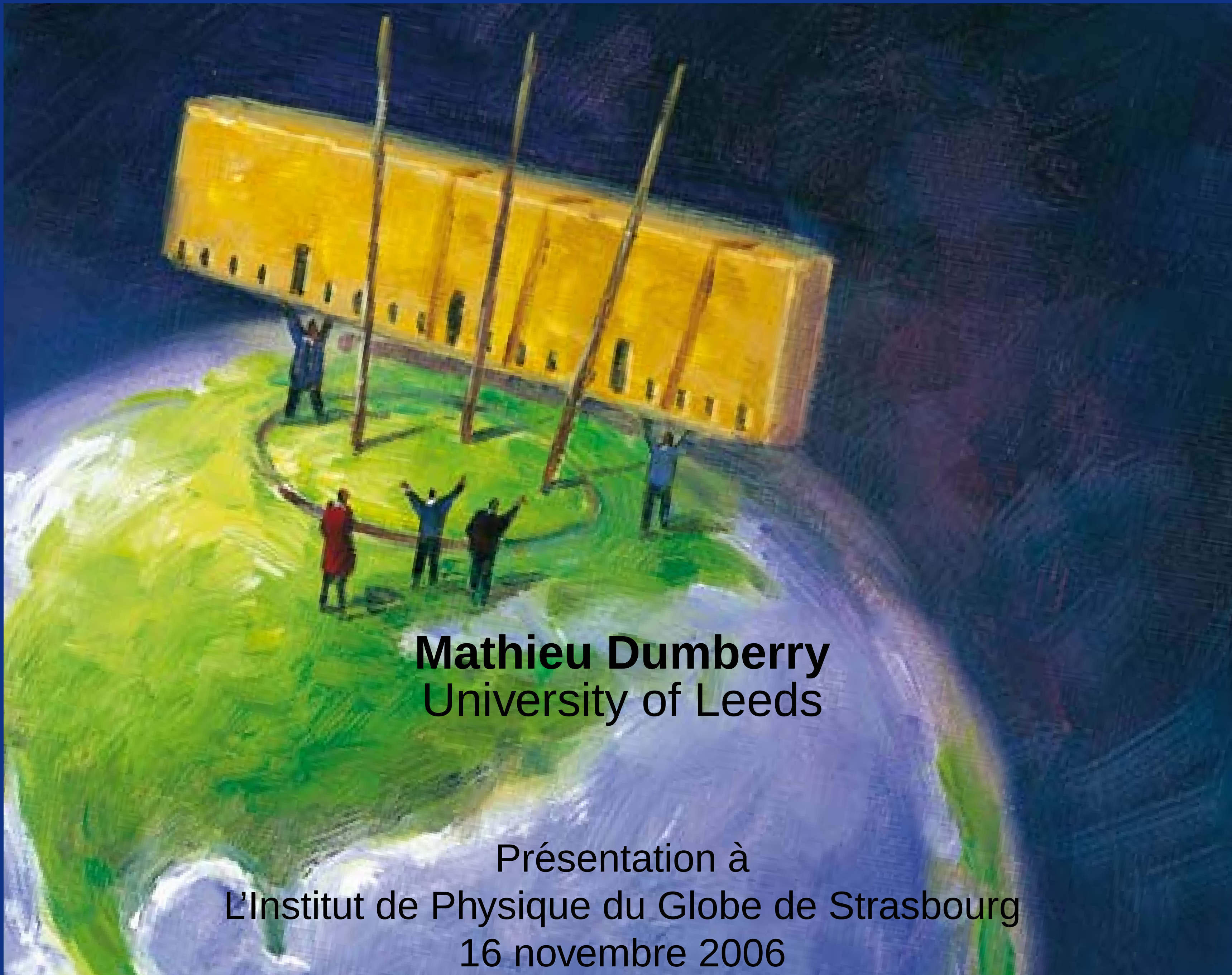
Inclinaison du noyau solide et mouvement du pôle de rotation de la Terre



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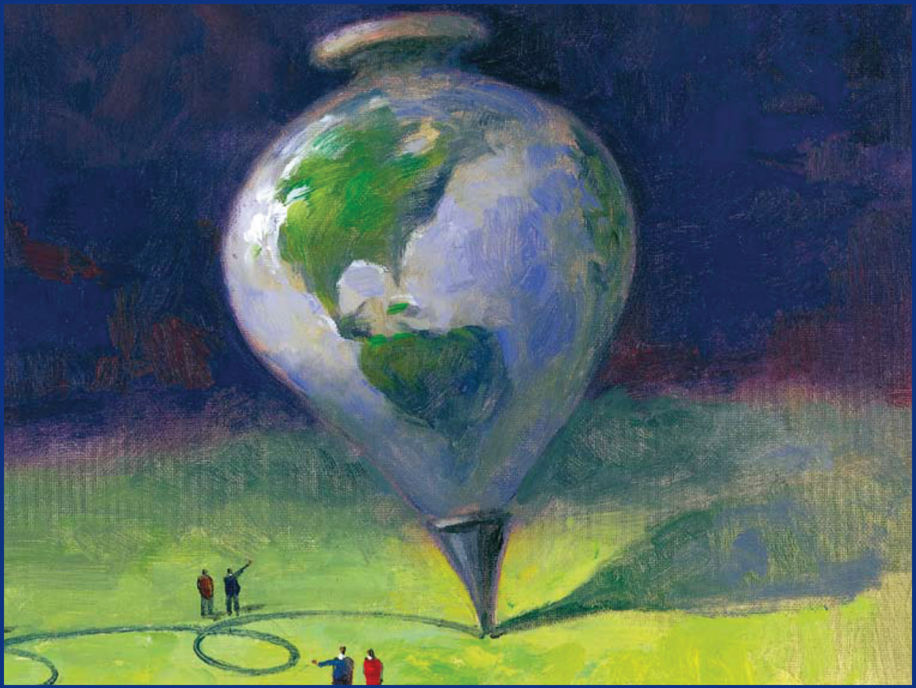
Présentation à
L'Institut de Physique du Globe de Strasbourg
16 novembre 2006

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

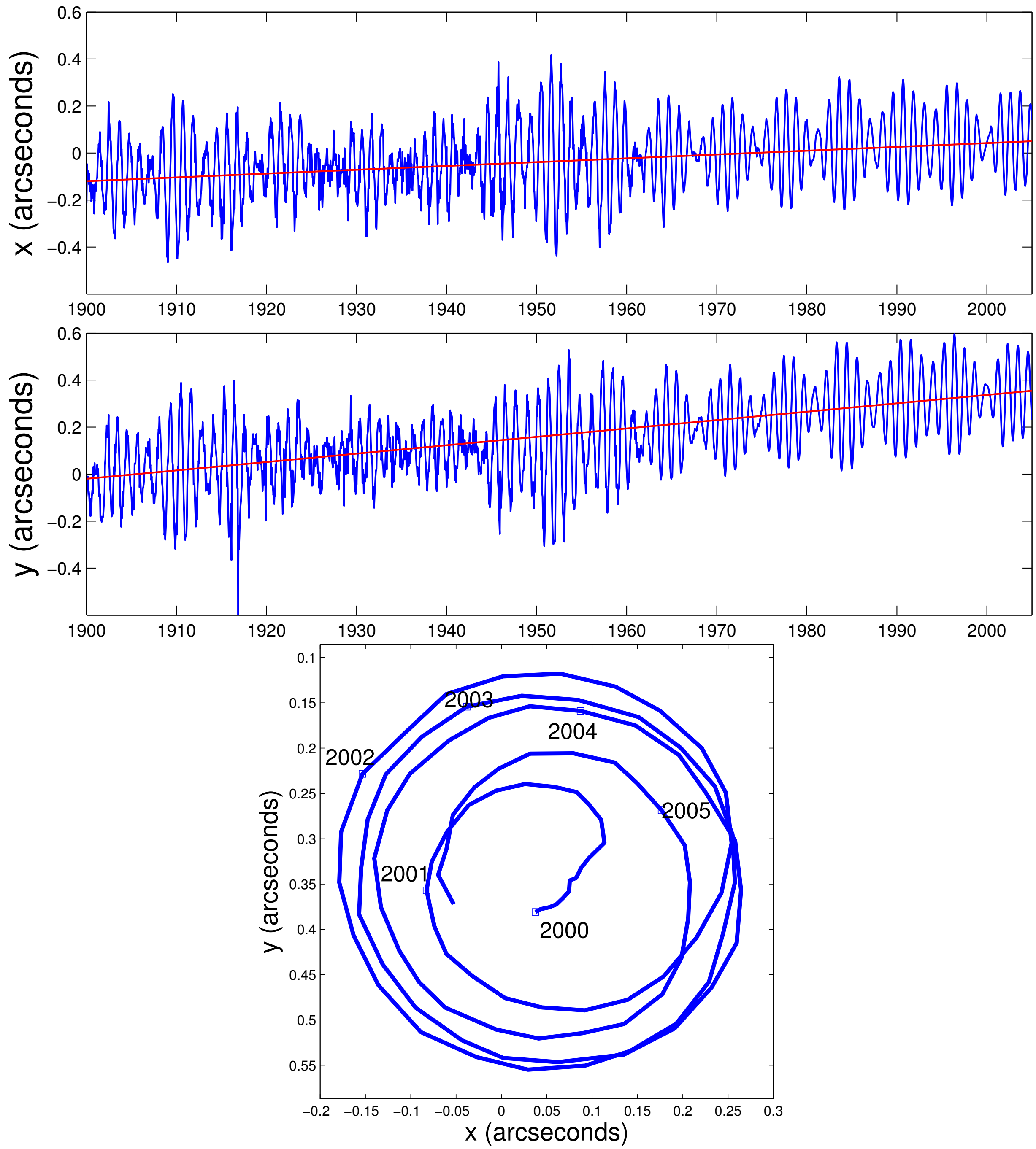
Variations in Earth's rotation



- 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)

