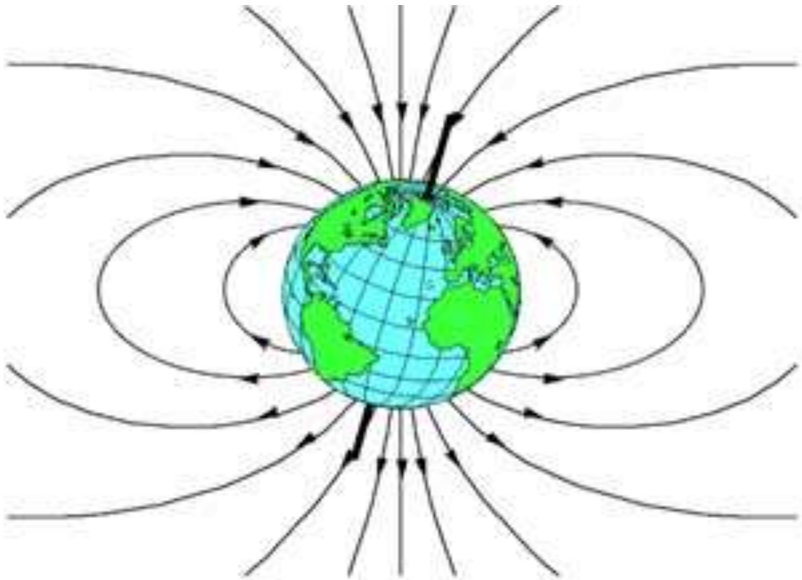
Dynamics of Earth's Interior and Geodynamo



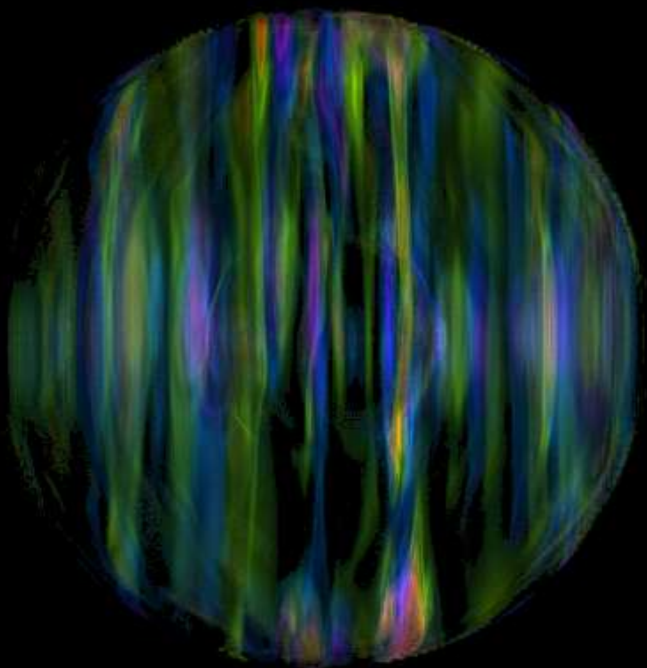
Structure and Dynamics of Earth-like Planets, Collège de France

