A NEW DYNAMICAL MODEL OF THE LUNAR CORE AND IMPROVED OBSERVATIONAL CONSTRAINTS FROM LUNAR LASER RANGING

N. Rambaux[1], V. Viswanathan [(2,1)], A. Fienga [3], J. Laskar [1], M. Gastineau [1]

[1] ASD/IMCCE, Observatoire de Paris, PSL Université, Sorbonne Université - France
Nicolas.Rambaux@obspm.fr

[2] NASA Goddard Space Flight Center, Greenbelt - USA

[3] AstroGéo/Geoazur - CNRS/UMR7329, Observatoire de la Côte d'Azur - France.

ABSTRACT. Constraints on the interior structure of the Moon are revisited using gravity data from GRAIL, topography data from LRO-LOLA, Apollo seismic data and Lunar Laser Ranging data. Here, we present recent results obtained by Viswanathan et al. (2019) on the determination of the size and shape of the lunar fluid core through these dataset.

1. INTRODUCTION

Our Moon is one of the most studied objects in the Solar system; we benefit from chemical, geophysical, and geodetic observations achieved by multiple Earth ground-based telescopes, orbital and in situ missions. However, its deep interior properties remain a puzzle because the lunar core is very small, implying weak signature in the observational data set. This paper focuses on the description of a new lunar core rotational model included in INPOP (Viswanathan et al.2019) and used to provide a determination of the radius and geometry of the lunar core-mantle boundary (CMB) from the LLR observations. The obtained CMB radius is in full agreement with one seismological model Garcia et al.2011).

2. LLR AND GRAIL OBSERVATIONS

The Moon's rotation is now measured with a remarkable accuracy of few milli-arcseconds thanks to the Lunar Laser Ranging (LLR) experiment that has been active since 1969 (e.g. Dickey et al.1994). This experiment consists of the measurement of the round-trip travel time of a short laser pulse between an Earth observatory and one of the five corner cube retroreflector arrays settled on the Moon (Williams et al. 2014; Pavlov et al., 2016; Viswanathan et al. 2018; Fienga et al. 2019). Earth observatories such as the APOLLO station (Murphy, 2013) and OCA station (Courde et al. 2017) regularly range to the retroreflectors for the collection of LLR data. The OCA laser station switched to ranging in infrared (1064 nm) allowing a better coverage of the retroreflectors and improving the precision of the LLR data (Courde et al. 2017). A strong interest from the laser ranging science has led to the emergence of new LLR stations Hartebeesthoek-South Africa (Munghemezulu et al., 2016), Yunnan-China, Wettzell-Germany (Eckl et al. 2019) and next-generation of retro-reflector developments (Dell'Agnello et al., 2018; Currie et al., 2013).

In addition, the Moon has been the target of the space mission Gravity Recovery and Interior Laboratory mission (GRAIL) that determined the gravity field of the Moon at an unprecedented accuracy (Konopliv et al., 2013; Lemoine et al., 2013, Konopliv et al., 2014). It has been obtained with an improved accuracy of 4-5 order of magnitude up to degree and order 1200-1500 (see e.g. Konopliv et al. 2014). In addition, the love number k_2 has been improved by a factor 5. Such great accuracy is reached thanks to the intersatellite link based on a mission concept similar to GRACE. Also there were DSN two-way S-band doppler measurements for GRAIL (see Konopliv et al,, 2013; Lemoine et al. 2013) and reference therein).

3. DYNAMICAL MODEL AND RESULTS

The lunar rotation is integrated numerically in INPOP ephemeris and fitted to the LLR observations (Viswanathan et al,, 2019; Fienga et al. 2019). This model is obtained from a joint numerical integration of the orbits of the Moon, the Earth, the planets and asteroids, and of the lunar rotation. The dynamical partial derivatives of the orbits and lunar Euler angles with respect to solution parameters such as moment of inertia, gravity field, tides, dissipation, interaction with a fluid core and initial conditions are computed and the adjustment provides the determination of these geophysical parameters (for a complete description of the last INPOP version see Fienga et al. (2019) and references therein).

