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Mechanics of inner core super-rotation

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Abstract. A mechanism is proposed to explain the seismologically-inferred prograde rotation of the Earth's solid inner core in terms of the structure of convection in the fluid outer core. Numerical calculations of convection and dynamo action in the outer core exhibit excess temperatures inside the tangent cylinder surrounding the inner core. We show that this temperature difference generates a prograde thermal wind and a strong azimuthal magnetic field inside the tangent cylinder. Electromagnetic torques on the inner core derived from induced azimuthal magnetic fields and the ambient poloidal field equilibrate when the inner core angular velocity lags the nearby tangent cylinder fluid angular velocity by approximately 14%. The inferred prograde rotation of the inner core (1.1-3°/year relative to the mantle) can be produced by a very small (≈ 0.001 K) temperature anomaly within the tangent cylinder and indicates strong toroidal magnetic fields with peak intensities of 24-66 mT in that region of the core.

Introduction

Song and Richards [1996] have recently identified a secular change in travel times of seismic waves traversing the Earth's solid, anisotropic inner core. They have interpreted these observations as indicating a prograde (eastward) differential rotation of the inner core at a rate of about $\Delta\Omega_{IC} \approx 1.1^\circ/\text{yr}$ relative to the mantle. Using a different seismic data set and a different data reduction technique, Su, Dziewonski and Jeanloz [1996] have also identified a secular change in seismic travel times for the same region, and have inferred an even faster prograde rotation for the inner core, nearly $3^\circ/\text{yr}$.

Existence of inner core super-rotation, especially at the rapid rates implied by the seismic observations, has profound implications for the dynamics of the core and for the process of magnetic field generation (Whaler and Holme, 1996; Gubbins, 1981; Steenbeck and Helmis, 1975). The traditional methods for inferring angular velocity of fluid motion just below the core-mantle boundary (CMB) are based on secular variation of the geomagnetic field and typically yield estimates of $0.2^\circ/\text{yr}$ or less, generally in the retrograde (westward) sense relative to the mantle (Jault et al., 1988). Taken to-

gether, the seismic and geomagnetic observations indicate a large-scale variation in angular velocity, with the deepest portion of the core having an angular velocity excess and the outer portion an angular velocity deficit, relative to the mantle.

Prograde rotation of the inner core relative to the rest of the core and relative to the mantle are featured in recent numerical calculations of dynamo action in rotating, electrically conducting fluid shells. The Glatzmaier and Roberts [1995a,b] dynamo calculations which explicitly permit variable rotation of the inner core, show prograde rotation of the inner core at a rate of about $1^\circ/\text{yr}$ when scaled to Earth conditions. The physical explanation for this effect can be found in the structure of the convective motions maintaining the dynamo, which are strongly influenced by the planetary rotation and the particular geometry of the core. The tendency for rotationally-constrained two-dimensional motion implied by the Taylor-Proudman theorem effectively divides the core into two dynamically distinct regions, separated by the *tangent cylinder*, an imaginary cylinder circumscribing the inner core and aligned parallel to the Earth's spin axis. Because of planetary rotation, the convection tends to be columnar in the region outside the tangent cylinder where the direction of gravity is nearly perpendicular to the rotation axis, but within the tangent cylinder, where gravity is nearly aligned with the rotation axis, the convection tends to be more three-dimensional (Busse, 1983). In the Glatzmaier-Roberts dynamo calculations, the convection results in a higher average temperature within the tangent cylinder compared to fluid at the same radius outside. As shown schematically in Figure 1, the large-scale temperature difference across the tangent cylinder drives an azimuthal *thermal wind* flow within the tangent cylinder that is directed eastward near the inner core boundary (ICB). A combination of frictional and electromagnetic coupling drags the inner core into super-rotation in the same direction as the thermal wind, but at a slightly reduced rate.

There are other proposed explanations for the seismically-inferred super-rotation of the inner core, such as spin-down of the whole core in response to tidal friction (Su et al., 1996). We prefer the preceding explanation, as it is consistent with our present understanding of the geodynamo. Specifically, a recent reanalysis of the Glatzmaier-Roberts dynamo verifies that thermal winds with electromagnetic coupling constitute the principal mechanism driving the inner core super-rotation in their calculations [Glatzmaier and Roberts,

