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Viscosity of the Earth's inner core: Constraints from nutation observations

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ABSTRACT

The gravitational torque applied on the Earth by the other celestial bodies generates periodic variations in the orientation of the Earth's rotation axis in space which are called nutations. Observations of Earth's nutations allow for insights into the physical properties of the inner core because of the presence of a normal mode, the Free Inner Core Nutation (FICN), which is characterized by a tilt of the inner core figure and rotation axes with respect to the mantle and outer core. The frequency of the FICN is controlled by the strength of the mechanical coupling acting at the inner core boundary (ICB) and by the ability of the inner core to deform under the action of centrifugal and gravitational forces. Attenuation of the FICN reflects energy dissipated by electromagnetic (EM) and viscous friction at the ICB and through viscous relaxation of the inner core. Here, we show that it is possible to explain the observed frequency and damping of the FICN by a combination of EM coupling at the ICB and viscoelastic deformation of the inner core. This imposes a strong constraint on the viscosity of the inner core which has to be in the range ~$2–7\times10^{14}$ Pa s. We also obtain an estimate of the RMS strength of the radial magnetic field at the ICB, which has to be between 4.5 and 6.7 mT. Interestingly, if a viscoelastic Maxwell rheology is assumed for the inner core, our estimated inner core viscosity is in very good agreement with the shear quality factor inferred from seismic normal modes observations. This suggests that the viscous deformation of the inner core at the nutation (diurnal) time scale and at the seismic normal modes time scale may be due to the same physical mechanisms.

1. Introduction

The viscosity of the Earth's inner core strongly affects many of its dynamical processes. Whether thermal convection occurs in the inner core depends crucially on its viscosity (e.g. Buffett, 2009; Jeanloz and Wenk, 1988). Viscous relaxation within the inner core also affects the rotational dynamics of the Earth, including polar motion (Dumberry and Bloxham, 2002), nutations (Greff-Lefftz et al., 2000), and inner core super rotation (Buffett, 1997; Dumberry, 2010; Dumberry and Mound, 2010). Furthermore, viscous deformation may lead to a preferential alignment of crystals and this may explain a part of the observed seismic anisotropy in the inner core (e.g. Buffett and Wenk, 2001; Karato, 1999; Yoshida et al., 1996).

Despite its importance, inner core viscosity remains a poorly known parameter, with estimates covering several orders of magnitude. Theoretical estimates based on mineral physics require the knowledge of microphysical properties of the inner core, such as its grain size, which are mostly unknown. For this reason, such computations yield a wide range of results, from 10^{11} Pa s (Van Orman, 2004) to 10^{21} Pa s (Yoshida et al., 1996). Laboratory experiments on iron samples cannot reach the extreme conditions of pressure and temperature typical of the Earth's inner core ($P\sim350$ GPa, $T\sim5000$ K). Experiments are instead typically carried out at ambient pressure and temperatures close to the melting point, the latter condition being likely representative of the state of iron inside the inner core. Such experiments give a viscosity of solid iron of the order of 10^{12} Pa s (Jackson et al., 2000). However, the extrapolation of this result to pressures typical of the Earth's inner core is uncertain and this value is more likely to be a lower bound.

Viscous relaxation of the inner core affects seismic observations which can thus be used to constrain inner core viscosity. Studies relying on the observation of normal modes having energy in the inner core show that it is strongly attenuating (Andrews et al., 2006), with estimates of the inner core shear quality factor Q_μ in the range 85–110 (Dziewonski and Anderson, 1981; Resovsky et al., 2005; Widmer et al., 1991). Once a particular rheological model for the inner core is assumed, Q_μ can be interpreted in terms of an inner core viscosity. For instance, a Maxwell rheology yields a viscosity of the order of 10^{14} Pa s (see Section 6). Body waves traveling through the inner core are also intrinsically attenuated by viscoelasticity. However, they cannot be used to constrain inner core viscosity because their attenuation is thought to be mainly due to scattering by lattice heterogeneities (e.g. Cormier and Li, 2002; Monnereau et al., 2010).

