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Mechanism of the interannual oscillation in length of day and its constraint on the electromagnetic coupling at the core–mantle boundary

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A B S T R A C T

A significant 6 yr oscillation exists in the length of day (LOD) on the interannual scales. There are mainly two models currently to explain this oscillation, i.e., mantle–inner core gravitational (MICG) coupling mode and the fast torsional waves within the fluid outer core. The former has been doubted, while the source of the excitation of the latter is not yet understood. Therefore, the mechanism of the 6 yr oscillation is still not clear. Here, by considering the mantle and inner core angular momentum, we investigate the MICG coupling mode and its natural period (T_0). Given that the strength of gravitational core–mantle coupling ($\bar{\Gamma}$) within a recently constrained range is quite weaker than that estimated previously, the mechanism of the 6 yr oscillation still can be attributed to MICG coupling mode (i.e., T_0 equals to 6 yrs), but, we require the inertia moment of fluid within the tangent cylinder involved in the 6 yr oscillation to be smaller than 1.23×10^{35} kg m^2. This interpretation can be used to constrain the electromagnetic (EM) coupling at the inner core boundary (ICB). In order to study quantitatively the constraints on the EM coupling at the core–mantle boundary (CMB) from the observed 6 yr oscillation with a quality factor Q (∼51.6), we further develop the mathematical expression between the Q value based on the observations and EM coupling at the CMB. According to the $\bar{\Gamma}$ value from recent estimates and assuming that the 6 yr oscillation is in a free decay, we can obtain the radial magnetic field at the CMB is 0.52 mT∼0.62 mT when conductance at the CMB is 10^8 S.

1. Introduction

The 6 yr oscillation is a significant periodic signal in the Earth's variable rotation on the interannual scales. There have been many studies (e.g., Mound and Buffett, 2003, 2006; Gillet et al., 2010; Silva et al., 2012; Holme and de Viron, 2013; Duan et al., 2015) to investigate this oscillation since it was discovered by Abarco del Rio et al. (2000) in the observed LOD series using a wavelet method. However, the mechanism of this oscillation has been still controversial up to now. For example, Mound and Buffett (2003, 2006) interpreted the 6 yr oscillation signal as a MICG coupling mode and they suggested that the inner core–mantle gravitational coupling strength $\bar{\Gamma}$ equals to 3.0×10^{20} N m. On the other hand, Gillet et al. (2010) indicated that this oscillation is attributed to the fast torsional waves with a 6 yr period.

As the previous studies (e.g., Mound and Buffett, 2003; Dumberry, 2010; Davies et al., 2014) indicated, $\bar{\Gamma}$ is a very important parameter to further understand the dynamics of the inner core. Buffett (1996) first estimated $\bar{\Gamma}$ based on two models of the mantle density (which are based on viscous flow computations using seismically inversion of the mantle density anomalies) and obtained $\bar{\Gamma} \approx 3.0 \times 10^{20}$ N m. However, Davies et al. (2014) indicated that the viscous flow calculation is highly uncertain, causing large uncertainties in $\bar{\Gamma}$; they further estimated $\bar{\Gamma}$ from a broad range of viscous mantle flow models with density anomalies inferred from seismic tomography and they have constrained the outputs of their chosen mantle flow model to the following two conditions: (1) provide a larger than 70% correlation to the surface geoid and (2) match the dynamic CMB topography inferred from Earth's nutations. As the result, they constrained $\bar{\Gamma}$ and gave it a range of $3.0 \times 10^{19} \sim 2.0 \times 10^{20}$ N m, which is $2 \sim 10$ times smaller

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than that of the previous value. Therefore, they argue that $\bar{\Gamma}$ is too weak for MICG coupling mode to explain the 6 yr oscillation.