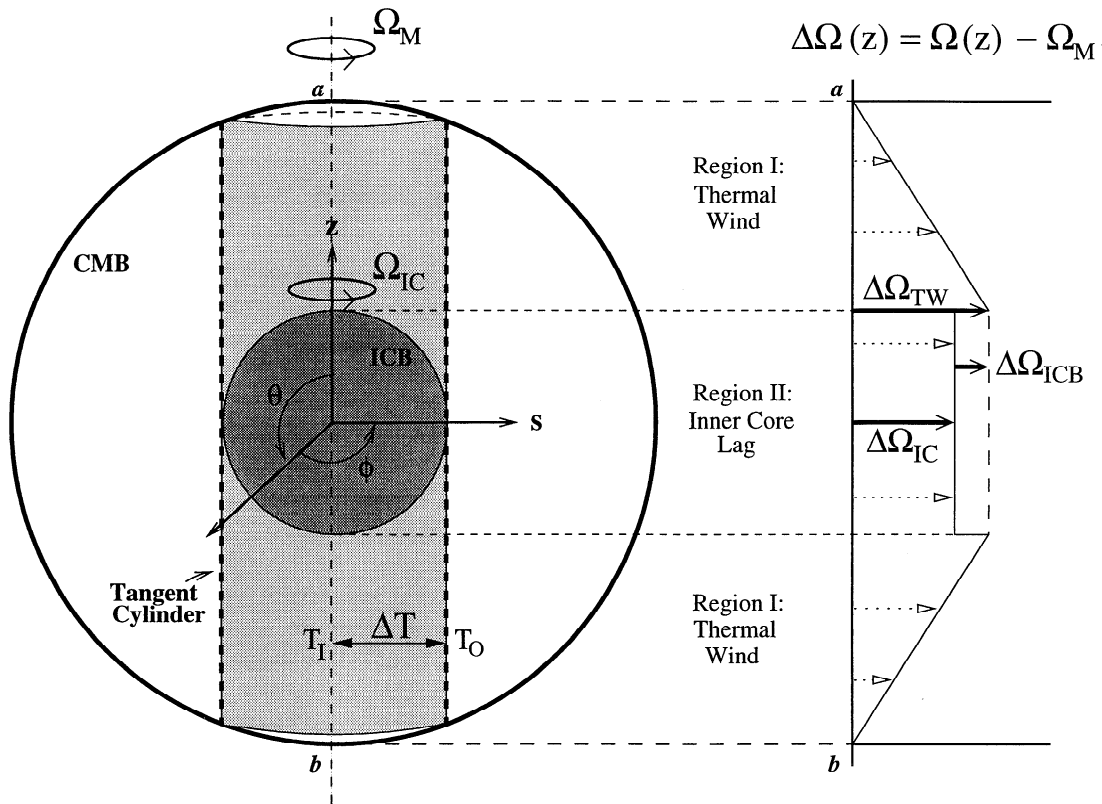


Figure 1. Illustration of model geometry. Left: Sketch showing the tangent cylinder surrounding the solid inner core. Right: Profile of the prograde angular velocity along the rotation axis $\Delta\Omega(z)$ relative to the mantle angular rotation rate, Ω_M . Because of the rotational constraint on convection, the temperature of the outer core fluid near the axis of the tangent cylinder T_I is slightly higher than the temperature outside of the tangent cylinder T_O . This temperature difference drives a prograde “thermal wind” inside the tangent cylinder (*Region I*). This thermal wind produces a difference in angular velocity $\Delta\Omega_{TW}$ between the mantle and the fluid at the base of the tangent cylinder near the ICB. Electromagnetic torques are derived from the interaction of the ambient poloidal magnetic field and induced toroidal fields. These toroidal fields are generated by the thermal wind and by the lag of the inner core relative to the surrounding fluid in *Region II* of the tangent cylinder $\Delta\Omega_{ICB}$. The torques equilibrate when the inner core rotates in a prograde direction relative to the mantle at a rate $\Delta\Omega_{IC}$.

1996]. Furthermore, it is substantiated by magnetoconvection calculations, which exhibit similar flow structures in the so-called “strong-field” regime where the imposed magnetic field is comparable to the generated field (Olson and Glatzmaier, 1995; 1996).

Tangent Cylinder Thermal Wind

We formulate a simple, analytical model of inner core super-rotation, based on the mechanism just described. The essential features of the model are illustrated in Figure 1. We suppose the temperature of the fluid along the axis of the tangent cylinder T_I is slightly different than the fluid temperature outside T_O , so that the temperature difference across the tangent cylinder is $\Delta T = T_I - T_O \neq 0$. The model works equally well if core convection is predominantly compositionally-driven (Loper, 1989). In that case, thermal buoyancy is replaced by compositional buoyancy due to light element enrichment in the tangent cylinder. We also suppose that the tangent cylinder, including the solid inner

core, is permeated by a uniform poloidal magnetic field B_z oriented anti-parallel to the spin axis.