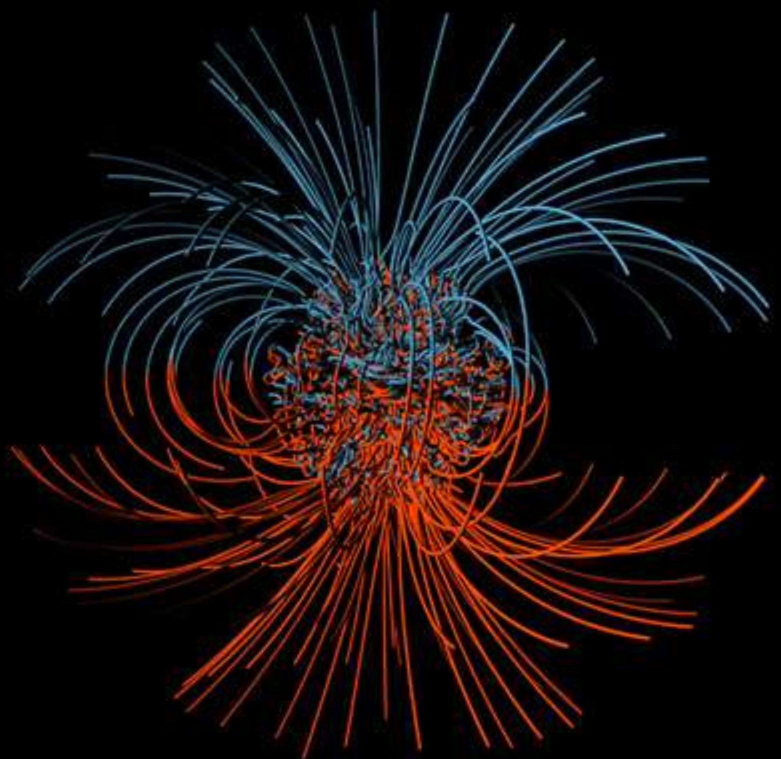
Bruce Buffett, Earth & Planetary Science, UC Berkeley

