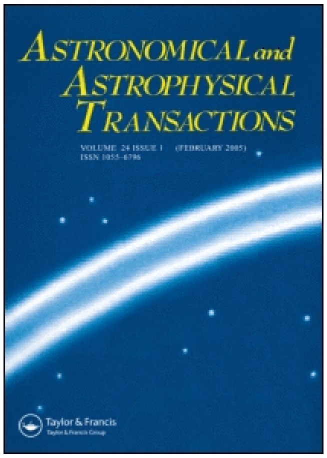

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GRAVITATIONAL INVESTIGATIONS ON THE SELENE MISSION (JAPAN) AND THE EXISTENCE OF A LUNAR CORE

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The existence of a lunar core is still an open question. If a core existence is verified by future direct measurements, this core would impose constraints on the model of origin of the Moon. Significant prospects in the decision of this problem are opened up by the Japanese SELENE project. A short review of results concerning the facts about the core existence is given in the article. Most advances in this study were obtained as results of the investigation of lunar gravity and physical libration. The scientific objectives and perspectives of the SELENE project are described.

Keywords: Lunar evolution; Lunar core; SELENE project; Research in selenodesy (RISE) project; Two-layer model; Free core nutation

1 INTRODUCTION

The Moon has been stimulating the interest of scientists for many centuries because it is the most familiar planetary body in the Solar System. Since the 1950s, the Moon has been explored repeatedly by unmanned and manned missions. In particular, the Apollo and Lunokhod missions have provided many new findings about the Moon and brought about significant progress in the field of lunar science. However, although the Moon has been studied more extensively than any other planetary body, the most basic questions in lunar science concerning the origin and early evolution of the Moon are still left open. The study of the Moon is particularly important in planetary science because it is directly related to the origin and evolution of the Earth and other terrestrial planets.

Four major models have been proposed for the origin of the Moon: fission, capture, binary accretion and accretion by giant impact. In order to address the question concerning the origin of the Moon, further exploration that is more elaborate than before with respect to the constituent materials, interior structure and magnetic fields is required. Information on the interior's structure and state of the Moon impose constraints on the model of its origin. If we assume that the Moon was produced by accretion of primitive meteoroids, then the core of the Moon is estimated to be larger than 360 km in order to explain the abundance of metal in the lunar rocks. On the other hand, if the Moon was made of the same material as the

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Earth's mantle, the radius of the core must be less than 285 km. Information on the internal structure can be obtained by precise measurement of the gravity of the Moon.

There is an international movement to challenge the study of the origin and evolution of the Moon, using advanced observation technologies (a short review has been given by Petrova and Gusev (2001a). The Clementine mission in 1994, the Lunar Prospector mission in 1998–1999, the European lunar mission SMART-1, which is a remote-sensing mission and was launched in 2002, the Japanese Lunar-A mission, which is a penetrator mission planned for 2003 and, finally, the Japanese explorer SELENE, planned to be launched in 2005, are all experiments aimed at obtaining broad information about lunar gravity and the heat field, geometrical and dynamic figures and the lunar structure.

2 GRAVITATIONAL AND LUNAR LASER RANGING DATA PROVIDING EVIDENCE OF THE LUNAR CORE

There are two most important factors providing powerful progress in the development of the study of the Moon and advancing significantly knowledge about our natural satellite: firstly, a series of studies of the gravitational field of the Moon with the help of artificial lunar satellites; secondly, a great volume of data accumulated during the 30 years of lunar laser ranging (LLR), which has allowed us to detect fine features of the lunar rotation due to the high accuracy of observations.

