Inclinaison du noyau solide et mouvement du pôle de rotation de la Terre

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Summary

- Hypothesis: Markowitz wobble can be explained by torques on the inner core

- Two possible mechanisms for the torque: gravitational or electromagnetic

- We can explain general characteristics of Markowitz wobble

- Provides a way to probe dynamics inside the tangent cylinder
  - Torsional oscillations
  - Time-dependent thermal wind
Variations in Earth’s rotation

- Earth’s rotation is not constant
  - changes in its rate of rotation: changes in Length of day
  - changes in its direction with respect to crust: polar motion
  - timescale of the changes: hours to millions of years

- Cause of these changes
  - Torques from Moon, Sun and Planets
  - Deformation leading to changes in moment of inertia
  - Relative motion between core, mantle, fluid envelope
Long period polar motion (> 1 day)
Variations in the position of the Earth’s rotation axis: polar motion

- True Polar Wander:
  - Mantle convection: $10^6$ year timescale
  - Post glacial rebound: $10^3$ year timescale
  - Change in polar ice mass: $10^2 - 10^3$ year timescale

- Annual Wobble:
  - From mass transport in atmosphere, oceans, ground water

- Chandler Wobble:
  - Free Eulerian precession with a period of $\sim 14$ months

- Markowitz Wobble
  - Decadal polar motion
Markowitz Wobble

- Motion of the rotation axis viewed from above geographic North Pole

- Markowitz wobble:
  - amplitude 30-50 milliarcseconds
  - quasi-periodic $\sim$ decades
  - polarized

- Potential problems:
  - artifact of data
  - artifact of signal modelling
  - no known physical mechanism
What is the physical mechanism responsible for the Markowitz Wobble?

- Exchange of angular momentum between the Mantle and fluid envelope (atmosphere and oceans)
  - Free wobble of coupled Ocean - Solid Earth system (Dickman, 1983)
  - Forcing from climate (Celaya et al., 1999)

  \[\text{resulting polar motion is } \sim 10\text{ times too small (Gross et al. 2005)}\]

- Exchange of angular momentum between the Mantle and the Core
  - Electromagnetic coupling at CMB (Greff-Leftz & Legros, 1995)
  - Topographic coupling at CMB (Greff-Leftz & Legros, 1995; Hide et al, 1996; Hulot et al., 1996)

  \[\text{resulting polar motion is } \sim 10\text{ times too small}\]

- Influence of the Inner Core
  - Free Eulerian precession of tilted Inner Core (Busse, 1970)
  - Forced polar motion due to equatorial torques on Inner Core
Equatorial Torques on Inner core

- Equatorial torques produce a tilt of elliptical Inner Core
- Conservation of angular momentum + internal torques:
  - offset between rotation axis and geometric figure of Mantle
Equatorial torques on the inner core

• Need a torque on the inner core that produces:
  – polar motion with amplitude 30-50 milliarcseconds
  – with period of \(\sim\) decades
  – and oriented along a specific longitude

• What is the dynamical mechanism producing the torque?

• Hypothesis:
  – Equatorial gravitational torque
    * from inner core topography misaligned with mantle density structure
  – Equatorial electromagnetic torque
    * from poloidal flows acting on \(B_r\) at ICB
Goal

- Extract information on core dynamics from its effect on polar motion
- Analogy: decadal variations in axial rotation, or changes in length of day

Connection with core flows predicted by geodynamo theory
Torsional oscillations in core flows

- Rigid azimuthal oscillations of cylindrical surfaces (Braginsky, 1970)
- Cylinders extend to CMB: should be contained in core flows
- Timescale of decades: we can perhaps observe them in historical data
Torsional oscillations in core flows

- Rigid azimuthal oscillations of cylindrical surfaces (Braginsky, 1970)
- Cylinders extend to CMB: should be contained in core flows
- Timescale of decades: we can perhaps observe them in historical data
- Torsional oscillations in Earth’s core (Zatman & Bloxham, 1997):

![Graph showing torsional oscillations](image)
Confidence test: angular momentum balance

- Change in core angular momentum carried by torsional oscillations
  - must equal change in angular momentum of mantle

- Should result in changes in rotation rate of the mantle
  - changes in length of day
Variations in length of day

- shows that $\Delta$ LOD are from core-mantle angular momentum exchange
- confirms the presence torsional oscillations
- suggests that LOD data, field models, and inverted core flows are all valid
A connection between decadal polar motion and core dynamics?

- torques on the inner core induced by flows near the ICB
- Can we find time-dependent torques on the inner core consistent with:
  - core-dynamics
  - observed Markowitz wobble
- which is the appropriate flow regime near the inner core boundary?

Torsional oscillations

changes in thermal wind
Thermal wind inside tangent cylinder

• observed in numerical simulations (e.g. Sreenivasan and Jones, 2006)

• observed in laboratory experiments (e.g. Aurnou et al., 2003)
Thermal wind inside tangent cylinder

- consistent with secular variation inside the tangent cylinder

from Olson & Aurnou, Nature, 1999

- decadal changes in thermal wind?
Axial electromagnetic torques on the inner core

- Torsional oscillations in the fluid core
  - oscillations of rigid cylinders
  - decade periods

- Electromagnetic coupling at Inner core boundary
  - Inner core is entrained by fluid motion
Equatorial torque produced by inner core – mantle gravitational coupling

- Inner core boundary is an equipotential surface
- Topography at ICB reflects mantle density structure
Equatorial gravitational torque on the inner core

Gravitational potential $\Phi_m$ at ICB from $\delta \rho_m$ in the mantle

Resulting inner core deformation producing an equivalent $\delta \rho_i$

Torque on the inner core:

$$\Gamma = -r \times \int_V \delta \rho_i \nabla \Phi_m \, dV$$

$$\Gamma = \Gamma_1 + \Gamma_2 = 0$$
Gravitational potential $\Phi_m$ at ICB from $\delta \rho_m$ in the mantle

$\delta \rho_i$ after axial rotation of inner core

Torque on the inner core:

$$\Gamma = -r \times \int_V \delta \rho_i \nabla \Phi_m \, dV$$
We need to include internal coupling
- Internal gravitational and pressure torques

Elastic deformations

Earth model for Moments of Inertia, ellipticities...