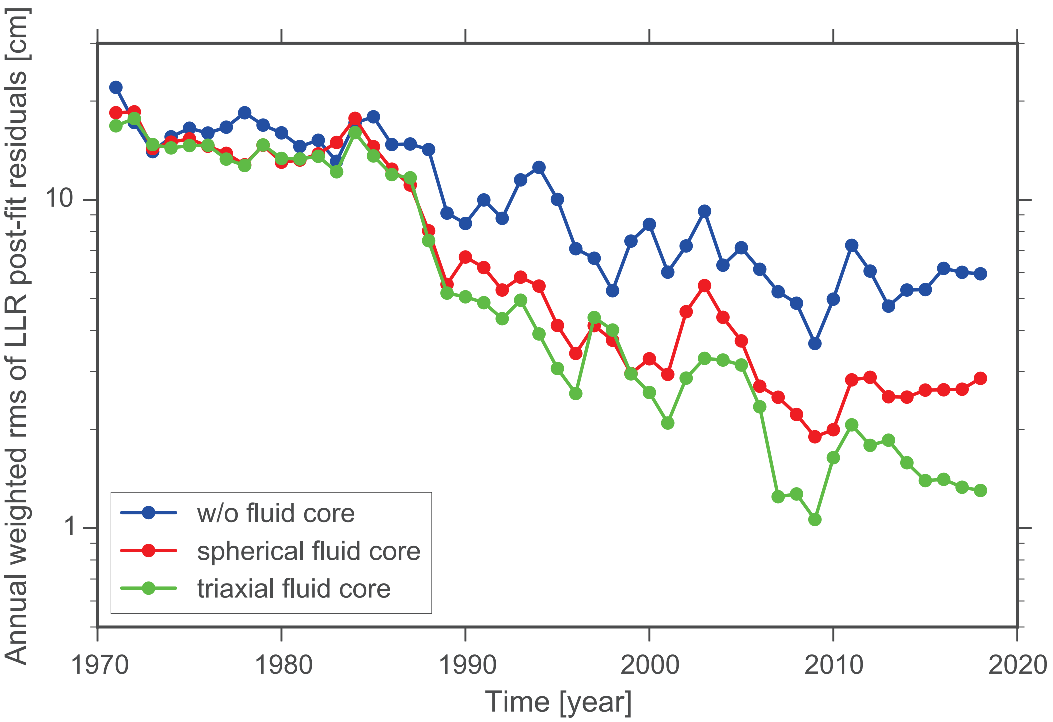

Figure 1: This plot shows the influence of the presence of the fluid core is sustained by a significant decrease in the annual wrms of the LLR over 50 years. In blue the solution without the fluid core provides a wrms of 5 cm, that reduces to 3 cm for a spherical fluid core with friction and further below 2 cm in the presence of a non-spherical fluid core.

A full set of rotational equations for the whole Moon and for the fluid-core that take into account the pressure torque due to the fluid core on the non-spherical CMB interface, including the triaxiality of this interface, has been developed. Such set of equations was used for Mercury (Rambaux et al., 2007) and icy satellites (Richard et al., 2014) studies and here extended to the rotational motion of a differentiated Moon. The basic equations are

$$\frac{d[I]\boldsymbol{\omega}}{dt} + \boldsymbol{\omega} \wedge [I]\boldsymbol{\omega} = \boldsymbol{\Gamma} \quad (1)$$

$$\frac{d\boldsymbol{H}^c}{dt} + \boldsymbol{\omega} \wedge \boldsymbol{H}^c = \boldsymbol{\Gamma}_c \quad (2)$$

where $[I]$ is the inertia tensor of the Moon, $\boldsymbol{\omega}$ is the angular velocity vector, and $\boldsymbol{\Gamma}$ are the external gravitational torques, the $\boldsymbol{H}^c$ is the angular momentum of the core and the $\boldsymbol{\Gamma}_c$ represents the interaction between the core and the mantle through two mechanisms. The first one is related to the friction at the CMB due to the differential rotation, that perturb the lunar Cassini state. The second one is due to the pressure of the fluid core on the core-mantle boundary and so it depends on the non-sphericity at the CMB.

The presence of fluid core has been identified few decades ago due its influence on the lunar Cassini state and the second clue has been the detection of the oblateness of the fluid core boundary that is an independent result of the existence of the fluid core (Williams et al., 2014). For example, in INPOP, the presence of the fluid core is sustained by significant decreases of the annual weighted root mean square (wrms) of the LLR post-fit residuals over 50 years. Figure 1 shows the influence of the non-sphericity and highlights the necessity to have accurate and long time series in order to separate the physical parameters of the lunar core.

