: Earth rotation, atmospheric circulation, climate change

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The mechanism and regularities of heat planets and satellites due to the excitation of their shells by external celestia

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Mechanism, providing a high endogenous activity of the Earth and other celestial bodies, was proposed by the author in 1996-2002 (Barkin, 2002). Its essence lies in the fact that the external celestial bodies are not only deform the Earth's mantle layers and excite the system itself, its shells, primarily the core and mantle. The gravitational attraction of non-spherical shells of the earth by external celestial bodies, occupying, generally speaking, the eccentric positions relative to each other, inevitably causes a small relative displacements of the shells and their relative rotations (swinging) and as a consequence deformations, additional to the classical tidal deformations, and new dissipation processes.

In this paper we study the deformations, changes of the elastic energy, of the energy of dissipation in a viscous-elastic mantle as a result of the polar drift and oscillations of the core, both globally across the planet, and in relation to the northern and southern hemisphere. The basis of study is a solution of problem of elasticity theory of deformation of the mantle at the polar displacements and oscillations of the core under certain boundary and initial conditions (Barkin, Shatina, 2005). It is assumed that the core and mantle separated by a thin viscous-elastic layer, similar to the corresponding layers of zone D", whereby it becomes possible the small oscillations of the core and its secular drift, which have been confirmed with modern data on space geodesy about the displacements and oscillations of the mass center of the Earth. That is, the core-mantle system is considered as not rotating. In the unperturbed state the mantle is characterized by concentric density distribution. The excess (superfluous) mass of the core by its displacements and due to its gravitational attraction causes the deformation of all layers of the mantle. Deformations of the planet are described by the linear model of a viscous - elastic Kelvin-Voigt body. As the basic parameters the appropriate parameters of elasticity and viscosity of the Earth and their average values in accordance with the classical model of the Earth (PREM) have been taken (Dziewonski, Anderson, 1981). For these deformations the elastic energy of the planet and energy of dissipation is determined and estimated.

The northern hemisphere plays dominant role, and (at the northern drift of the core) obtains the elastic energy and thermal energy by about 30% more than in the southern hemisphere. Thus, the geomodel explains the observed in present the natural phenomena: activation of volcanic and seismic activity in the northern hemisphere, more active increased warming and catastrophic events in the northern hemisphere compared to the southern hemisphere and oth. On the basis of this model an explanation of fundamental geodynamic phenomena of tidal acceleration of Earth's axial rotation, the secular drift of the Earth's pole in the present epoch, the global rise in sea level and contrast of secular changes in mean sea level in northern and southern hemispheres has been given.

An explanation of the phenomenon of dichotomy of geological structures and geophysical phenomena and natural processes on Mercury, the Moon, Mars, Vesta, Titan, Enceladus, Pluto, Charon and other bodies of the solar system has been given. Similar phenomena of inversion, contrast, asymmetry, cycling, curling of hemispheres and polar regions, ordering, synchronization, etc. will be opened in the near future for celestial bodies in others exo-planetary systems and for pulsars (Barkin, 2007-2011).

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Keywords: endogenous energy, heat flow, shell dynamics, planets, satellites

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Dependence of the tidal response on the internal structure of the Moon: Geodetic implication to the partial melt layer

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Generally, internal energy dissipation associated with tidal deformation and physical libration of a planetary body depends on its internal structure, especially viscosity structure. Here magnitude of the tidal dissipation is mainly represented by the quality factor (Q) and the Love number (k_2). These values inevitably depend on its viscosity structure, and thus, give us clues of its thermal state and history.

Although dependence of the tidal dissipation on the viscosity structure of the Moon has already been demonstrated by previous research, its parameter study unfortunately has certain limitations. First, it assumes the lunar interior as a uniform sphere. However, the realistic interior on the Moon has been revealed to be differentiated by observation of the moonquakes. Therefore, it should be based on the seismic velocity structure instead of a homogeneous body. Second, Only Q has been calculated. However, geodetic observation actually show us not only Q but also k_2. Therefore, both of them need to be estimated. Third, in the past, there are no observational values which correspond to the calculation results. However, both Q and k_2 on the Moon has been derived from rotation and gravity field measurements by lunar laser ranging and precise orbit determination of the orbiters, respectively. Therefore, the parameter study should be confronted with the current result of Q and k_2.