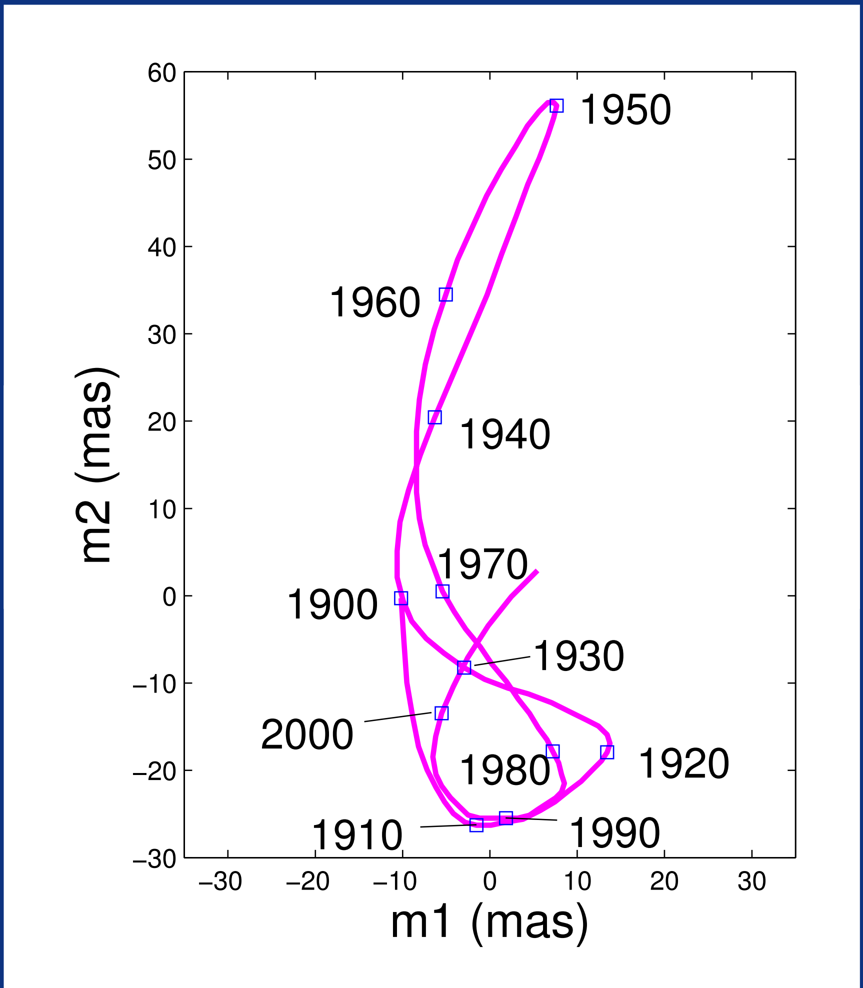


Variations in the position of the Earth's rotation axis: polar motion

- True Polar Wander:
  - Mantle convection: $\mathbf{10^6}$ year timescale
  - Post glacial rebound: $\mathbf{10^3}$ year timescale
  - change in polar ice mass: $\mathbf{10^2 - 10^3}$ 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 ∼ 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*)

  resulting polar motion is $\sim$ 10 times too small (Gross et al. 2005)

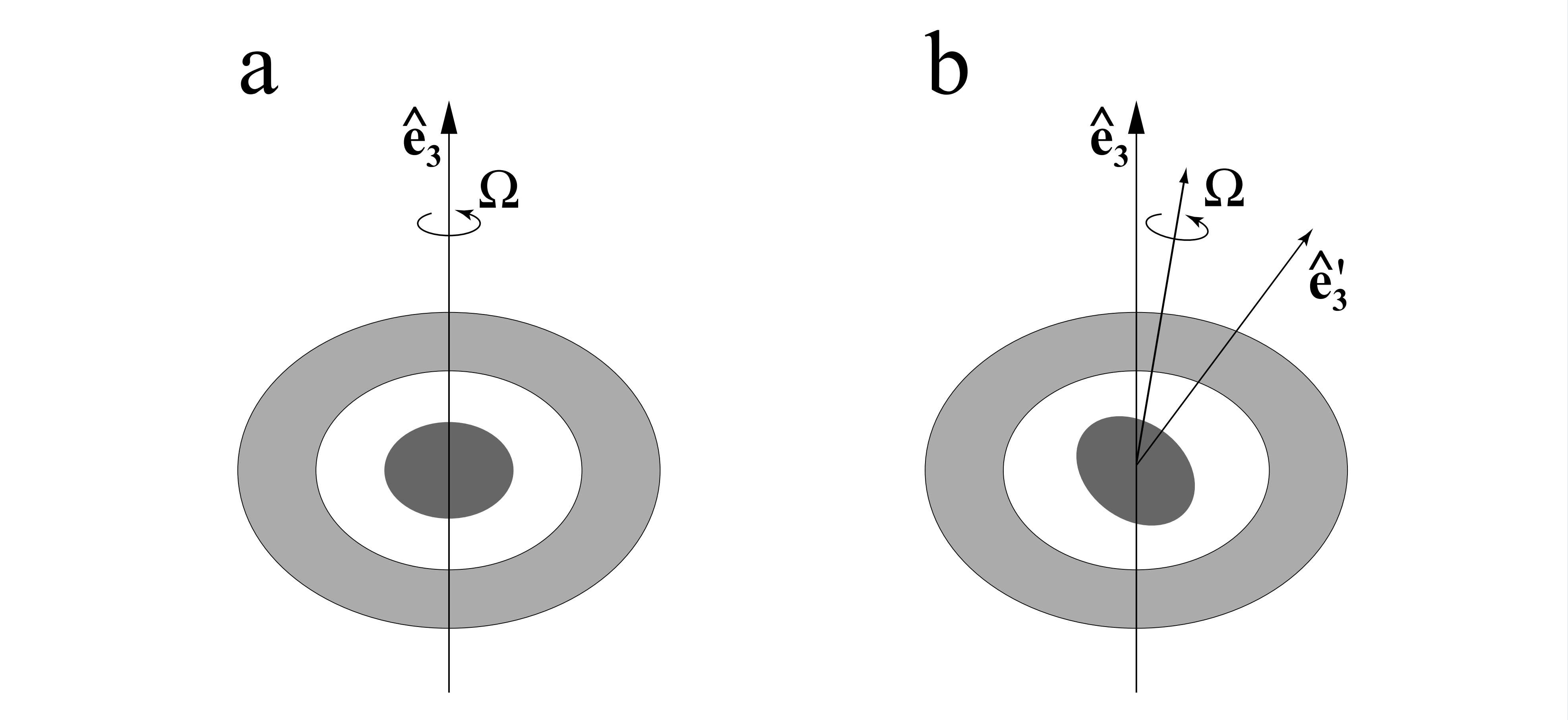
- Exchange of angular momentum between the Mantle and the Core
  - Electromagnetic coupling at CMB (*Greff-Leftz & Legros, 1995*)
  - Topographic coupling at CMB (*Greff-Leftz & Legros, 1995; Hide et al, 1996; Hulot et al., 1996*)

  resulting polar motion is $\sim$ 10 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



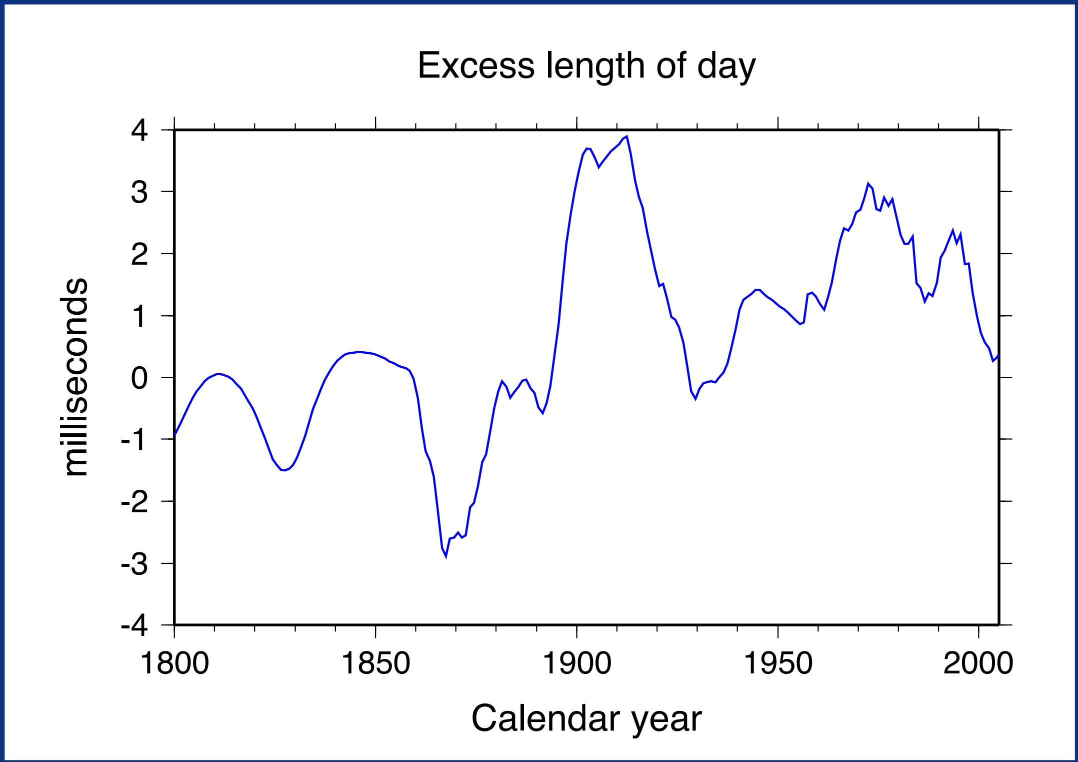
Equatorial torques on the inner core

- 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

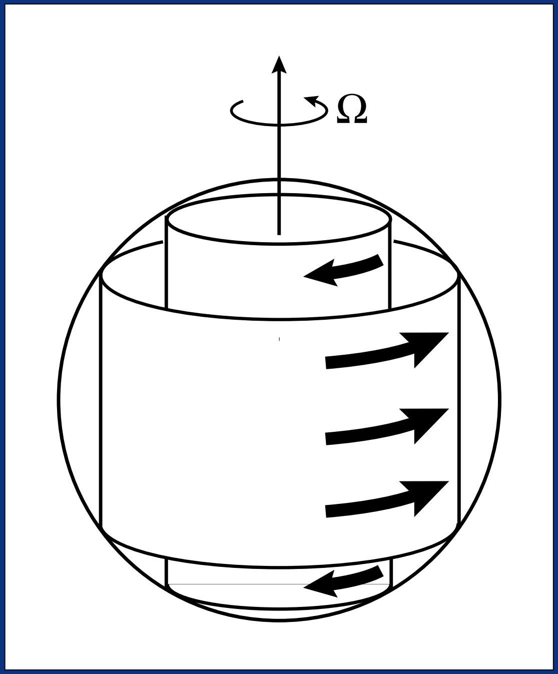
- Analogy: decadal variations in axial rotation, or changes in length of day