The size of the lunar core, about 381 km, was determined in Viswanathan et al. (2019) by comparing flattening determined through LLR data and the theoretical flattening computed by assuming a hydrostatic CMB enclosed by a non-hydrostatic mantle and disturbed by tidal and centrifugal potentials. The bounded core size is consistent with an analysis of the seismic data (Garcia et al., 2011) and previous LLR model (Williams et al., 2014) but the accuracy of the core oblateness and radii of a presently-relaxed lunar core is improved by a factor of 3. This determination brings new constraints on the interior of the Moon. Notably, it allows to compute an estimation of the eigenfrequency and period of the free core nutation (FCN) of the Moon as shown in Figure 2. This figure shows the dependence of the FCN period onto interior parameters where a first order linear approach allow to estimate the FCN frequency equal to

$$\sigma_{\mathrm{FCN}} = \frac{1}{2} n(\alpha"_c + \beta"_c) \quad (3)$$

with $\alpha''_c \sim \frac{AC_c - A_c B_c}{A - A_c}$ and $\beta''_c \sim \frac{BC_c - A_c B_c}{B - B_c}$ where (A, B, C) and (A_c, B_c, C_c) are the moment of inertia of the whole Moon and core, n is the lunar mean motion. This relationship is consistent with the estimation used in Rambaux and Williams (2011). However, in Rambaux and Williams (2011) the numerical value of the FCN was estimated based on DE421 flattening estimation and with the new determination of the flattening, the FCN is estimated at about 367 $\pm$ 100 years (Viswanathan et al., 2019).

Acknowledgments V.Viswanathan acknowledges the post-doctoral fellowship by ESEP for funding this research. The authors acknowledge the PNGRAM and PNP for funding this research. The computations were carried out on computational servers of Geoazur, OCA. This work benefited from the previous contribution of H. Manche to the INPOP ephemeris development. The LLR data were processed using CNES-GRGS software (GINS).

4. REFERENCES

Courde, C., Torre, J. M., Samain, E., Martinot-Lagarde, G., Aimar, M., Albanese, D., Exertier, P., Fienga, A., Mariey, H., Metris, G., Viot, H., and Viswanathan, V. 2017, "Lunar laser ranging in infrared at the Grasse laser station", A&A 602:A90.

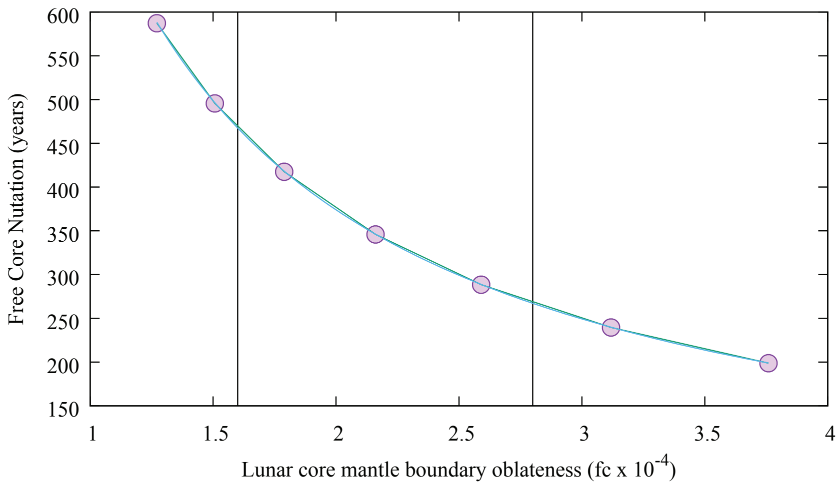

Figure 2: Period of FCN for the Moon as function of its oblatness. This gives a present-day $P_{FCN} \sim (367 \pm 100)$ years for the hydrostatic case, assuming a Poincaré flow within the lunar fluid core. The large value of P_{FCN} with respect to the mantle precession (18.6 years) confirms that the present-day lunar core should be decoupled with the mantle (Meyer and Wisdom, 2011).

Currie, D. G., Dell'Agnello, S., Delle Monache, G. O., Behr, B., and Williams, J. G., 2013, "A Lunar Laser Ranging Retroreflector Array for the 21st Century", Nucl. Phys. B - Proc. Suppl. 243-244, pp. 218–228.

Dell'Agnello, S., Boni, A., Cantone, C., Ciocci, E., Martini, M., Patrizi, G., Tibuzzi, M., Delle Monache, G., Vittori, R., Bianco, G., et al., 2018, "Next-generation laser retroreflectors for GNSS, solar system exploration, geodesy, gravitational physics and earth observation", in International Conference on Space Optics-ICSO 2014, volume 10563, p. 1056317. International Society for Optics and Photonics.