By resolving the above issues, we would be able to put a new constraint on the interior structure on the Moon. That is, it allows us to consider what kind of viscosity structure can explain both Q and k_2 with no contradiction. Moreover, such consideration further enables us to tell what should be investigated in the framework of the lunar exploration project in the next generation.

Therefore, parameter studies on visco-elastic deformation are performed based on more realistic interior structure, and then, its calculation results are compared with pre-existing results derived from selenodetic observation. Concretely speaking, by employing the density and elasticity structures from seismic inversion, and by defining the viscosity of the asthenosphere as a free parameter, Q and k_2 are calculated. The knowledge of seismology also indicates the presence of a strong attenuation zone at the lower-most part of the lunar mantle. The viscosity in this zone is probably lower than that in the upper part. Therefore, this study prepares two extreme viscosity structures for the sake of simplification. One is the case in which the viscosity of the asthenosphere is regarded to be uniform and changed over several orders of magnitude in this parameter study. The other is the case in which just the viscosity of the high attenuation zone is changed over the same range. After that, by comparing the result for each of the above cases with the observational values obtained from Kaguya, Chang'e-1, and LRO, it is examined whether the viscosity value satisfying Q and k_2 at the same time is admissible or not.

As a result, it is clarified that the viscosity solution consistent with geodetic observations of both rotation and gravity field exists only if the interior structure includes the specific low viscosity zone, and also if the value from Kaguya or Chang'e-1 is referred. This case defines only one narrow range of viscosity corresponding to the observational Q. This viscosity range determines a numerical k_2 which is consistent with each of the observed values. On the other hand, this determined value is not consistent with the observed value from LRO because it is slightly larger than the others. In contrast to the above case, if it does not include the low viscosity zone, this case defines two ranges of corresponding to the observational Q. However, both these ranges are not consistent with any of the values from either Kaguya, Chang'e-1, or LRO.

As a conclusion, the seismic attenuation zone inside the lunar interior is probably equivalent to the low viscosity zone.

Keywords: the Moon, tidal response, internal structure, partial melt, quality factor, Love number

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The expanding Earth confirmed by geodetic observations

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Whether the Earth is expanding or contracting is an interesting question in geoscience. Some scientists support the viewpoint of the Earth expansion, and some are against this viewpoint. This study focuses on estimating the Earth expansion rate using the space-geodetic data over land, global gravimetric observations, and altimetry data over oceans. Space-geodetic data recorded at stations distributed over land areas were used to estimate the Earth expansion rate, and the results suggest that the Earth is expanding at a rate about 0.24mm/a. Based on the EGM 2008 and the secular variation rates of the second-degree coefficients determined by satellite laser ranging and Earth mean-pole data, the principal inertia moments of the Earth (A, B, C) and in particular their temporal variations were determined, and the results show that the Earth is expanding at a rate ranging from 0.17 mm/a to 0.21 mm/a, which coincides with the space-geodetic evidences. Further, by examining the sea level rise observed by satellite altimetry, taking into account the contributions of the mass migration due to glacier and ice sheet melting, global temperature increase and post-glacier respond effects, we find that the Earth is expanding at a rate around 0.9+/- 0.6 mm/a. A relative large uncertainty (+/- 0.6mm/a) is due to the fact that the sea level rise and the relevant contributions to it cannot be relatively well estimated at present, and further investigations are needed. Finally, a possible expansion mechanism is provided in this investigation. This study is supported by Natural Science Foundation of China (grant No. 41174011; 40974015; 40637034).

Keywords: Earth expansion, space-geodetic data, gravimetric data, sea level rise