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On the lunar dissipation law

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Abstract

Our Moon is one of the most studied objects in the Solar system; we benefit from chemical, geophysical, and geodetical observations achieved by multiple Earth ground based telescopes and in situ missions. However, the dissipation law remains a puzzle because the power law determined through the Lunar Laser Ranging measurements [8], [9] has a slope of opposite sign to the one obtained in rheological models (e.g. [5]). Here, we explore causes of dissipation in the Moon to obtain a full agreement between LLR observations and rheological models.

1. Introduction

The Gravity Recovery and Interior Laboratory mission (GRAIL) yielded highly accurate gravity measurements that have allowed the refinement of the lunar crust and geological evolution as well as the determination of key geophysical parameters, such as the tidal Love numbers of degree 2 and 3 [3], [4]. Combined with the rotational data of the continuing Lunar Laser Ranging measurements the lunar dissipation law can be inferred [8], [9]. We attack this problem by using a forward modeling approach of the dissipative Moon to infer the physical interior lunar properties capable to match the observational constraints.

2. LLR Observations

Periodic deformation of the Moon can be derived from ground-based laser ranging and that technique (LLR) has significantly contributed to lunar science and to the knowledge of the Earth-Moon system for the past 40 years (e.g [2]). A major result is the early detection of the signature of a fluid core due to its impact on the direction of the spin axis [8]. Notably, a fluid core does not exactly follow the motion of the mantle, which induces a torque and dissipates energy. The determination of phase shifts in the spin axis orientation and in several periodic libration terms allow separating the tidal and fluid core contributions to the observed tidal response [8]. The energy dissipation is quantified through a factor Q that depends on the excitation frequency (e.g., [8]; [9]). In the case of the Moon that dissipation is expressed as [8]:

$$Q = Q_F \left(\frac{\omega}{\dot{F}}\right)^{w} \qquad (1)$$

where F is the draconic month frequency (node to node) such that $\dot{F} = 2\pi/27.212$ days, and ω is the tidal frequency and the power dependence is w. The interpretation of dissipation factors inferred from LLR observations have led to the inference of a negative power law with $w = -0.19 \pm 0.13$ and $Q_F = 37 \pm 6$ ([8]). Updated analysis from [9] leads to similar results. The peculiar negative power law has remained unexplained to date (e.g. [5]).

3. GRAIL data

The space mission Gravity Recovery and Interior Laboratory mission (GRAIL) has determined the gravity field of the Moon at an unprecedented accuracy ([10], [3], [4]). The lunar gravity field has been obtained with an improved accuracy of 4-5 order of magnitude up to degree and order 660 in spherical harmonics ([3]). In addition, the love number k_2 has been improved by a factor 5 and has been determined to be equal to 0.02405 ± 0.00018. Such great accuracy is reached thanks to a mission concept similar to GRACE and the use of a Ka-band transponder instead of S-band transponder (see [10]).

4. Interior model

We follow a forward approach where the tidal response of a multilayered interior model is solved to assess the compliance and the complex Love number k_2 ([6]; [1]). The interior density profile comes from the seismic analysis of [7]. The density and seismic velocities profiles have been obtained by re-processing the seismic data from the Apollo missions through modern techniques. Their analysis supports the presence of a molten boundary region with a thickness of about 150 km, overlaying a fluid core layer at R = 330 km radius as well as the presence of a solid inner core.

5. Results

We explore a large set of rheological parameters represented by the Andrade model that can fit the rotation and k_2 measurements. As preliminary results, we found that typical successful model is characterized by a significant decrease in viscosity at a radius of about 490-510 km. The depth at which that contrast is found is consistent with the [7] seismic observations and our dissipative model seems to reproduce the dissipation behavior inferred from LLR and k_2 determined by GRAIL.

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