Dickey, J. O., Bender, P. L., Faller, J. E., Newhall, X. X., Ricklefs, R. L., Ries, J. G., Shelus, P. J., Veillet, C., Whipple, A. L., Wiant, J. R., Williams, J. G., and Yoder, C. F., 1994, "Lunar Laser Ranging: A Continuing Legacy of the Apollo Program", Science 265, pp. 482–490.

Eckl, J., Schreiber, U., and Schüler, T., 2019, "Lunar laser ranging utilizing a highly efficient solid-state detector in the near-IR", Quantum Optics and Photon Counting 2019, 1102708(April), p. 7.

Fienga, A., Deram, P., Viswanathan, V., Di Ruscio, A., Bernus, L., Durante, D., Gastineau, M., and Laskar, J., 2019, "INPOP19a planetary ephemerides", Notes Scientifiques et Techniques de l'Institut de Mecanique Celeste 109.

Garcia, R. F., Gagnepain-Beyneix, J., Chevrot, S., and Lognonné, P., 2011, "Very preliminary reference Moon model", Physics of the Earth and Planetary Interiors 188, pp. 96–113.

Konopliv, A. S., Park, R. S., Yuan, D.-N., Asmar, S. W., Watkins, M. M., Williams, J. G., Fahnestock, E., Kruizinga, G., Paik, M., Strekalov, D., Harvey, N., Smith, D. E., and Zuber, M. T., 2013, "The JPL lunar gravity field to spherical harmonic degree 660 from the GRAIL Primary Mission", J. Geophys. Res. (Planets) 118, pp. 1415–1434.

Konopliv, A. S., Park, R. S., Yuan, D.-N., Asmar, S. W., Watkins, M. M., Williams, J. G., Fahnestock, E., Kruizinga, G., Paik, M., Strekalov, D., Harvey, N., Smith, D. E., and Zuber, M. T., 2014, "High-resolution lunar gravity fields from the GRAIL Primary and Extended Missions", Geophys. Res. Lett. 41, pp. 1452–1458.

Lemoine, F. G., Goossens, S., Sabaka, T. J., Nicholas, J. B., Mazarico, E., Rowlands, D. D., Loomis, B. D., Chinn, D. S., Caprette, D. S., Neumann, G. A., Smith, D. E., and Zuber, M. T., 2013, "High-degree gravity models from GRAIL primary mission data", Journal of Geophysical Research: Planets 118(8), pp. 1676–1698.

Meyer, J. and Wisdom, J., 2011, Precession of the lunar core, Icarus 211(1), pp. 921–924.

Munghemezulu, C., Combrinck, L., and Botai, J. O. (2016), "A review of the lunar laser ranging technique and contribution of timing systems", South African Journal of Science, Volume 112 (Number 3/4), pp. 1–9.

Murphy, T. W., 2013, "Lunar laser ranging: the millimeter challenge", Reports on Progress in Physics 76(7), p. 076901.

Pavlov, D. A., Williams, J. G., and Suvorkin, V. V., 2016, "Determining parameters of Moon's orbital and rotational motion from LLR observations using GRAIL and IERS-recommended models", Celest. Mech. Dyn. Astr. 126(1-3), pp. 61–88.

Rambaux, N., van Hoolst, T., Dehant, V., and Bois, E., 2007, "Inertial core-mantle coupling and libration of Mercury", A&A 468(2), pp. 711–719.

Rambaux, N. and Williams, J. G., 2011, "The Moon's physical librations and determination of their free modes", Celest. Mech. Dyn. Astr. 109, pp. 85–100.

Richard, A., Rambaux, N., and Charnay, B., 2014, "Librational response of a deformed 3-layer Titan perturbed by non-Keplerian orbit and atmospheric couplings", Planetary and Space Science 93, pp. 22–34.

Viswanathan, V., Fienga, A., Minazzoli, O., Bernus, L., Laskar, J., and Gastineau, M., 2018, "The new lunar ephemeris INPOP17a and its application to fundamental physics", MNRAS 476, pp. 1877–1888.

Viswanathan, V., Rambaux, N., Fienga, A., Laskar, J., and Gastineau, M., 2019, "Observational constraint on the radius and oblateness of the lunar core-mantle boundary", Geophys. Res. Lett. 46(13), pp. 7295–7303.

Williams, J. G., Boggs, D. H., and Ratcliff, J. T. (2014), "Free Libration Modes of a Structured Moon", In Lunar and Planetary Science Conference, Lunar and Planetary Inst. Technical Report 45, p. 1579.