Observations of the Earth's nutations provide an alternative and independent way of quantifying the dissipation in the Earth's inner core. Nutations are the motion of the Earth's rotation axis in a space-fixed reference frame caused by the external gravitational torque from the Moon, the Sun and other planets. The nutation amplitudes are

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slightly enhanced by the existence of two normal modes, the Free Core Nutation (FCN) and the Free Inner Core Nutation (FICN), which have natural frequencies close to diurnal. These modes are characterized by misalignments between the mantle, the outer core, and the inner core, leading to internal torques between them. The strength of these internal torques depends directly on physical properties of the deep Earth and, therefore, so do the frequency and damping of the normal modes (e.g. Mathews et al., 1991a; Mathews and Shapiro, 1992). Numerical values of the frequency and damping of these modes can be estimated from the resonance effect they induce on the observed forced nutations (e.g. Koot et al., 2008; Koot et al., 2010; Mathews et al., 2002). Interpretation of these natural frequencies and dampings allows then for insights into the physical properties of the deep Earth (Buffett et al., 2002; Koot et al., 2010; Mathews et al., 2002; Mathews and Guo, 2005).

The FICN mode is of particular interest to study the physical properties of the inner core. As shown in Fig. 1, in this mode, the rotation axes of the mantle and outer core are aligned with the Earth's figure axis whereas both the rotation and figure axes of the inner core are tilted with respect to them (e.g. Mathews et al., 1991b). As a result of this tilt, the outer core and mantle apply a torque on the inner core. In response to this torque, by gyroscopic effect, the figure and rotation axes of the inner core both precess about the Earth's figure axis with an angular frequency that depends on the strength of the torque and on the way the inner core deforms under the action of centrifugal and gravitational forces.

The dominant contribution to the torque acting on the inner core is from the pressure force on its tilted ellipsoidal boundary. Another important contribution comes from the differential rotation at the ICB, which leads to surface stresses from viscous and electromagnetic (EM) forces. The EM torque results from the shearing of the radial magnetic field lines by the differential rotation. A smaller contribution

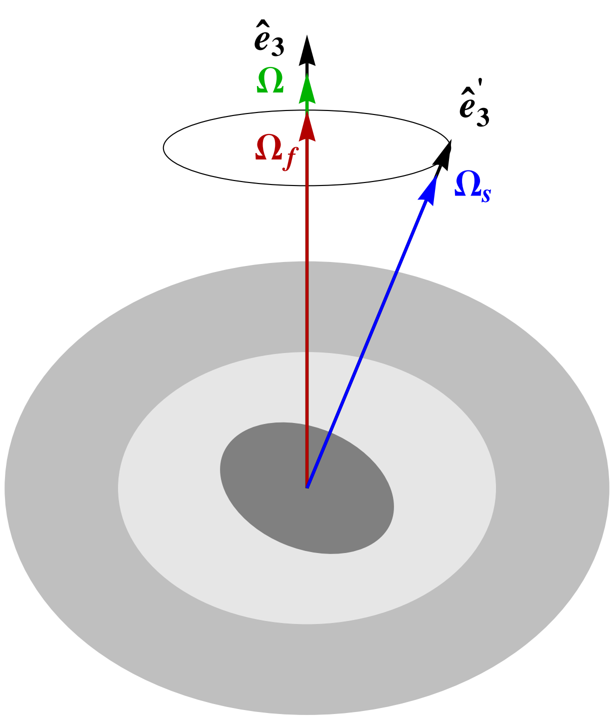

Fig. 1. Schematic description of the Free Inner Core Nutation (FICN). In this mode the inner core figure axis ($\hat{\mathbf{e}}_3'$) and rotation axis ($\mathbf{\Omega}_s$) are aligned together and are both misaligned with the outer core and mantle rotation axes ($\mathbf{\Omega}_f$ and $\mathbf{\Omega}$). The latter two are aligned with the Earth's figure axis ($\hat{\mathbf{e}}_3$).

comes from the gravitational force acting to realign the figure of the inner core with that of the mantle and fluid core. The dominant contribution to internal inner core deformation is from the centrifugal force which tends to increase the ellipticity of the inner core and thus reinforce the pressure torque acting on its ellipsoidal shape.