The analysis of LLR data provides a wealth of information concerning the dynamic figure and internal structure of the Moon. At present, 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 the analysis of lunar satellite data and LLR. As result, a highly accurate value of the lunar polar moment of inertia (C/MR^2, where R is the lunar radius) may be obtained. Unfortunately, the observation error in C_{22} or C_{20} is larger than that of dynamic flattening γ and β so far. If the error is improved by one order or so, the lunar core density can be estimated more precisely from the moment of inertia assuming a two-layer model for the lunar body, for example. An interpretation of the polar momentum when combined with compositional, thermal and density models of the lunar crust and mantle can allow some useful inferences to be drawn about the mass and size of the core. So, a density jump (from about 3 to 7 g cm^3) in the vicinity of the 1400 km depth, or, in other words, a depth of the lunar core–mantle boundary was evaluated for the first time (Dickey et al., 1994). The structure of the gravity field of the Moon derived from the high-precision trajectory measurements by the Lunar Prospector was compared with results of the laser altimetry obtained earlier from the Clementine and with the LLR data. An interpretation of these data in the light of the lunar interiors has allowed us to expect the presence of a metallic core. The present determination of a C/MR^2 value of $0.392\,32 \pm 0.0002$ is consistent with an iron core with a radius of 220–450 km.

The independent conformation of this conclusion was obtained as result of magnetometric measurements by the Lunar Prospector in April 1998 during intersection by the Moon of a geomagnetic tail of the Earth. The preliminary interpretation of these data also indicates the existence in the Moon of a metal core with a radius from 250 to 430 km (Lin et al., 1999).

Analyses of lunar rotational dissipation, obtained by LLR, has shown that two possible sources of dissipation are monthly solid-body tides caused by the Earth (and Sun) and a fluid core with a rotation distinct from the solid body (Williams et al., 2001). Both effects were calculated by numerical integration of the lunar rotation. As result, the core radius

TABLE I Values of Core Radius[a]

Observation method	Estimated core radius[a]	Reference
Seismic data	(km) $\leqslant 500$	Dickey et al. (1994)
Surface magnetometric measurements	(km) 435 ± 15	Russel et al. (1981)
	(km) $\leqslant 400$	Nakamura et al. (1982)
Lunar Prospector magnetometric measurements	(km) 250–430	Lin et al. (1999)
	(km) 220–450	Dickey et al. (1994)
Polar moment interpretation	(km) 320 $\binom{+50}{-100}$ (iron core)	
	(km) 510 $\binom{+80}{-180}$ (FeS core)	Konopliv et al. (1998)
LLR analyses of lunar rotational dissipation	352 (iron core)	Williams et al. (2001)
	374 (FeS core)	
Depth of the core–mantle boundary	≈ 1400 km	Dickey et al. (1994)
Core ellipticity (a − c)	≈ 140 m	Dickey et al. (1994)

[a]The inferred existence of a metallic core with mass exceeding 1% of the lunar mass was made on the basis of many experiments and theoretical simulations and is indirect and provisional. Because of this, new direct measurements are planned in new lunar experiments, such as the Lunar-A (Mizutani et al., 1998) and SELENE (Kawano et al., 2001).

could be as much as 352 km for an iron core and 374 km for a Fe–FeS eutectic composition. When this modelling has been performed for different structures of the core, the adopted core densities were as follows: liquid iron, $7.0\,\mathrm{g\,cm^{-3}}$; solid iron, $7.7\,\mathrm{g\,cm^{-3}}$; Fe–FeS eutectic, $5.3\,\mathrm{g\,cm^{-3}}$.

The different values of the core radius obtained by the different methods are represented in Table I.

3 LUNAR TOPOGRAPHY AS A CLUE TO THE LUNAR INTERIOR

Detailed maps of the lunar gravity field, lunar topography and crust thickness were obtained as a result of global topographic mapping by Clementine (Zuber et al., 1994; Frank et al., 1997) and by Lunar Prospector (Konopliv et al., 1998; 2001). Some surprising features in the lunar surface and dynamic figure were revealed from laser altimetry and Doppler tracking.

(i) The most pronounced topographic feature on the Moon is the South Pole–Aitken Basin as the largest and deepest impact basin in the Solar System.
(ii) Distribution of elevations on the Moon determined by the Clementine mission deviates strongly from a normal distribution.
(iii) The Clementine and the Lunar Prospector missions provided data which strengthen the contrast between the near and far sides, that is the geochemical dichotomy between the near and far sides; the far-side crust is, on average, thicker (68 km) than on the near side (60 km), accounting for much of the offset in the centre of the figure from the centre of mass.
(iv) New large mass concentrations (mascons) in the lunar crust and, in particular, four positive gravitational forces in the thick far-side basins were discovered, which poses the problem of the formation and maintaining mechanism of the mascons as uncompensated buried loads (excess mass) in a basin.