Within the tangent cylinder fluid we presume a balance between Coriolis, buoyancy and Lorentz forces, as is appropriate for the Earth’s core (Moffatt, 1978). Then the azimuthal component of the steady-state vorticity balance reduces to the thermal wind equation

$$\frac{\partial u_\phi}{\partial z} = \frac{\alpha g}{2\Omega_M} \frac{dT}{ds} \quad (1)$$

where u_ϕ is the azimuthal fluid velocity, α is the thermal expansion coefficient, g is gravity, Ω_M is the angular velocity of planetary rotation, and (s, ϕ, z) are cylindrical coordinates. We assume that the temperature gradient in the tangent cylinder is only a function of cylindrical radius s , while the temperature outside the tangent cylinder is held constant at T_O . This temperature profile generates thermal winds that are located entirely within the interior of the tangent cylinder and that only vary in the \hat{z} -direction.

In this model the thermal wind equation holds in the parts of the core labeled *Region I* in Figure 1. We treat these upper and lower sections of the tangent cylinder as right circular cylinders which have the radius of the inner core R_{ICB} , and a height $H = R_{CMB} - R_{ICB}$ where R_{CMB} is the radius of the CMB. Consistent with the observation that the geomagnetic secular variation is five to fifteen times smaller than the inferred inner core rotation rate, we impose zero flow boundary conditions at the CMB.

With these simplifying assumptions (1) can be integrated to determine $\Delta\Omega_{TW}$, the difference in angular velocity between the fluid at the base of the tangent cylinder near the ICB and the mantle:

$$\Delta\Omega_{TW} = \frac{\alpha g H}{\Omega_M R_{ICB}^2} \Delta T \quad (2)$$

Using the thermal wind velocity from (1), the steady-state magnetic induction equation

$$\nabla \times (\mathbf{u} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B} = 0 \quad (3)$$

reduces to

$$(\nabla^2 - \frac{1}{s^2}) B_1 = \frac{\Delta\Omega_{TW} B_z s}{\eta H} \quad (4)$$

where $\hat{\phi} B_1$ is the azimuthal magnetic field induced by the thermal wind and η is the magnetic diffusivity of the core fluid. Subject to the condition $B_1 = 0$ at $s = 0$ and a zero-gradient boundary condition $dB_1/ds = 0$ at $s = R_{ICB}$, the solution is

$$B_1 = \frac{\Delta\Omega_{TW} B_z}{8\eta H} s(s^2 - 3R_{ICB}^2) \quad (5)$$

We approximate this cylindrical solution along the spherical ICB using the projection $s(s^2 - 3R_{ICB}^2) \Rightarrow -R_{ICB}^3 \sin 2\theta$, yielding

$$B_1(r = R_{ICB}) \simeq -\frac{\Delta\Omega_{TW} B_z R_{ICB}^3}{8\eta H} \sin 2\theta \quad (6)$$

where θ denotes colatitude.

Induction at the ICB

Coupling between the tangent cylinder fluid and the solid inner core is provided by a combination of viscous and electromagnetic stresses, and perhaps additional stresses arising from topography on the ICB. According to most estimates, electromagnetic coupling should be the largest of these (see Whaler and Holme, 1996) although the lack of constraints on ICB topography makes its contribution impossible to calculate. In our model, electromagnetic coupling is dominant because of the strong toroidal field generated by the thermal wind in the tangent cylinder.

Equilibrium electromagnetic coupling causes the inner core to rotate in the same sense as the adjacent fluid in the tangent cylinder, although at a slightly slower

rate, as determined by the condition that the sum of all electromagnetic torques on the inner core is zero (Gubbins, 1981). One torque is due to the azimuthal field induced by the thermal wind, B_1 . This must be balanced by the torque produced by a second azimuthal field B_2 , induced at the ICB by the difference in rotation between the inner core and the surrounding core fluid. This jump in angular velocity is denoted by $\Delta\Omega_{ICB}$ and occupies *Region II* in Figure 1. The induction equation (3) for this field reduces to, in spherical (r, θ, ϕ) coordinates

$$(\nabla^2 - \frac{1}{s^2}) B_2 = \frac{\Delta\Omega_{ICB} B_z \sin 2\theta}{2\eta} \delta(\frac{R_{ICB} - r}{R_{ICB}}) \quad (7)$$

where $\delta(\frac{R_{ICB} - r}{R_{ICB}})$ is a Dirac δ -function centered on the ICB. This δ -function represents the source of toroidal field provided by the jump in the angular velocity between the tangent cylinder fluid surrounding the inner core and the solid inner core.

