FINE PHENOMENA OF THE LUNAR LIBRATION. A. Gusev[1,2], N. Kawano[2] and N. Petrova[1], [1] Kazan University, 18, Kremljevskaja str., Kazan, 420008, Russia. [2] National Astronomical Observatory, 2-12 Hoshigaoka, Mizusawa, Iwate 023-0861, Japan (e-mail: gusev@miz.nao.ac.jp)

Introduction: The idea is to detect fine variations in the lunar rotation caused by a complex stratigraphy of lunar interior, using the high-precision astronomical observations of the lunar rotation in the forthcoming mission SELENE [9]. An occurrence of additional oscillations in the polar motion of the Moon is one of manifestations of heterogeneous of a lunar body on its Eulerian (free) rotation. An evaluation of the eigenfrequencies describing the free librations of the Moon may be obtained as a solution of homogeneous equations for libration angles. The Hamiltonian approach, developed by Getino et al. [5] to description of non-rigid, three-layer Earth with dissipation, may be adopted to study of the analogous effects in free rotation motion of the Moon. It is only necessary to take into account that there is a coincidence of the rotational and orbital period when transferring to the lunar dynamical system of coordinate [1, 14].

Two-layer Moon: The first estimations of the lunar Free Core Nutation (FCN) period for a two-layer Moon (rigid mantle/solid core) have given the value about 140 – 190 years in inertial frame [16]. The fluid core does not share the rotation of the solid mantle: it can only weakly mimic the precession mantle motion. The resulting few cm/sec velocities differences at the core-mantle boundary causes a torque and dissipation of energy [18, 19].

Outer/inner core formation: There are reasons to view the Moon as a three-layer body: solid mantle/fluid outer / solid inner core. As result, new modes appear in free rotation. The most important unknown are related to the size, composition and physical state of the inner/outer cores. It is not known whether there would be solid inner core, nor how large it would be. The main uncertainties is the concentration of light element in the core, for example, sulfur, which has a big effects on the melting temperature of the core alloy. The liquid outer shell would have formed as a result of planetary cooling and core partly freezing from a hot initial state with an entirely molten core. Mainly iron precipitates and forms a quasi-pure iron solid inner core. The sulfur concentration of the outer lunar core gradually arises, until the outer core reaches the eutectic Fe-Fes composition [10], for which the solidification processes is another. The eutectic composition is the composition where the solidus and the liquidus of the core alloy meet. Due to solid inner core growth, the sulfur concentration would become enriched in the outer core shell and the increasing depression of the freezing point would keep an outer liquid in spite of lunar cooling. Older thermal history lunar models based on a parameterization of convection heat transport through the mantle invoked sulfur concentrations in the core between 1% and 5% to keep the core from freezing over the lunar lifetime. While pure Fe at 50 kbar melts at 1600°C, the Fe-FeS eutectic point is near 1000°C. It is likely, similar picture of outer liquid/inner solid core formation may observe in all terrestrial planets – Mars [3], Mercury [17].

Rotational normal modes of the three-layer Moon: For a planet with a solid inner core and a liquid outer core, there *are four rotational normal modes*. This numbers is reduced to two for a planet without inner core, and to one for a planet without liquid core [4, 5]. For a planetary model with three homogeneous ellipsoidal layers the Hamiltonian analytical method for the calculation of the rotation variations gives magnitudes of these normal mode frequencies: they may be derived from governing equations, they depend on a presence and on dimension of the inner core within the outer core, of their dynamical flattening. All types of modes are result of non-coincidence of rotation axes of mantle, outer and inner core (Figure 1).

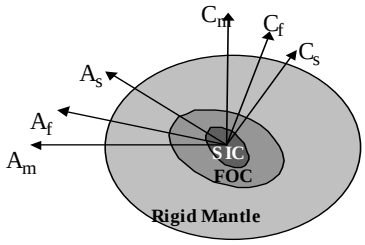

Figure 1. Three-layer Moon: Solid Inner Core (SIC), Fluid Outer Core (FOC), Rigid Mantle – with axes of inertia for each layer.

The analytical *theory of Lunar rotation for the rigid Moon* was obtained in many works (e.g. [2, 11, 12]). The Earth's rotation Hamiltonian theory was developed by Getino and his collaborators in a series of their works [5]. The *multi-layer Moon* is very difficult problem for the analytical description. Because of this, as the first approximation, we used the results of the analytical theory of the Earth's rotation developed by Getino, adapting them to the case of the resonance rotation of the Moon.

The Chandler Wobble: (CW), which is a motion of the rotation axis of the Moon around its dynamical figure axis due to the bulges of the Lunar body. It is the only global rotational mode for completely solid planet. For the Moon it has a long period 74.6 year in a frame tied to the Moon and *is prograde* (i.e. in the direction of lunar rotation). This mode was detected from LLR observation as 3"×8" elliptical component in the oscillation [13].