These discoveries of a planetary surface provides insight into very-large-scale planetary processes. The global observation of the gravity field, element abundance, mineralogical composition and geological features will characterize the difference between the near and far sides and constrain the lunar evolution models.

4 SELENE PROJECT

A Moon-orbiting mission SELENE (standing for selenological and engineering explorer) is being prepared as a joint space programme by two Japanese departments, ISAS and NASDA, for lunar science and technology development for future lunar exploration (Kawano et al., 2001). The spacecraft consists of a main orbiting satellite at about 100 km altitude in the polar orbit and two subsatellites (a relay satellite and a VRAD satellite) in the elliptical orbits. The scientific objectives of the mission are the study of the origin and evolution of the Moon, in-situ measurement of the lunar environment, and observation of the solar terrestrial plasma environment from the lunar orbit. SELENE will carry instruments for scientific investigation including mapping of lunar topography and surface composition, measurement of the gravity and magnetic fields. The launch by an H-IIA rocket is planned in 2005. 14 instruments on board will collect various scientific data during a 1 year mission period.

The National Astronomical Observatory is promoting the research in selenodesy (RISE) project, which is a part of the SELENE project, to investigate the lunar gravity field and topography. The scientific data from the RISE project include the first direction measurement of the lunar gravity field on the far side, tracking data of satellites with differential VLBI values, and a truly global topographic map of the Moon.

The SELENE mission scenario is planned in the following way. Differential VLBI observations among the transmitters both on a lunar orbiter and on the Moon are planned in order to estimate the precise lunar gravity field and to determine the lunar core density. It has 14 instruments, and three of these are for precise determination of lunar gravity field and the lunar topography. These are two VLBI transmitters, a relay satellite and a laser altimeter. The explorer consists of a main orbiter, a relay and a propulsion module. The relay satellite, in which one transmitter for differential VLBI (VRAD-1) is installed, is a free flyer and is separated from the explorer just after the explorer is injected into an elliptic lunar orbit. Its orbit has an apoapse of 2400 km altitude and periapse of 100 km altitude. The main orbiter gradually decreases its altitude and finally has circular orbit of 100 km altitude. After observation for about 1 year, a part of the propulsion module attached to the main orbiter is separated and lands softly on the lunar surface together with another VLBI transmitter (VRAD-2). Instead of a soft landing of the module, it has also been discussed whether VRAD-2 should be installed in another free flyer. The relay satellite relays radio waves from the Earth to the main orbiter, and the return waves from the orbiter are also relayed to the Earth by this satellite. The relay satellite makes Doppler shift measurements that are four-way possible on the far side of the Moon. These measurements must give precise information on the lunar gravity field of the far side since they are archived with a resolution of $0.1\,\mathrm{mm\,s^{-1}}$. The laser altimeter measures the round-trip time with an accuracy of 17 ns (5 m in altitude) and knows the altitude of the orbiter. Since the orbiter is tracked by two-way Doppler frequency measurements, the position of the orbiter is precisely determined; therefore, it will be possible to draw the figure of the Moon from the observed altitudes and the estimated position of the orbiter. In order to determine the orbit of the relay satellite, two radio transmitters (VRAD-1 and VRAD-2) both on the satellite and on the Moon play important roles. Differential VLBI measurements between two radio sources as well as Doppler measurement determining its precise position give us information on lunar librations in addition to LLR data. Figure 1 shows the concept behind the observations.