We use models developed for study of forced nutations
A prediction of polar motion from a realistic scenario

- Use mantle density anomalies obtained from seismology
- Calculate equilibrium hydrostatic shape of inner core
- Get history of inner core axial angular displacement from geomagnetism
- Integrate equations in time
- Cross our fingers
- Compare results with observed Markowitz wobble
Model of Mantle density anomalies

- Mantle density model obtained by inversion from splitting functions of free oscillation modes (Ishii and Tromp, 2001; 2004)

- Difficulty of building a density model inferred from seismic tomography:
  - Compressional ($V_p$) and shear ($V_s$) seismic velocities are related to density by
    \[ V_p^2 = \frac{\kappa + 4\mu/3}{\rho}, \quad V_s^2 = \frac{\kappa}{\rho} \]
  - Scaling to get density from seismic velocities:
    \[ d \ln \rho = \gamma_p d \ln V_p, \quad d \ln \rho = \gamma_s d \ln V_s \]

- With splitting functions, get density directly

- Does not constrain CMB topography
Axial fluid velocity forcing the Inner Core

- Core surface flow models from time-variations of the geomagnetic field
- Assume rigid flows: torsional oscillations
- Assume inner core follows fluid motion:
Axial rotation of Inner Core

- Integrate rotation rate of inner core to obtain a time-history of $\phi(t)$
- Get $\phi(t)$ for various inner core viscosity values

![Angular velocity and angular displacement](image-url)
• Amplitude and phase are similar

• Orientation is offset by $\sim 15$-$30$ degrees

• Details depend on precise history of $\phi(t)$ and on inner core viscosity
Problem: predicted changes in LOD from axial inner core rotation history

- historical axial inner core variations: gravitationally coupled with mantle
- if $\tau = 5$ yr, entrains changes in length of day 50 times larger than observed!

Flows at ICB must be smaller than at CMB
- time-dependent flows inside the tangent cylinder cannot be purely rigid
- Necessarily involves $z$-dependent flows: thermal wind
- Markowitz cannot be explained by gravitational torques
Equatorial torque from electromagnetic coupling at ICB

- Electromagnetic torque on inner core from thermal wind flow
Equatorial torque from electromagnetic coupling at ICB

- assume changes in $v_\phi$ at CMB correspond to changes in $v_\theta$ at ICB

- assume $B_r$ at ICB is a dipolar, with an amplitude of 7 mT, inclined at 25°

- integrate evolution of polar motion
Predicted vs Observed polar motion

- Amplitude and phase are similar
- Orientation is determined by choice of $B_r$ at ICB
- Details depend on precise history of $v_\theta(t)$ and on inner core viscosity
Conclusions

• Torsional oscillations + gravitational torque lead to polar motion which shares characteristics with Markowitz wobble

• BUT: axial angular displacements of inner core are incompatible with observed changes in length of day
  – azimuthal flows must be smaller at ICB than at CMB
  – flows cannot be rigid inside the tangent cylinder
  – gravitational torques cannot explain Markowitz wobble

• Decade timescale flows inside tangent cylinder must involve changes in thermal wind

• Time-dependent thermal wind + electromagnetic torque is promising (though results are preliminary)

• requires $B_r \approx 7$ mT at ICB: compatible with value inferred from nutations (Buffett et al. 2002)
What’s next?

⇒ IF we can improve the fit between the observed and predicted polar motion
⇒ shows that this is the mechanism behind Markowitz wobble

• Consequently, we can use this fit to constrain:
  – Magnetic field near the ICB
  – Viscous relaxation timescale of the inner core
  – Convective flows inside the tangent cylinder

• Can we detect a tilt of the inner core in surface gravity field data?
Equatorial torque from electromagnetic coupling at ICB

- Electromagnetic torque on inner core from torsional oscillations
Dynamical constraint in the core

- Force balance in the Earth’s fluid core

\[
\rho \left( \frac{\partial v}{\partial t} + v \cdot \nabla v + 2\Omega \times v \right) = -\nabla p + \frac{1}{\mu_o} (\nabla \times B) \times B + C\hat{r} + \nu \nabla^2 v
\]

- Magnetostrophic balance in the Earth’s fluid core

\[
2\rho \Omega \times v = -\nabla p + \frac{1}{\mu_o} (\nabla \times B) \times B + C\hat{r}
\]

Coriolis = pressure + Lorentz + buoyancy

- Integrate azimuthal component on cylinder surfaces: Taylor’s constraint, a condition on the morphology of the magnetic field in the core

\[
\int_{\Sigma} ((\nabla \times B) \times B)_{\phi} \, d\Sigma = 0
\]

Torque from magnetic force = 0
Torsional Oscillations

- When Taylor’s constraint is violated:
  - magnetic torque is balanced by a rigid acceleration of the cylinder surface

- System accepts oscillatory solutions of rigid cylinder surface

- Torsional oscillations (Braginsky, 1970), typical periods of $\sim$ decades