The Free Core Nutation: (FCN), which represents a differential rotation of the liquid core

relatively the rotation of the mantle. This mode does exist only if a core is liquid. It has a quasi-diurnal period in a frame connect to the Moon and *is retrograde*. The lunar FCN would have a long period in space of about 144 year, if dynamical figure of a core is similar to that of the mantle [6, 7, 15] or about 186 years for the axially symmetric core with ellipticity 4×10^{-4} [8].

The Free Inner Core Nutation: (FICN), which represents a differential rotation of the inner core with respect to the outer layers of the Moon. The mode does exist only if the lunar two-layer core contains outer liquid and inner solid portions. It has a quasi-diurnal period in a frame connect to the Moon and *is prograde*. As preliminary estimation show, the lunar FICN would have a very long period in space is in the range of 500–600 years for the core's radius 350 km [8].

The Inner Core Wobble: (ICW)**,** which represents a differential rotation of the figure axis of the lunar core with respect to the rotation axis of the Moon and is due to the equatorial bulge of the inner core, having an excess of density with respect to the liquid core. This mode does exist only if there is an ellipsoidal solid inner core within a liquid core in the Moon. It has a long period great than 100 years for the core's radius 350 km in a frame tied to the Moon and *is prograde* [8].

Conclusions: Despite of the small sizes, the lunar body can have composite structure. The geophysical evolution processes and conditions for the formation of a fluid outer/ solid inner core are considered. The models of formation of the lunar core are consistent with a variety of scenarios. For pure compositions (Fe or FeS, small or large core radii) an entirely solid core is likely, the mean composition of the core is close to the eutectic composition (20-25% S). In this case even an entirely liquid core seems possible due to the very low eutectic temperature.

In a case of free rotation of the three-layer Moon the four modes in its polar motion might be observed. The evaluations of the periods were made. The FCN period is in a range of 144 – 186 years in dependence on the ellipticity. The FICN has a very long period: 516 – 634 years for various core's radius. The P_{ICW} is 101 – 108 years [8].

References: [1] Bouquillon S., Kinoshita H., Souchay J. (2003) *Cel. Mech.&Dyn. Astr*, 86,29-57.[2] Chapront J., Fracou G. (2003) *A&A*.404, 735-742. [3] Defraigne P., A. Rivoldini, Van Hoolst T., V. Dehant (2003) *J.Geoph. Res.* 108. E12, 5128. [4] Dehant V., Van Hoolst T., O. de Viron, M. Greff-Lefftiz, H. Legros, P. Defraigne (2003) *J.Geoph. Res.* 108. E12, 5127. [5] Getino J., J.M. Farto, and J.M. Ferrandiz (1999) *Cel. Mech and Dyn. Astr*., 71, 95–108. [6] Gusev A., Petrova N., Kawano N. (2002) *IAA Transactions*, 8, 83-85. [7] Gusev A., Kawano N., Petrova N. (2003) *Astron. & Astroph. Trans.*, 22, 141-147. [8] Gusev A., Kawano N., Petrova N. (2004) *Adv.Space Res* (in press), [9] Kawano N., Hanada H., Tsubokawa T., Iwata T. (2003) *Proc. of Int. Conf. "New Geometry of Nature"*, Aug.25–Sept.5, 2003, Kazan Univ. Press. vol. 3, pp.114–119. [10] Konrad W., Spohn T. (1997) *Adv.Space Res*., 19, 1511-1521. [11] Moons M. (1982) *Cel. Mech. & Dyn. Astr*., 26, 131. [12] Moons M. (1984) *Cel. Mech. & Dyn. Astr*., 34, 263. [13] Newhall X X , Williams J.G. (1997) *Cel. Mech. & Dyn.Astron.*, 66, 21-30. [14] Petrova N., Gusev A. (1999)., *Proc. of Int. Conf. "Geom. of Phys. IV"*, Kazan, 276-282. [15] Petrova N, Gusev A. (2001) *Cel. Mech. and Dyn. Astron.* 80, 215-225. [16] Petrova N., Gusev A., Heki K., Hanada H., Kawano N. (2002) *IAA Transactions*, 8, 143-145. [17] Spohn T., Konrad W., Breuer D., Ziethe R. (2001) *Icarus*, 149, .54-65. [18] Williams J.G., Boggs D., Yoder Ch., Ratcliff J., Dickey J. (2001) *J. Geoph.Res*., v.106, No E11, pp. 27, 933-27, 968. [19] Williams J.G., Boggs D.H., Ratcliff J.T. and Dickey J.O. (2003) *LPS* XXXIV. 1161.pdf., [20] Williams J.G., Boggs D.H., Ratcliff J.T. (2004). *LPS* XXXV. 1398.pdf.