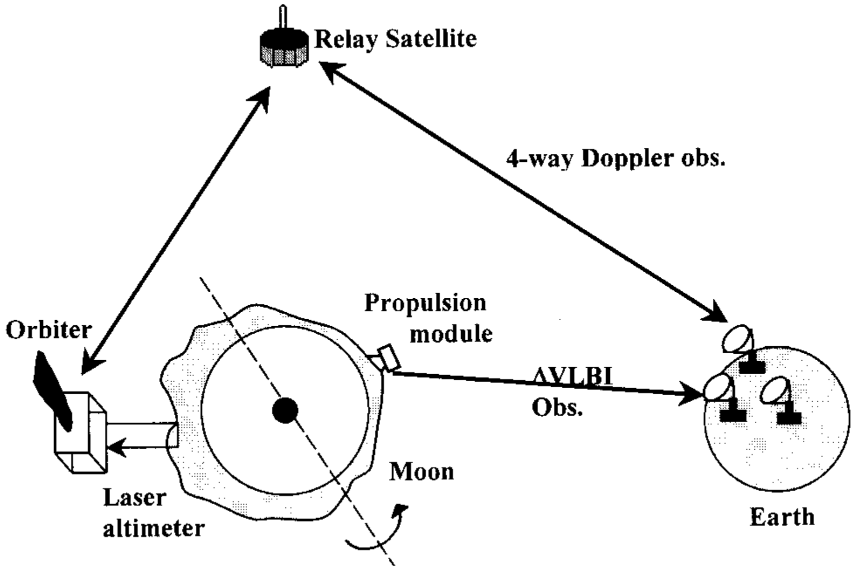

FIGURE 1 Concept behind the observations in the RISE project.

One of the scientific targets of the SELENE project is the estimation of the lunar core density. The lunar principal moment of inertia is derived from a set of dynamic flattenings and of the second-degree spherical harmonics of the lunar gravitational fields C_{20} and C_{22}. The VRAD mission can obtain the lunar moment of inertia with an accuracy of better than 0.1% by improving the values of C_{20} and C_{22}. An improved value of the lunar moment of inertia with 0.1% accuracy can put a constraint on the density of the lunar core when the radius is known. The lunar core density is closely related to the origin of the Moon because several hypotheses of the origin anticipate different core densities or chemical compositions, especially with respect to the total amount of ferrite. Information about lunar tectonics and thermal history can be obtained from high-degree gravity coefficients and altimeter data. Lunar gravity field modelling so far has been plagued by a lack of tracking data on the far side. However, this situation will be overcome by high–low satellite-to-satellite tracking (SST) which enables the far-side gravity field to be measured directly. The SST data will mainly contribute to the improvement in the high-degree gravity coefficients.

5 LUNAR CORE AND PHYSICAL LIBRATION

The results of the global topographic mapping of the lunar surface and the study of the Moon's gravitational characteristics will allow us to obtain a detailed dynamic figure with a high resolution and, as a consequence, to construct a more accurate theory of lunar rotation. On the other hand, the rotation of a celestial body is sensitive to its own internal structure. In particular, theoretical modelling of the rotation of a two-layer body (viscose mantle–liquid core) shows that a new mode, namely free core nutation (FCN), arises in polar rotation. The basis of the theory of a two-layer body rotation was given by Poincaré (1910); then it was developed by many workers and was applied to the Earth's rotation (see for example Dehant et al. (1993) and Getino (1995)) and to Mars (Van Hoolst et al., 2000). The FCN phenomenon is a consequence of the fact that the vector of the angular velocity of the liquid core is not aligned with the mantle's angular velocity. The numerical value of the FCN period depends on the parameters of the lunar core: its radius and its principal moments of inertia. The first estimation of this period was made on the assumption that the core dynamic figure is like to be the figure of the total Moon, and the core radius varies in the range 220–600 km (Petrova and Gusev, 1999; 2001b). It was shown also that, in view of the resonance rotation of the Moon with a large period and a relatively small size of the core, the FCN period is slightly sensitive to these variations and is approximately 144 years. For the future development of the physical libration theory, more accurate values of the period and, as a consequence, the core parameters are very important. However, the mere fact that FCN modes will be detected in lunar rotation means the existence of a core in the Moon.

6 SUMMARY

In summary it may be said that accumulated data about lunar gravity are now very numerous, but still many more are required to supplement the data about gravity and the topography picture of the far side. Although there is much inferential evidence that the Moon has a core, nevertheless direct experiments on the detection of the core and the determination of its characteristics are very important. Significant prospects of resolving this problem are provided by the RISE project on the SELENE mission. The data obtained will allow us to improve the physical libration theory of the Moon and, together with theoretical and observational libration data, will provide a further study of the lunar interior and, as a consequence, of its origin and evolution.

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