- Connection with core flows predicted by geodynamo theory

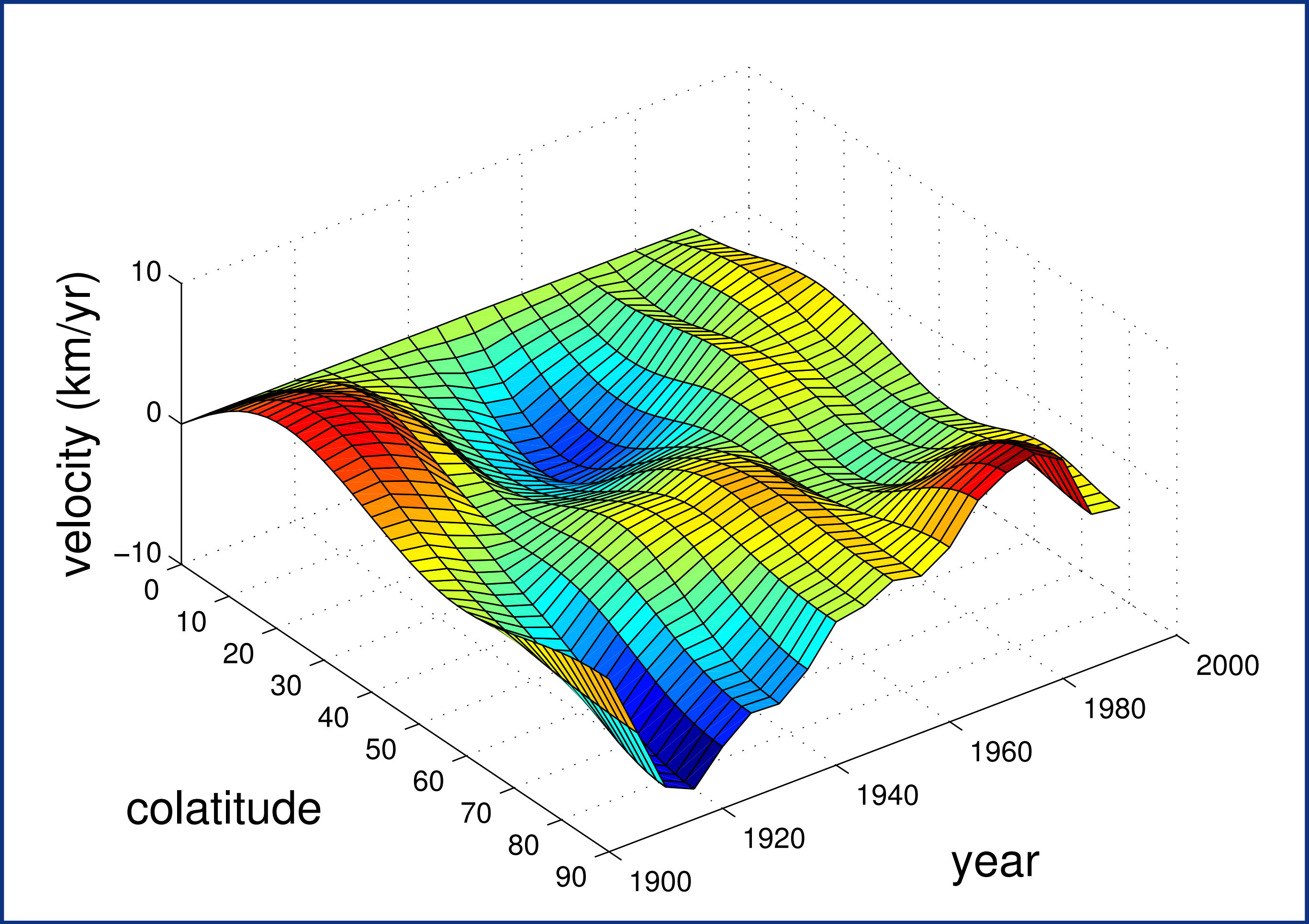
Torsional oscillations in core flows

- 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):

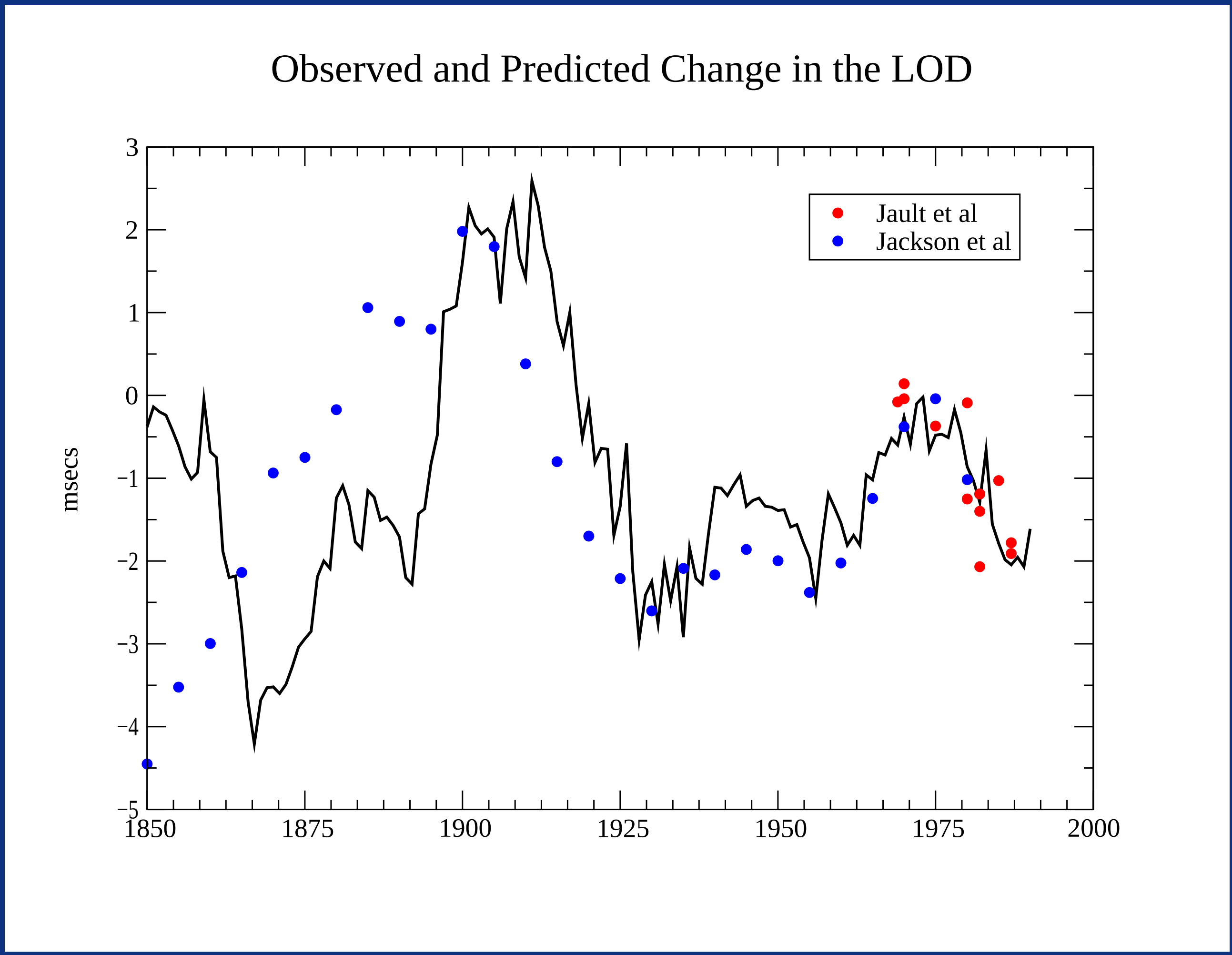


Confidence test: angular momentum balance

- 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

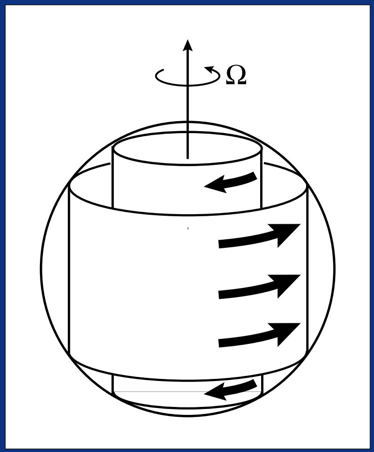


- shows that Δ LOD are from core-mantle angular momentum exchange
- confirms the presence torsional oscillations
- suggests that LOD data, field models, and inverted core flows are all valid

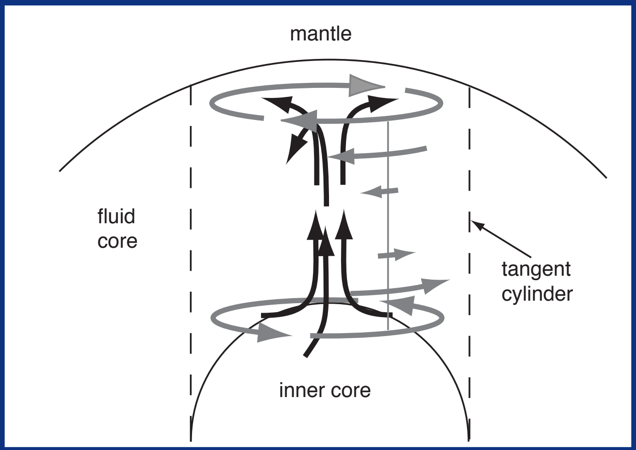
A connection between decadal polar motion and core dynamics?

- 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?