The model of fast torsional waves with a 6 yr period has also been proposed and it could explain this oscillation (Gillet et al., 2010). Unresolved is the source of the excitation of fast torsional waves and why the torsional waves have a 6 yr period of recurrence (Jackson, 2010; Gillet et al., 2015). Several other studies suggested that the 6 yr oscillation is related to geomagnetic jerks and geomagnetic oscillation as well (Holme and de Viron, 2013; Silve et al., 2012). Consequently, the mechanism of the 6 yr oscillation and whether MICG coupling mode can explain the 6 yr oscillation is an unresolved problem.

Assuming that the 6 yr oscillation is a decaying signal with the quality factor $Q \sim 51.6$, corresponding to a relaxation time $\tau \sim 100$ yr (Duan et al., 2017), a successful theory to account for the 6 yr oscillation should be capable of resolving the following two questions: 1) what is the mechanism of the 6 yr period; 2) what causes the signal to decay (i.e., Q value). As mentioned above, there have been mainly two models (i.e., MICG coupling mode and fast torsional waves) to explain the 6 yr oscillation (Mound and Buffett, 2006; Gillet et al., 2010). By comparison of the above two models, we find that MICG coupling mode not only can provide a reasonable explanation of the mechanism of the 6 yr period (which is actual the natural frequency of the inner core swing excited by a random torque predicted by geodynamo, so the 6 yr oscillation may be a resonance effect), but also can explain the decay of this oscillation. Although the fast torsional waves have a 6 yr period and also allow the signal to decay (Gillet et al., 2010), the mechanism exciting the 6 yr period is not yet resolved (Jackson, 2010).

Assuming that both of the above two models are correct, we can speculate that MICG coupling mode might be linked with fast torsional waves in nature. As Jackson (2010) showed, the latter may be excited by the former; that is to say, a random torque excites the motion of the inner core with a 6 yr natural period, which, in turn, excites the torsional waves with the same period. If this is the case, the 6 yr oscillation should be ultimately attributed to MICG coupling mode. Importantly, we find that the parameter ($\bar{\Gamma}$) in MICG coupling mode does not need to be 3.0×10^{20} N m. When $\bar{\Gamma}$ is constrained by the recent study of Davies et al. (2014), the observed 6 yr oscillation can be explained by MICG coupling mode, if moment of inertia of the fluid core (i.e., C_c) involved in this oscillation also departs from the conventional value. In the previous works (e.g., Mound and Buffett, 2003; Dumberry and Mound, 2010), C_c was considered to be the inertia moment of the whole fluid within the tangent cylinder (TC), which can be seen in Fig. 1. However, this work defines C_c as the inertia moment of the fluid core involved in the oscillation, which may be all or part liquid inside the TC. We relax the assumption that the fluid is locked to the inner core and effectively rotates as a rigid body under the effect of strong EM coupling at the ICB (see section 2).

If the previous value of $\bar{\Gamma}$ was overestimated relative to more recent value, then the value of C_c in the previous works may also be overestimated. In addition, because of the close relations between C_c and the EM coupling at the ICB, the previously EM coupling effect at the ICB may also be overestimated. In summary, studying C_c is also very helpful to understand the strength of EM coupling at the ICB accurately. In this work, we will show that the 6 yr oscillation due to MICG coupling mode causes damping under the influence of EM coupling at the CMB.

2. Inner-core free swing model

In general, the Earth can be divided into the following three parts, i.e., mantle, fluid outer core and the solid inner core. The total angular momentum within the whole Earth's system is conserved without any external force torques. Thus, from the angular momentum perspective, we here only give the results of the mantle and the inner core (Dumberry and Mound, 2010) as follow