The cause of the attenuation, or damping, of the FICN mode is *a priori* unknown. Coupling at the ICB through EM and viscous stresses generates ohmic and viscous dissipation, respectively, and contribute to an energy loss. Alternatively, anelastic deformation within the inner core, or dissipation of energy within the fluid core could also explain a part of the damping.

In a previous paper (Koot et al., 2010), we interpreted the observed damping of the FICN by assuming a purely elastic inner core and no energy loss in the fluid core. In this case, coupling at the ICB must be solely responsible for the dissipation, and we showed that the observations could not be explained by an EM coupling alone. Observations can be explained when a coupling from viscous stresses at the ICB is added, though this requires a large kinematic viscosity of the fluid outer core, of the order of $10\ \mathrm{m^2\,s^{-1}}$. This is much larger than the values of molecular viscosities of the order of $10^{-6}\ \mathrm{m^2\,s^{-1}}$ expected on the basis of both laboratory experiments on liquid iron (Rutter et al., 2002) and '*ab initio*' computations (Alfè et al., 2000). Hence, if viscous coupling at the ICB is responsible for the additional dissipation, the required kinematic viscosity must be interpreted to represent an effective eddy viscosity from turbulent motion in the fluid (e.g. Deleplace and Cardin, 2006). However, this interpretation presents its own problems as in the context of nutations, eddy viscosity should not be larger than $10^{-4}\ \mathrm{m^2\,s^{-1}}$ (Buffett and Christensen, 2007). If this latter upper bound is adopted, viscous coupling at the ICB must be negligible. Consequently, if EM coupling at the ICB alone cannot explain the observed dissipation, another mechanism must also participate.

A recent work suggests that the missing dissipation is from ohmic damping associated with inertial waves within the fluid core that are generated by the precession of the inner core tilt (Buffett, 2010). The purpose of the present paper is to suggest an alternative, and to show that the observed damping of the FICN mode can also be explained by a combination of EM coupling at the ICB and viscous deformation within the inner core. This too alleviates the need for a strong viscous coupling at the ICB. We show that, if this latter interpretation is correct, this imposes a strong constraint on the possible values of inner core viscosity.

2. Nutation observations constraints

The complex angular frequency of the FICN normal mode, of which the real (resp. imaginary) part characterizes the frequency (resp. damping), is given by (Mathews et al., 1991a; Mathews et al., 2002):

$$\omega_{\mathrm{FICN}} = -\Omega_0 + \Omega_0\left(1 + \frac{A_s}{A_m}\right)\left(\alpha_1 e_s + \nu - \alpha_3 \alpha_g e_s - K_{\mathrm{ICB}}\right) \tag{1}$$

where Ω_0 is the Earth's mean angular frequency of rotation, A_m, A_s are the principal mean equatorial moments of inertia of the mantle and inner core, respectively, e_s is the dynamical ellipticity of the inner core, α_1 is a parameter that involves the density contrast at the ICB, $\alpha_3 = 1 - \alpha_1$, and α_g is a parameter that captures the strength of gravitational torque on a tilted inner core and depends on the Earth's radial profiles of density and ellipticity. Exact definitions of these parameters can be found in Mathews et al. (1991a).

In Eq. (1), the term involving the product $\alpha_1 e_s$ characterizes the strength of the pressure torque acting on the tilted ellipsoidal ICB, whereas $\alpha_3\ \alpha_g e_s$ characterizes the strength of the gravitational torque. Since the pressure and gravitational forces are non-dissipative, both of these terms only contribute to the real part of ω_{FICN}. The non-dimensional complex parameter K_{ICB} captures the influence of EM and