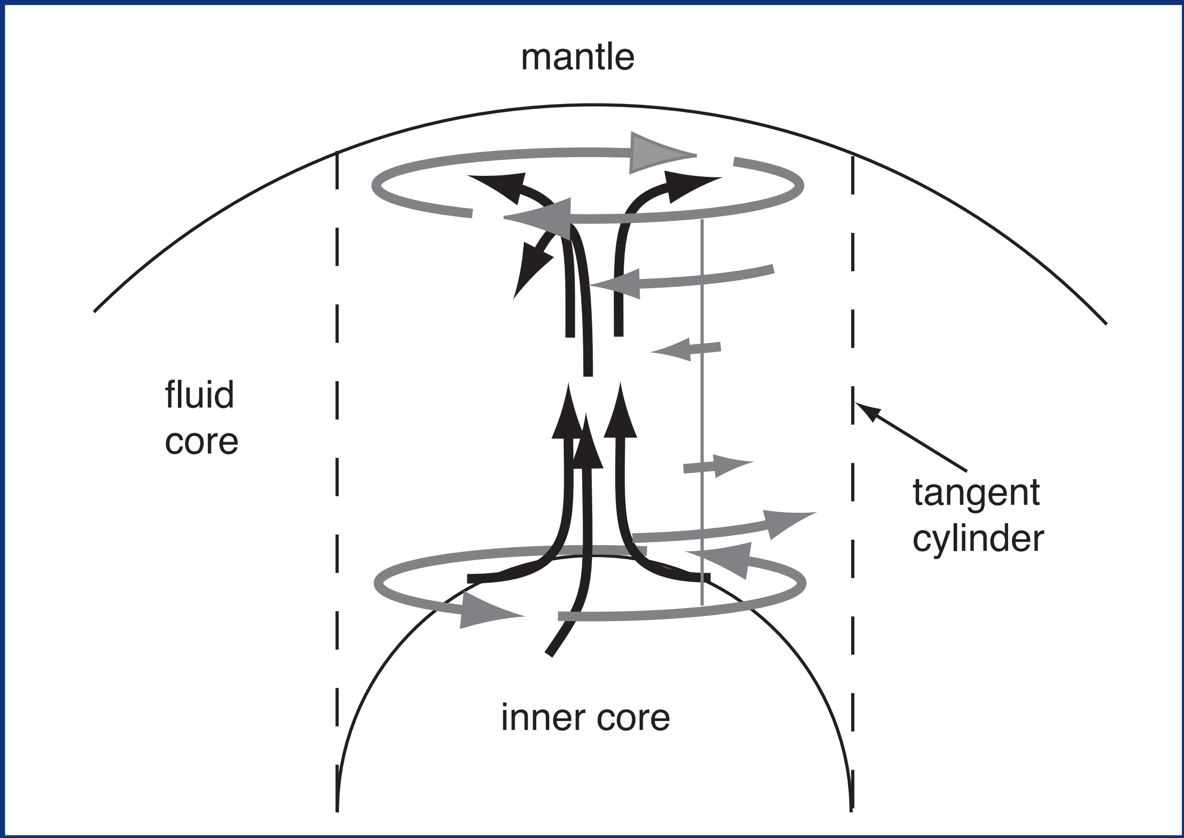
Torsional oscillations



changes in thermal wind



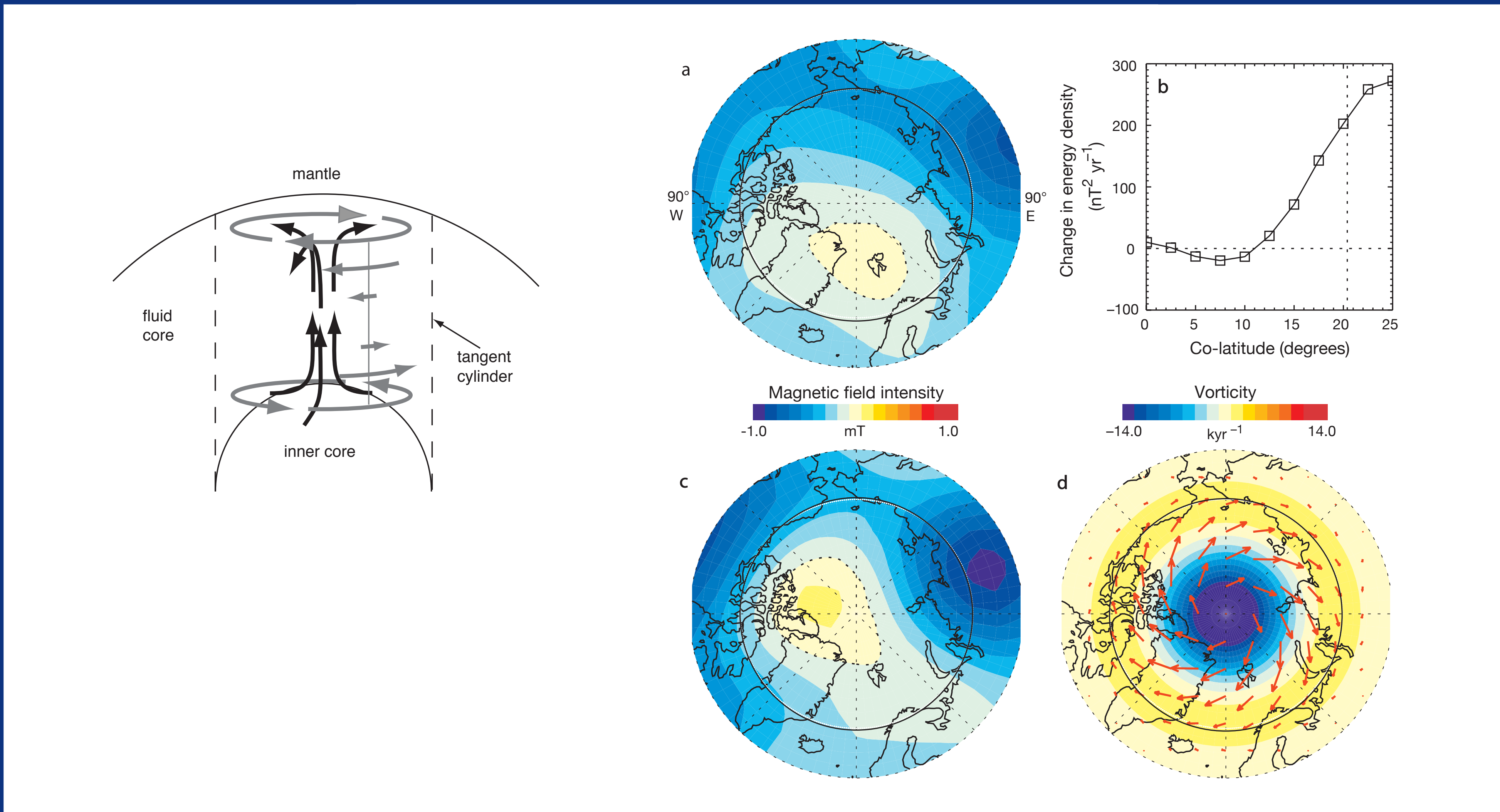
Thermal wind inside tangent cylinder



- 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

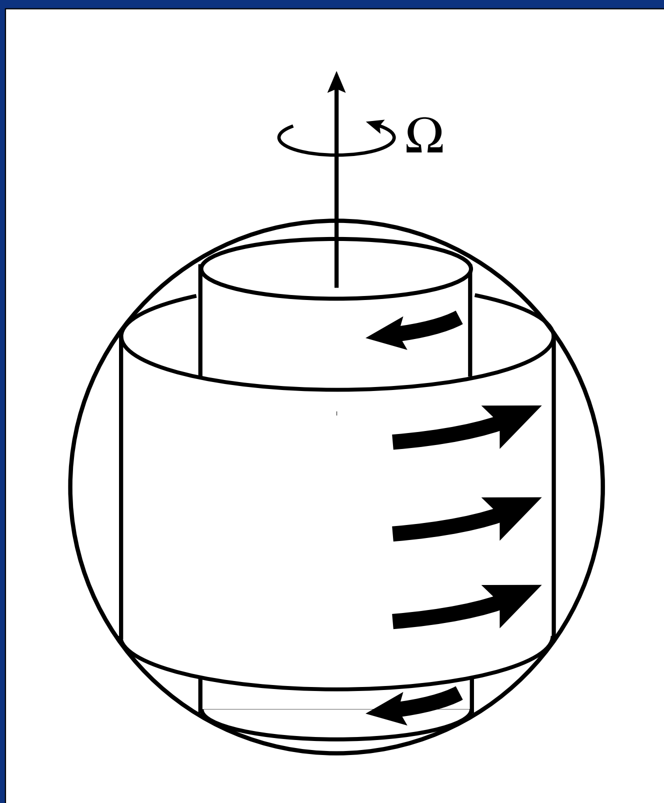


from *Olson & Aurnou, Nature, 1999*

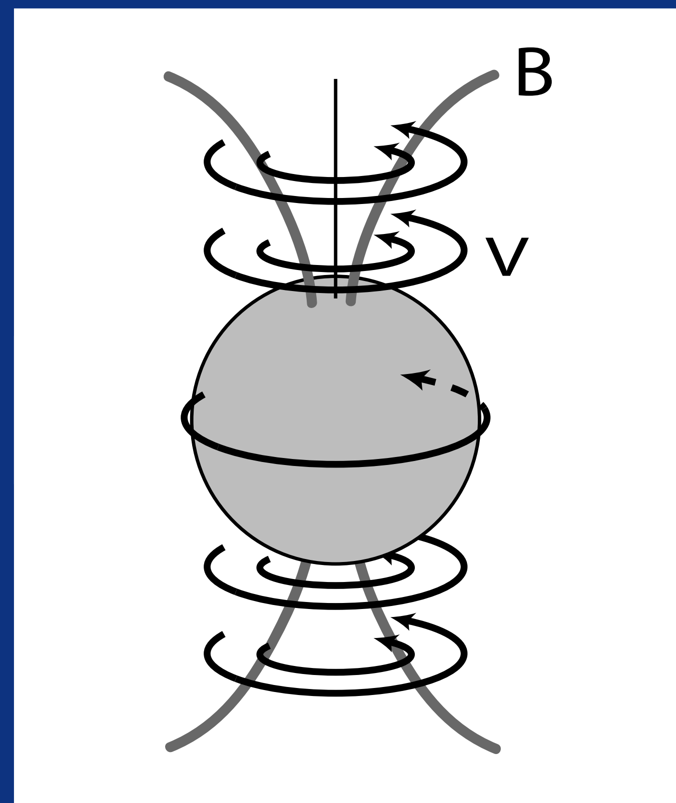
- decadal changes in thermal wind?

Axial electromagnetic torques on the inner core

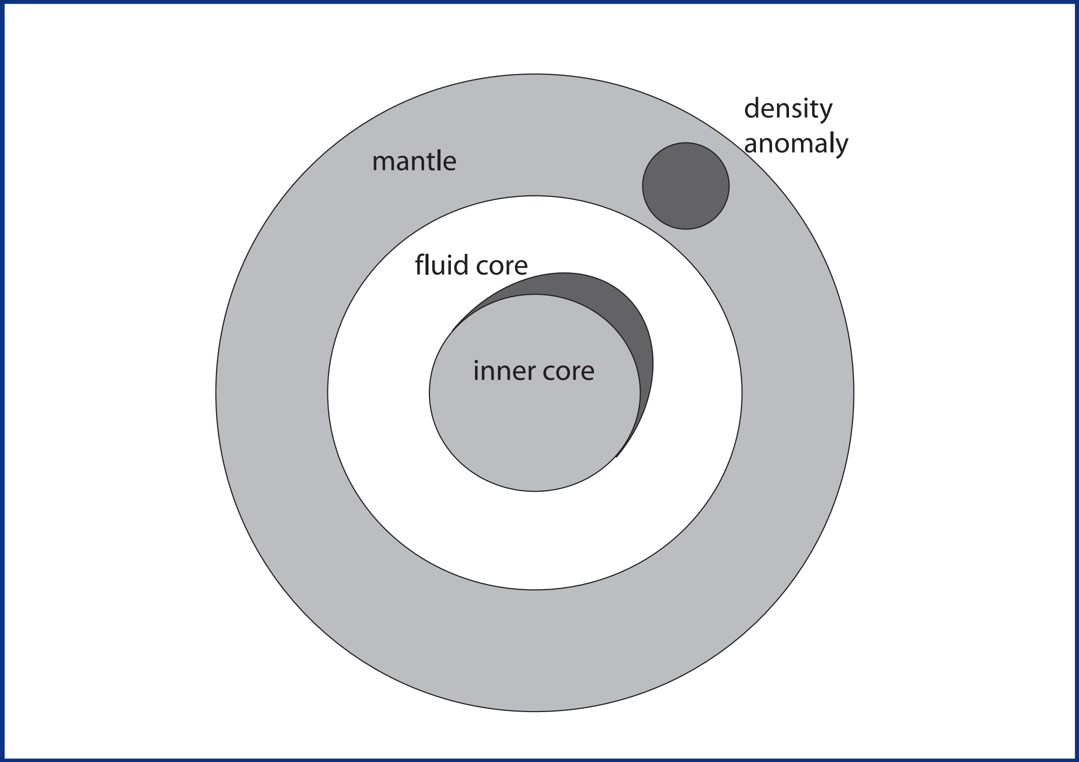
- Torsional oscillations in the fluid core
  - oscillations of rigid cylinders
  - decade periods



- Electromagnetic coupling at Inner core boundary
  - Inner core is entrained by fluid motion



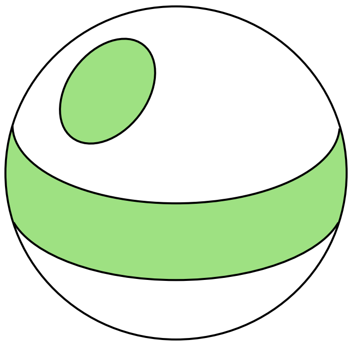
Equatorial torque produced by inner core – mantle gravitational coupling