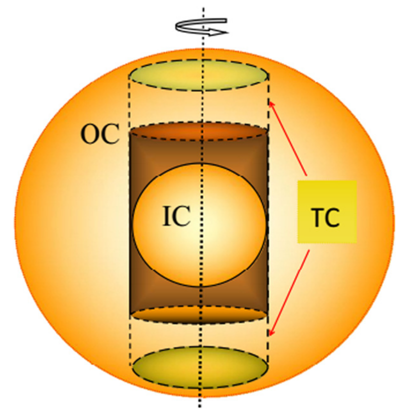

Fig. 1. Geometry of the core geostrophic system. The tangent cylinder (TC) is coaxial with the rotation axis (Cox et al., 2014; Aurnou et al., 2003) and it is displayed by the dashed lines; where, the region of black-colored background inside the TC reflects the locked part fluid (schematic diagram) under the effect of the EM coupling at the ICB; OC means outer core that is outside the TC; IC is the inner core.

$$\text{Mantle:} \quad C_m \frac{du_m}{dt} = \Gamma_{em}^m - \tilde{\Gamma}_g + \Gamma_{drag}^m \tag{1}$$

$$\text{Inner core:} \quad C_i \frac{du_i}{dt} = \Gamma_{em}^i + \tilde{\Gamma}_g + \Gamma_{drag}^i \tag{2}$$

where, u_m and u_i express the angular velocities of mantle and inner core, respectively; C_m and C_i are respective the axial mantle and inner core moment of inertia; Γ_{em}^m and Γ_{em}^i are respective the EM coupling torques at the CMB and ICB; $\tilde{\Gamma}_g$ is the mantle–inner core gravitational torque; Γ_{drag}^m and Γ_{drag}^i express the viscous and topographic torques at the CMB and ICB, respectively.

The relation between $\tilde{\Gamma}_g$ and $\bar{\Gamma}$ is $\tilde{\Gamma}_g = -\bar{\Gamma}\phi$, where, ϕ represents the differential rotation between inner core and mantle (Buffett and Glatzmaier, 2000). Additionally, the time differential expression of ϕ is $\frac{d\phi}{dt} = u_i - u_m - \frac{\phi}{\gamma_0}$, where γ_0 is the viscous relaxation time of the inner core shape. For simplicity, we assume that the inner core is rigid (i.e., $\gamma_0 \to \infty$). We also set the other torques besides $\tilde{\Gamma}_g$ to 0 (Dumberry and Mound, 2010), to obtain an idealized system of equations for a harmonic oscillation

$$\frac{d^2 W}{dt^2} + \Lambda W = 0 \tag{3}$$

where, $W = [u_m, u_i]^T$; $\Lambda = \begin{bmatrix} \frac{\bar{\Gamma}}{C_m} & -\frac{\bar{\Gamma}}{C_m} \\ -\frac{\bar{\Gamma}}{C_i} & \frac{\bar{\Gamma}}{C_i} \end{bmatrix}$. Formula (3) means that u_m represents a harmonic oscillation, which is consistent with the work of Aurnou and Olson (2000). The relationship between u_m and ΔLOD is $\Delta LOD = -\frac{u_m}{2\pi}(LOD_0)^2$ (Mound and Buffett, 2003). Hence, ΔLOD is also a harmonic signal with a quality factor $Q = \infty$. The eigenvalue of the matrix Λ is $\omega_0^2 = \frac{\bar{\Gamma}(C_m + C_i)}{C_m C_i}$, where, ω_0 is called natural frequency of this system. The natural period $T_0 = 2\pi\sqrt{\frac{C_m C_i}{(C_m + C_i)\bar{\Gamma}}}$. Because of $C_i \ll C_m$ (where C_i and the other related parameters are listed in Table 1), so $T_0 = 2\pi\sqrt{\frac{C_i}{\bar{\Gamma}}}$.

Interestingly, the form $T_0 = 2\pi\sqrt{\frac{C_i}{\bar{\Gamma}}}$ is the same as $T = 2\pi\sqrt{\frac{L}{g}}$, which represents the typical simple pendulum model in physics. Without considering any external torques and damping effects, the inner core motion under the action of the gravitational torque ($\tilde{\Gamma}_g$) alone is a simple pendulum in a free swing with the natural period T_0, where, the restoring force of the swing is pro-