Using standard techniques, the solution to (7) which vanishes at the CMB and on the rotation axis gives the following azimuthal field on the ICB:

$$B_2(r = R_{ICB}) = -\frac{\Delta\Omega_{ICB} B_z R_{ICB}^2}{2\eta} \sin 2\theta \quad (8)$$

Electromagnetic Coupling of the Inner Core to the Tangent Cylinder Fluid

The axial component of the electromagnetic torque on the inner core can be written as a surface integral (Rochester, 1962)

$$\Gamma = \frac{1}{\mu} \int_{ICB} r B_r B_\phi \sin \theta dA \quad (9)$$

where μ is magnetic permeability. Setting $B_r = B_z \cos \theta$, $B_\phi = B_1 + B_2$, and substituting (6) and (8) into (9), yields, at equilibrium ($\Gamma = 0$) the following relationship between the angular velocity increments shown in Figure 1.

$$\Delta\Omega_{ICB} = -\left(\frac{R_{ICB}}{4H}\right) \Delta\Omega_{TW} \simeq -0.14 \Delta\Omega_{TW} \quad (10)$$

In electromagnetic equilibrium, the inner core lags the nearby tangent fluid cylinder in prograde rotation only by about 14%.

As illustrated in Figure 1, the seismically-inferred rotation of the inner core relative to the mantle is the sum of these two increments, $\Delta\Omega_{IC} = \Delta\Omega_{ICB} + \Delta\Omega_{TW}$. Using (2) we can express the temperature excess across the tangent cylinder in terms of the inner core super-rotation as

$$\Delta T \simeq \frac{1.16 \Omega R_{ICB}^2}{\alpha g H} \Delta\Omega_{IC} \quad (11)$$

and using (6) the maximum toroidal field, found on the tangent cylinder, is

$$B_\phi(s = R_{ICB}) \simeq -\frac{1.16 B_z R_{ICB}^3}{4\eta H} \Delta\Omega_{IC} \quad (12)$$

From (6), (8) and (9) it can also be seen that the torque Γ is a function of B_z^2 , so the polarity of the axial magnetic field does not affect the torque. The direction of rotation of the inner core depends only on the sign of the temperature difference ΔT across the tangent cylinder.

Model Results

The inferred super-rotation of the inner core can be driven by an extremely small temperature (or equivalently, light element) excess in the tangent cylinder. Using $\Omega = 7.29 \times 10^{-5}/s$, $\alpha = 1 \times 10^{-5}/K$, $g = 7 m/s^2$, $R_{ICB} = 1.22 \times 10^6 m$, and $H = 2.26 \times 10^6 m$, (11) gives $\Delta T \simeq 5 \times 10^{-4} K$ and $\Delta T \simeq 1.3 \times 10^{-3} K$ for $\Delta\Omega_{IC} = 1.1^\circ/yr$ and $\Delta\Omega_{IC} = 3^\circ/yr$, respectively. On the other hand, the toroidal field induced by this small anomaly is quite large. Using the characteristic radial field intensity on the CMB (Bloxham et al., 1989) for the axial field in the tangent cylinder $B_z = -0.5 mT$, and $\eta = 3 m^2/s$ for the core magnetic diffusivity, (12) predicts peak toroidal field intensities on the tangent cylinder of $B_\phi \simeq 24 mT$ and $B_\phi \simeq 66 mT$ for $\Delta\Omega_{IC} = 1.1^\circ/yr$ and $\Delta\Omega_{IC} = 3^\circ/yr$, respectively. We note that these toroidal field intensities are consistent with the toroidal field intensities obtained in the tangent cylinder region of the Glatzmaier-Roberts dynamo calculations, and that the thermal anomalies in those calculations, when scaled to Earth conditions, are comparable to the thermal anomaly in our model.

The fact that *a priori* calculations of convection and dynamo action in a rotating, electrically spherical shell can account for the direction and the magnitude of the seismically-inferred super-rotation of the inner core offers significant support for the convection theory of the geodynamo. Our model of inner core rotation, in which the tangent cylinder plays a central role, is motivated by the results of those calculations. Although highly idealized, it demonstrates how inner core rotation can be used to probe the heart of geodynamo, to constrain critical variables such as flow velocity and toroidal magnetic fields near the Earth's center.

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