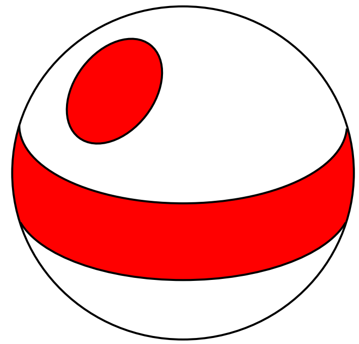
- Inner core boundary is an equipotential surface
- Topography at ICB reflects mantle density structure

Equatorial gravitational torque on the inner core

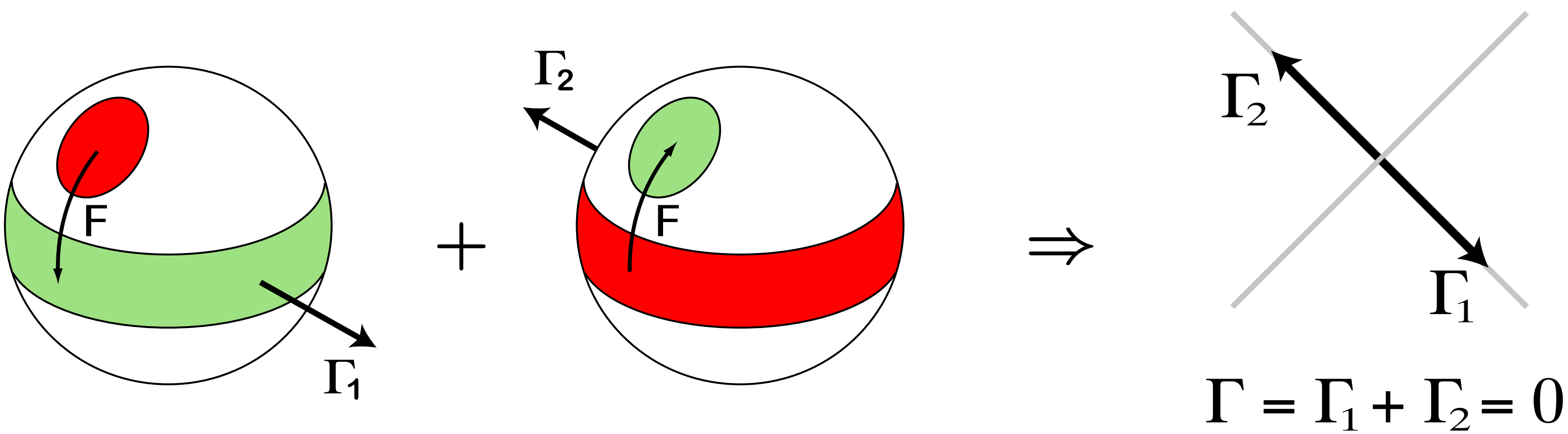
Gravitational potential Φ_m at ICB from $\delta\rho_m$ in the mantle



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

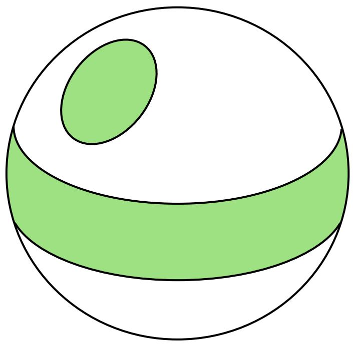


Torque on the inner core: $\boldsymbol{\Gamma} = -\boldsymbol{r} \times \int_V \delta\rho_i \boldsymbol{\nabla} \Phi_m \, dV$

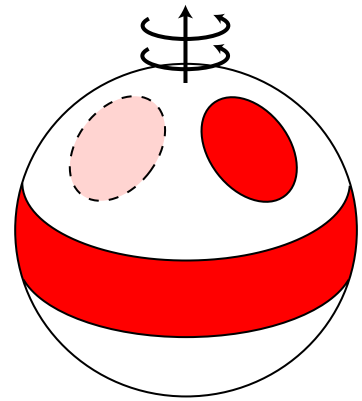


Equatorial gravitational torque on the inner core

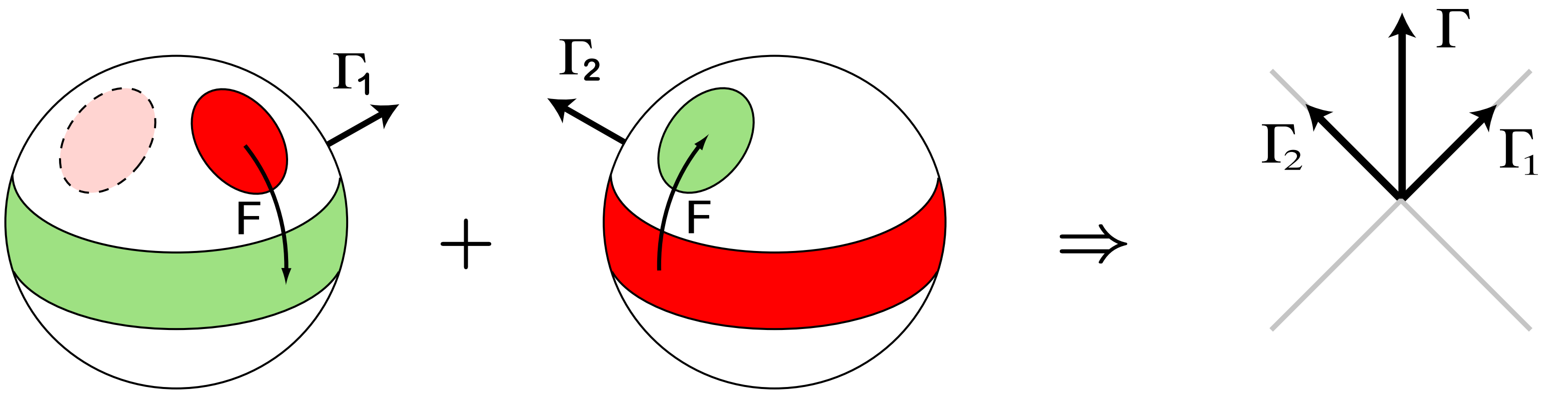
Gravitational potential $\boldsymbol{\Phi_m}$ at ICB from $\boldsymbol{\delta\rho_m}$ in the mantle



$\boldsymbol{\delta\rho_i}$ after axial rotation of inner core

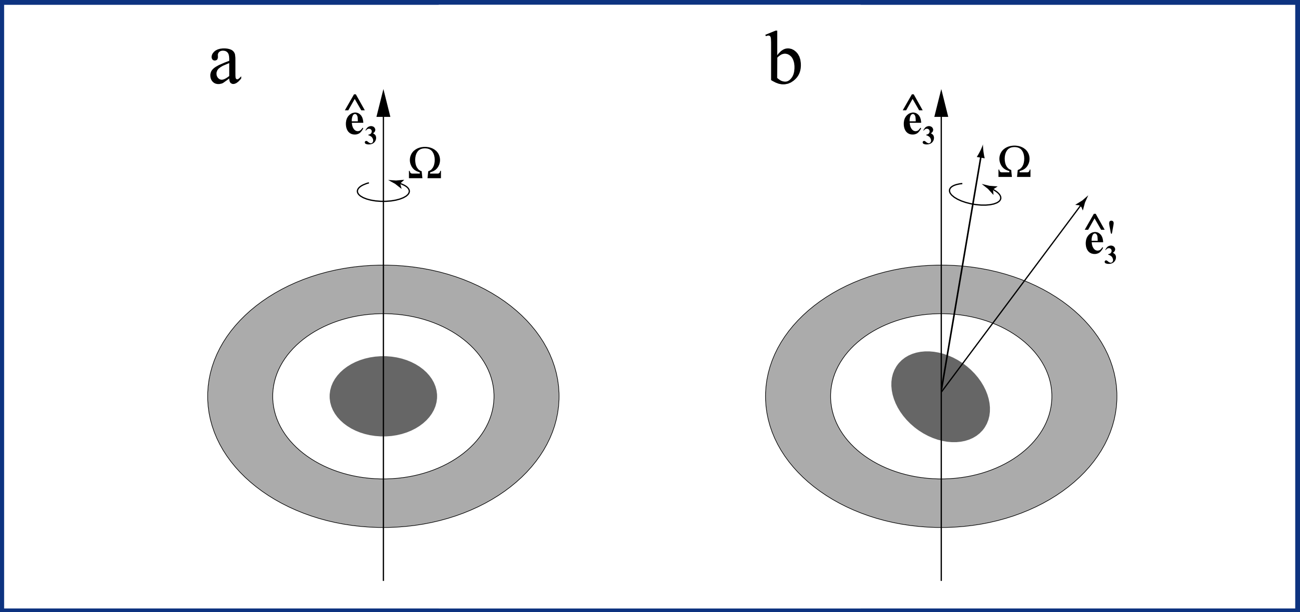


Torque on the inner core: $$\boldsymbol{\Gamma} = -\boldsymbol{r} \times \int_{\boldsymbol{V}} \boldsymbol{\delta\rho_i \nabla \Phi_m \, dV}$$



$\Gamma = \Gamma_1 + \Gamma_2$

Formulation of the problem



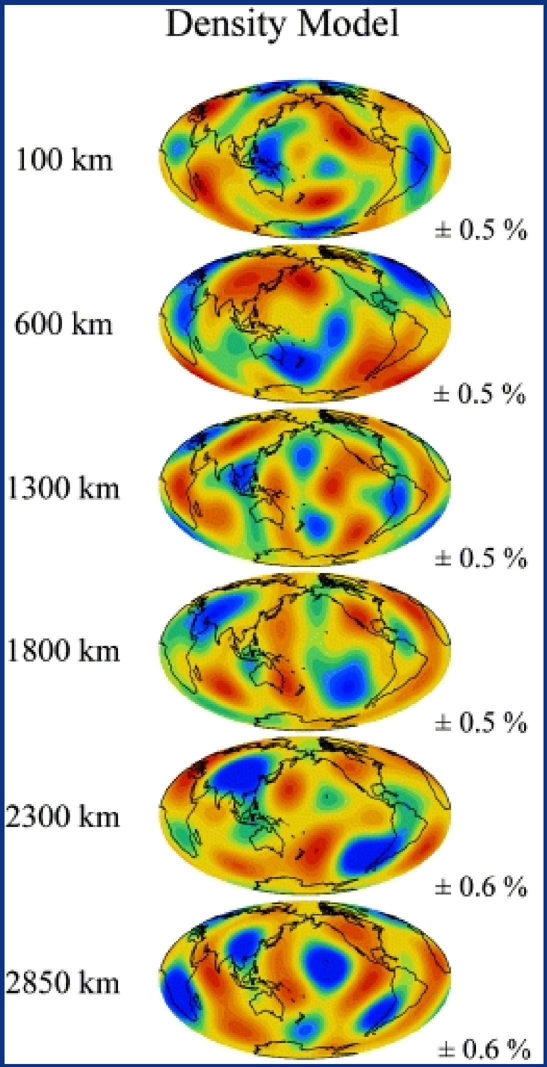
- We need to include internal coupling
  - Internal gravitational and pressure torques
- Elastic deformations
- Earth model for Moments of Inertia, ellipticities...
- We use models developed for study of forced nutations

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

$$V_p^2 = (\kappa + 4\mu/3)/\rho, \;\; V_s^2 = \kappa/\rho$$

  - Scaling to get density from seismic velocities:

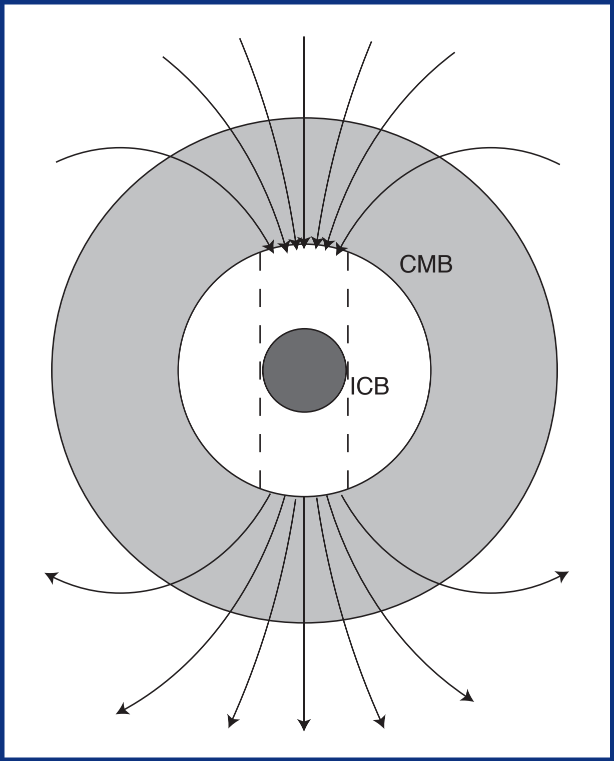
$$d\,ln\,\rho = \gamma_p\,d\,ln\,V_p, \;\; d\,ln\,\rho = \gamma_s d\,ln\,V_s$$

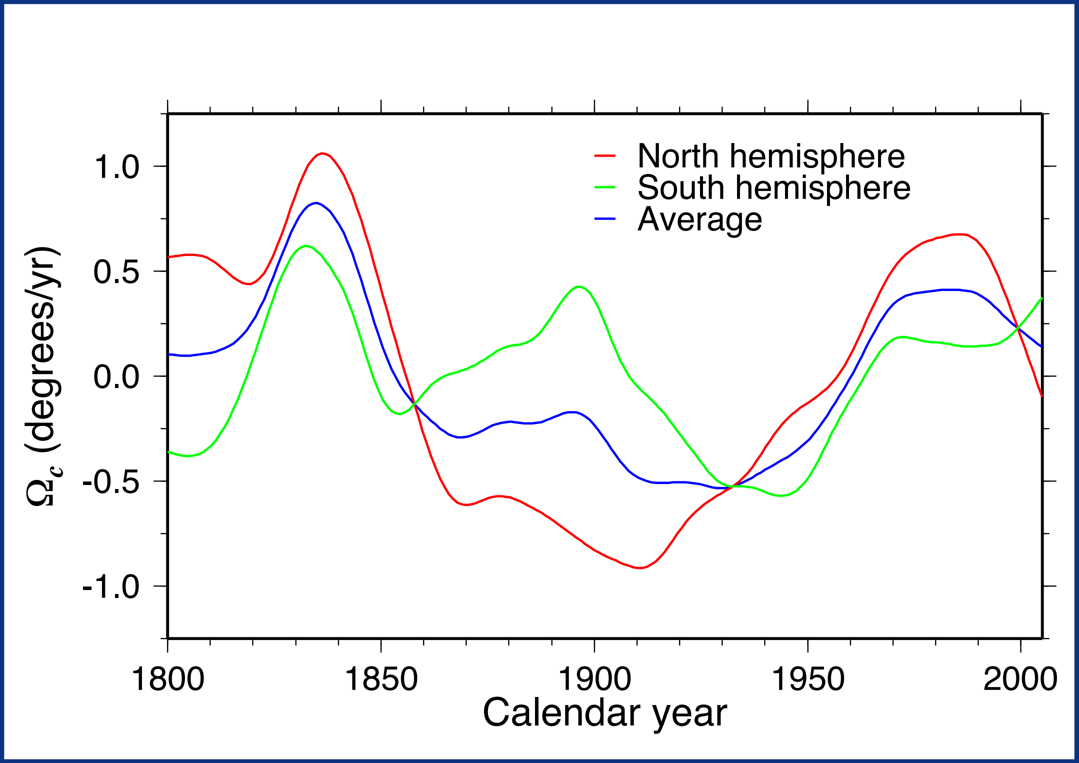
- With splitting functions, get density directly

- 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:

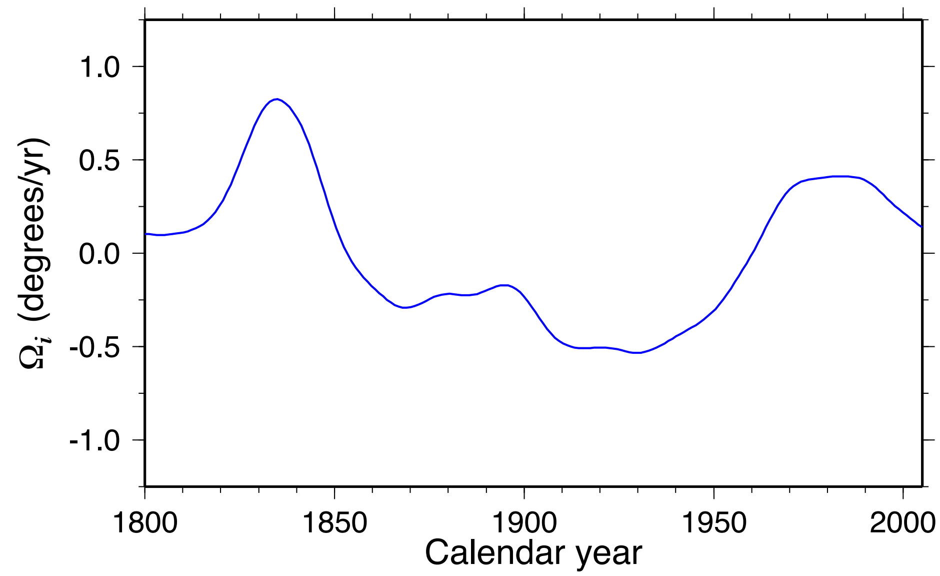




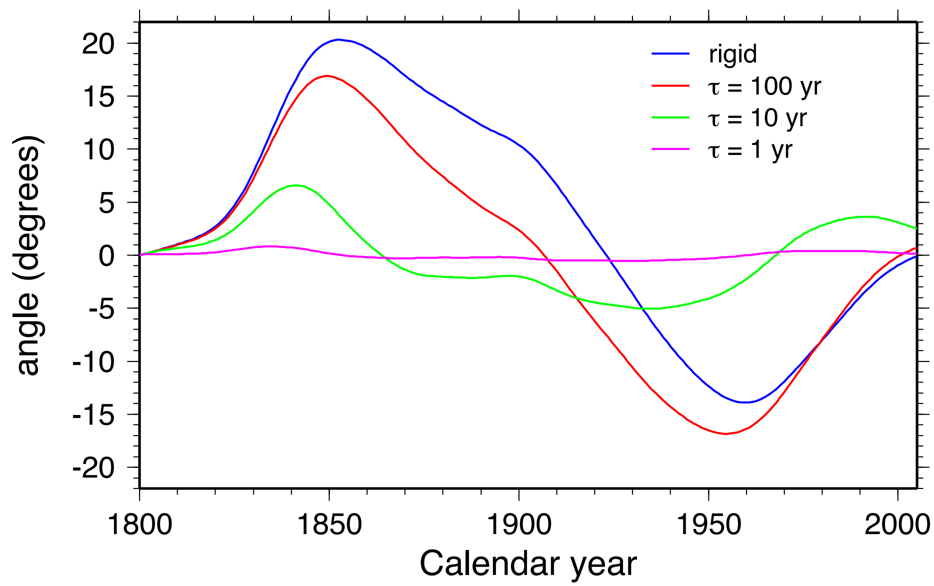
Axial rotation of Inner Core

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

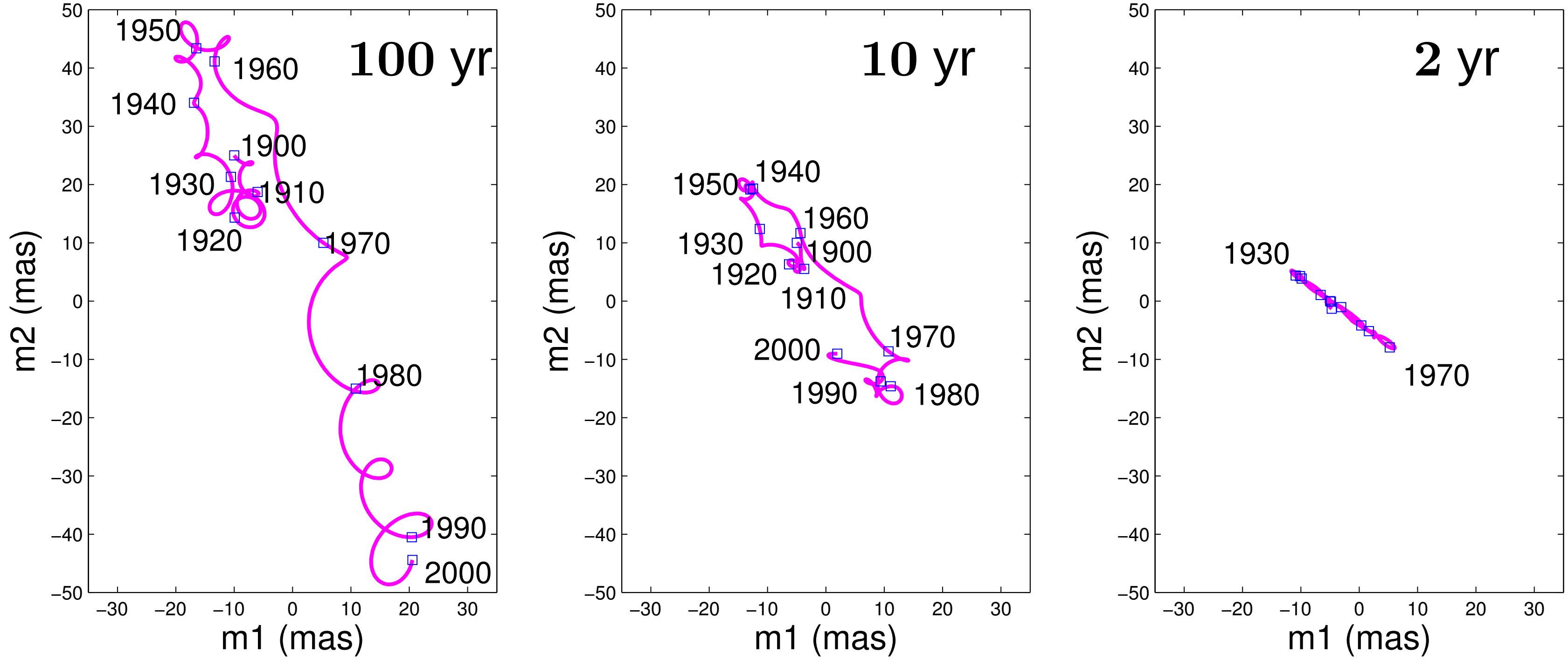
angular velocity of the inner core

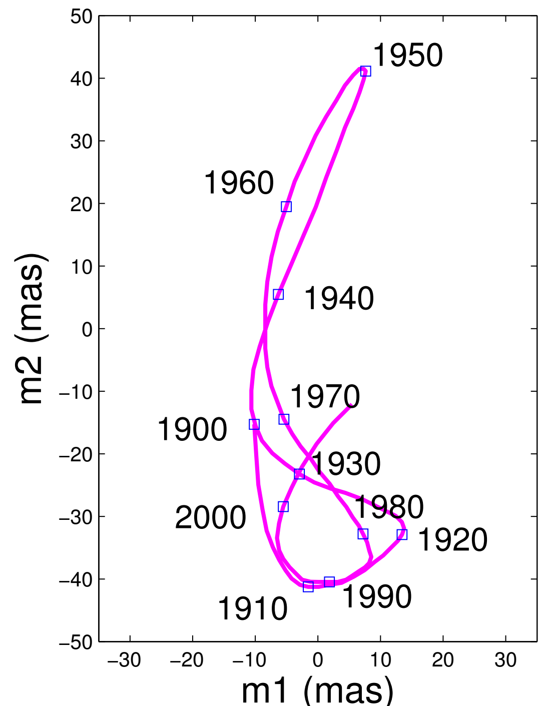


angular displacement of the inner core



Predicted vs Observed polar motion

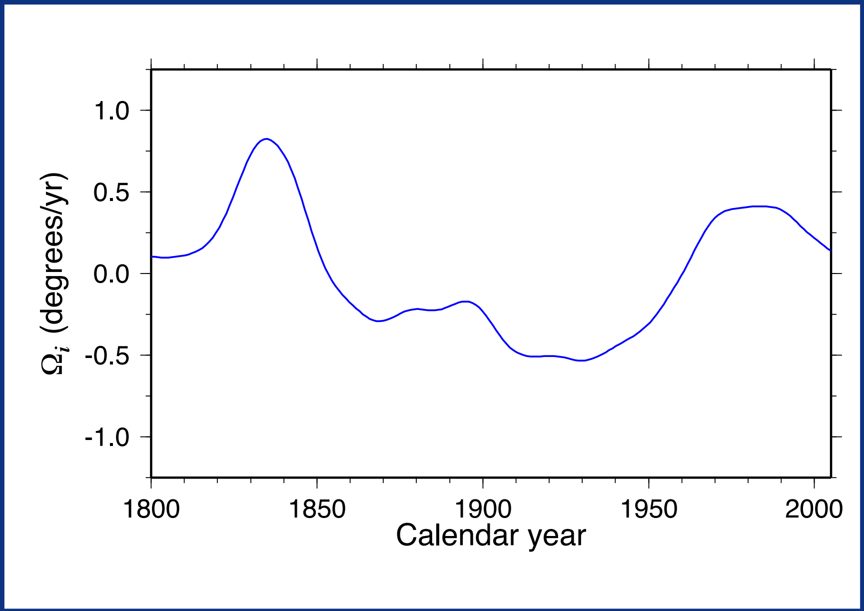


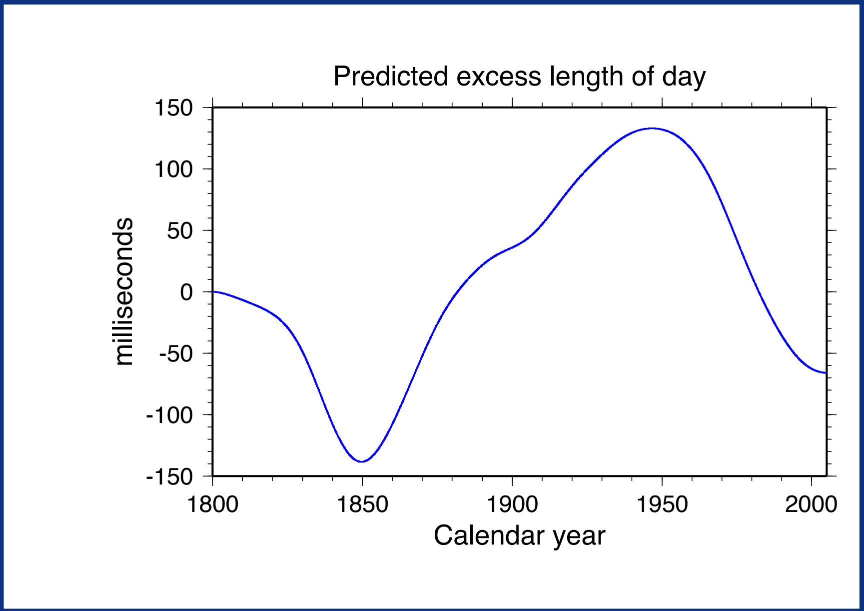


- Amplitude and phase are similar
- Orientation is offset by $\sim$ 15-30 degrees
- Details depend on precise history of $\phi(t)$ and on inner core viscosity

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!

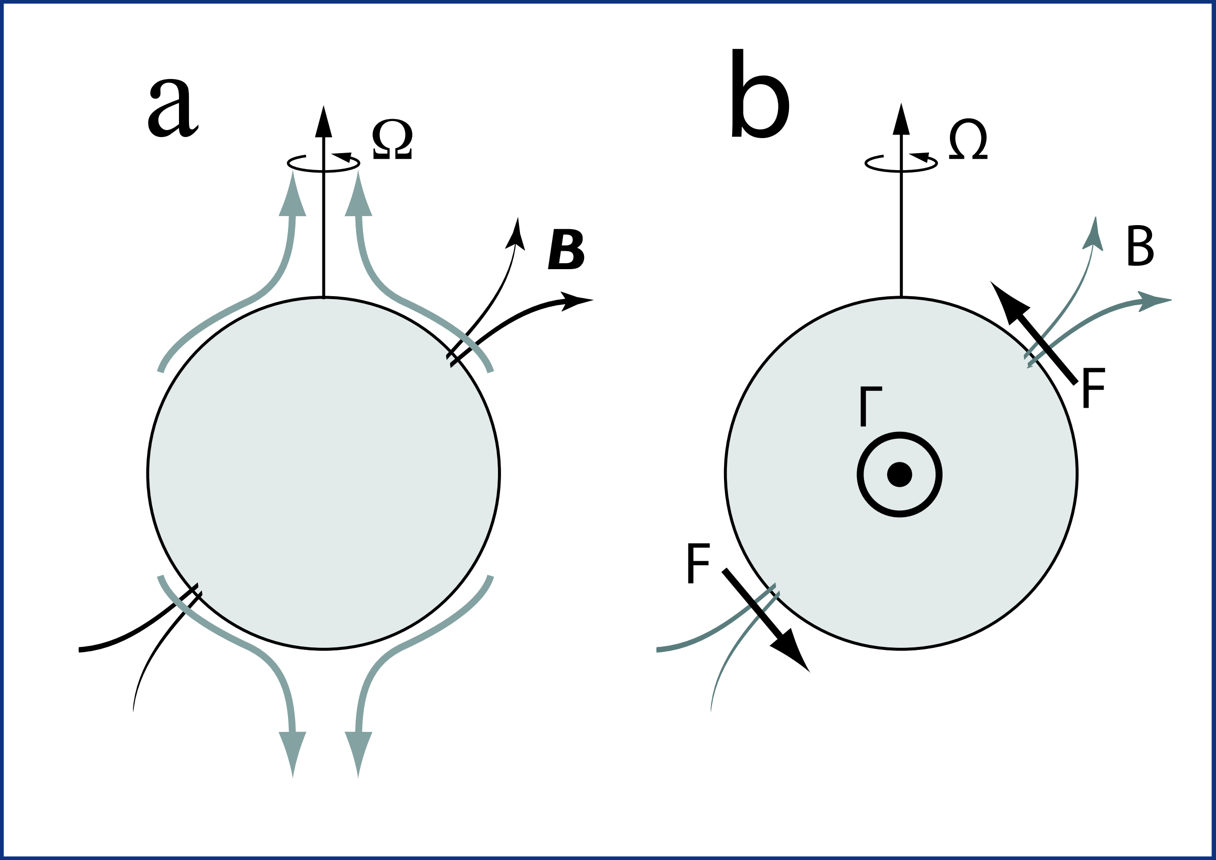




- Flows at ICB must be smaller than at CMB
- time-dependent flows inside the tangent cylinder cannot be purely rigid
- Necessarily involves z-dependent flows: thermal wind
- Markowitz cannot be explained by gravitational torques

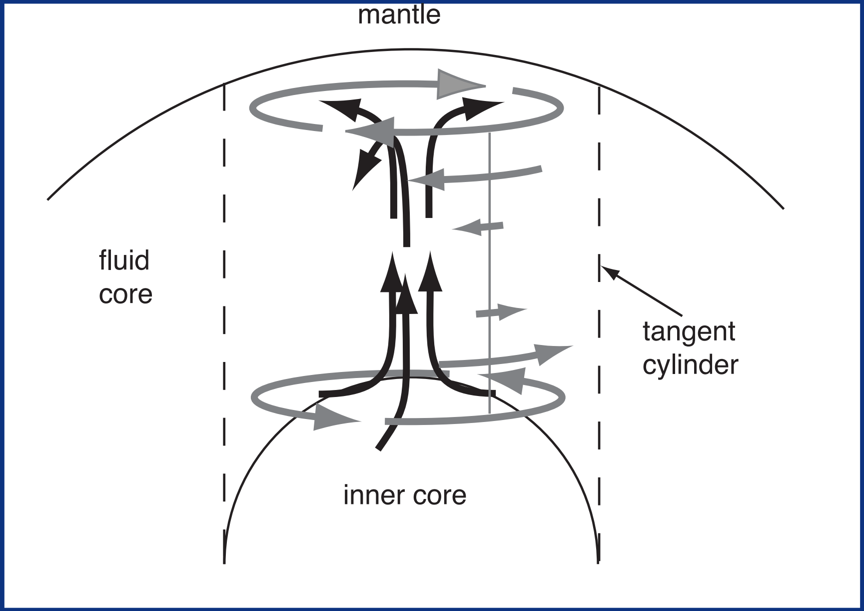
Equatorial torque from electromagnetic coupling at ICB

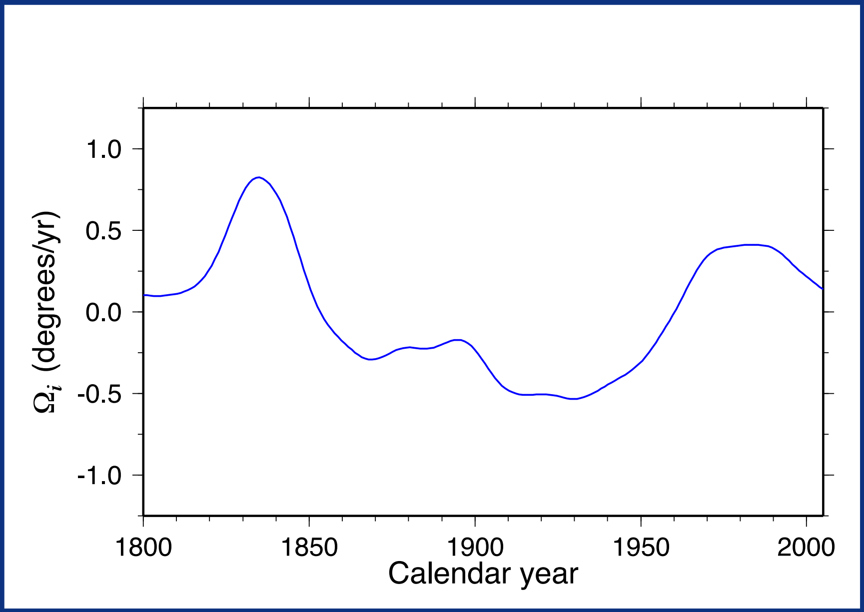
- Electromagnetic torque on inner core from thermal wind flow



Equatorial torque from electromagnetic coupling at ICB

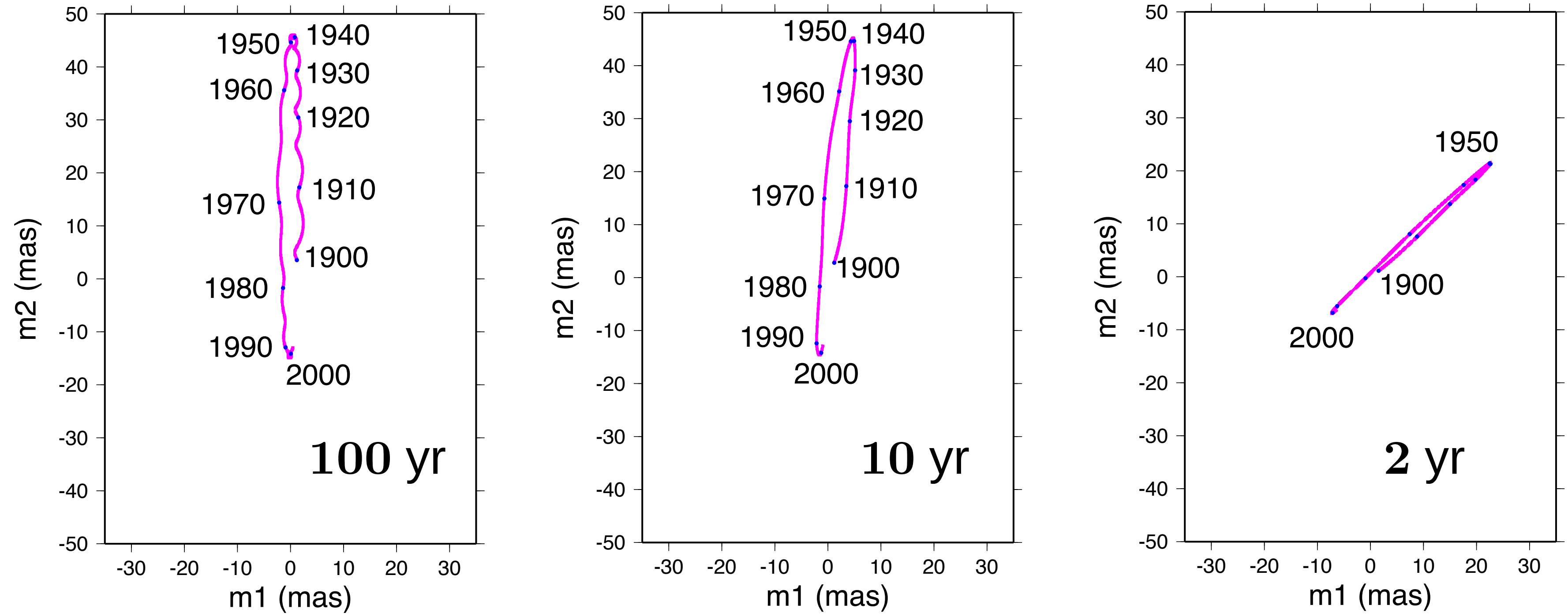
- assume changes in v_ϕ at CMB correspond to changes in v_θ at ICB



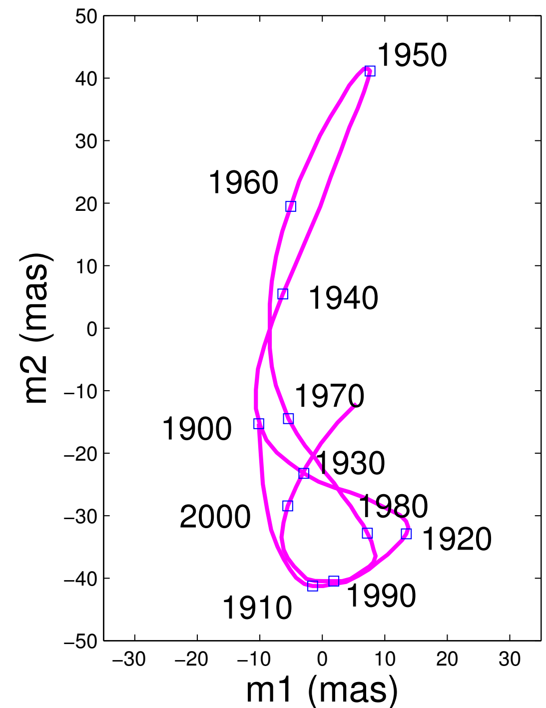


- assume B_r at ICB is a dipolar, with an amplitude of 7 mT, inclined at 25°
- integrate evolution of polar motion

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

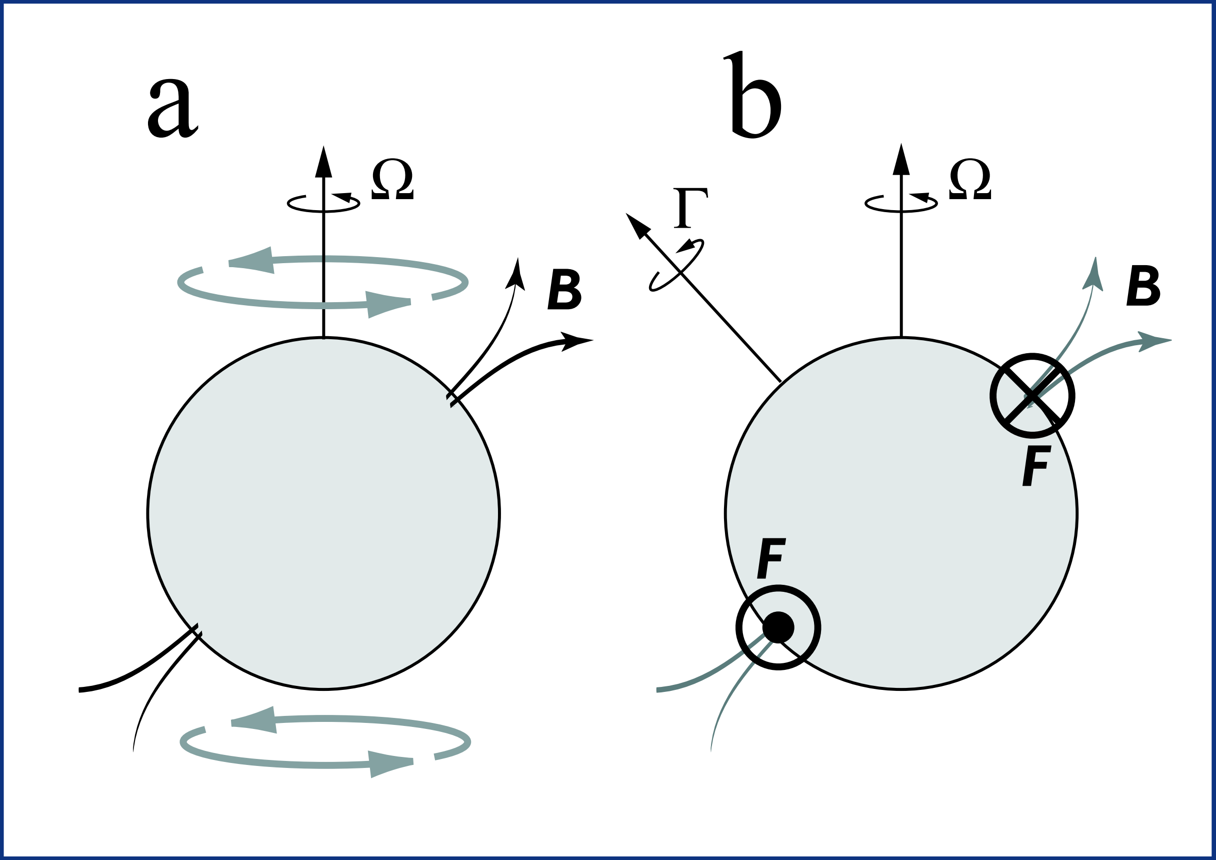
- Consequently, we can use this fit to constrain:
  - Magnetic field near the ICB
  - Viscous relaxation timescale of the inner core
  - convective flows inside the tangent cylinder

- Can we detect a tilt of the inner core in surface gravity field data?

Full Screen

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

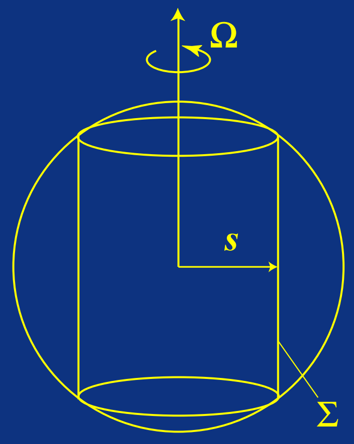
$$\rho\left(\frac{\partial v}{\partial t}+v\cdot\nabla v+\ 2\Omega\times v\right)=-\nabla p+\frac{1}{\mu_o}(\nabla\times B)\times B+C\hat{r}+\nu\nabla^2 v$$

- 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

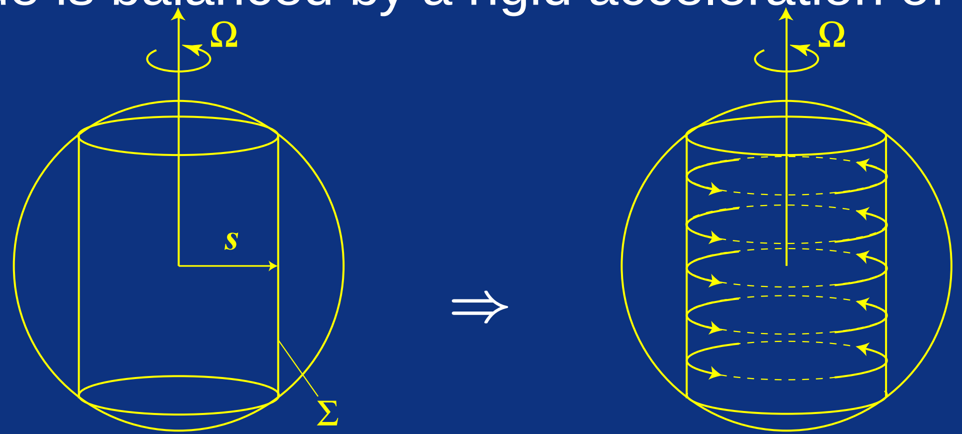


$$\int_{\Sigma}((\nabla\times B)\times B)_{\phi}\,d\Sigma=0$$

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