Terrestrial Planets

Gas and Ice Giants

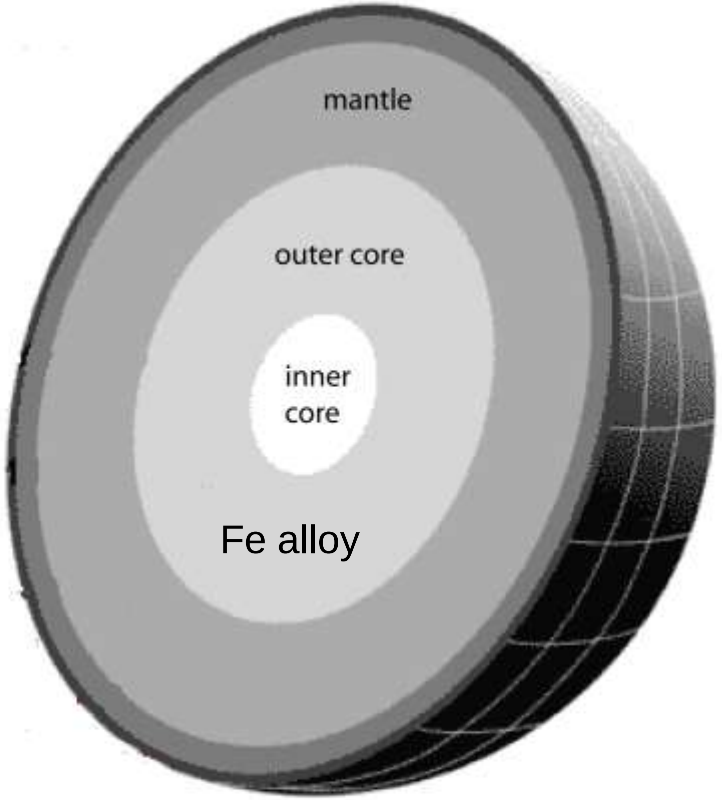
Generation Mechanism



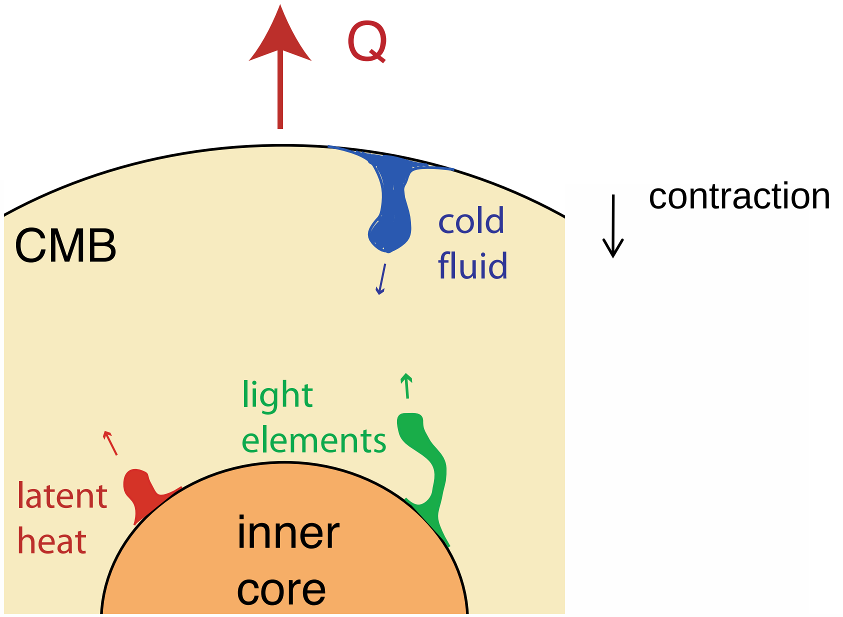


fluid motions in an electrical conductor generate the magnetic field

Internal Structure

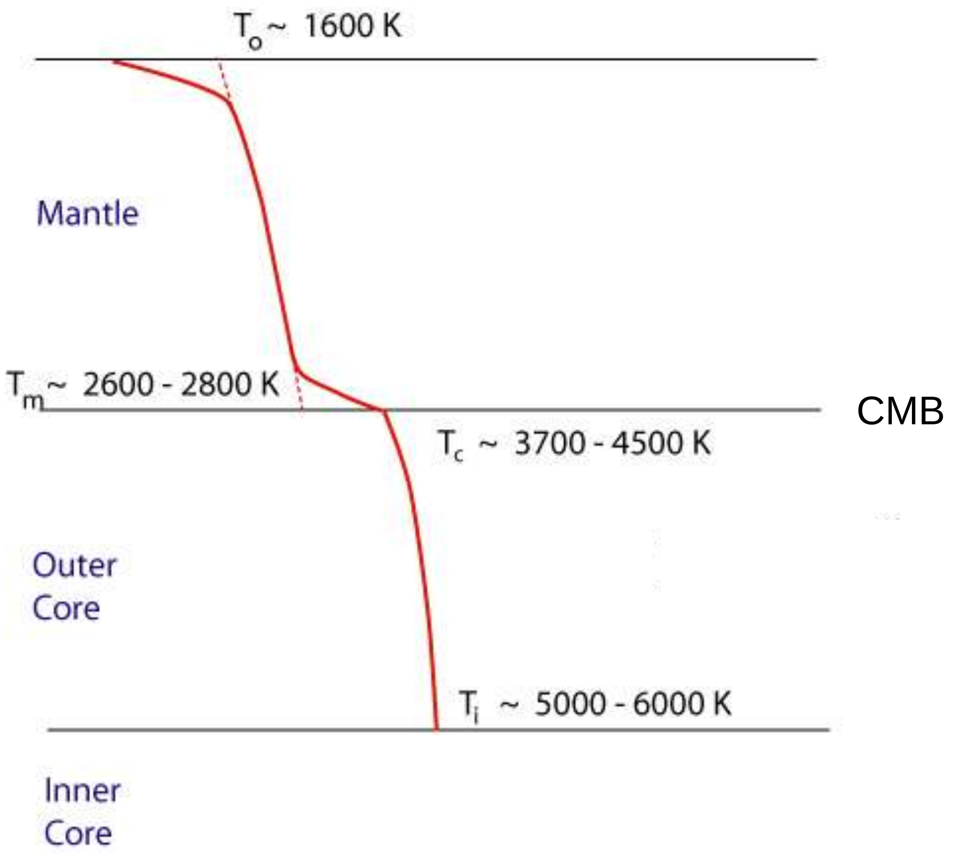


Physical Processes



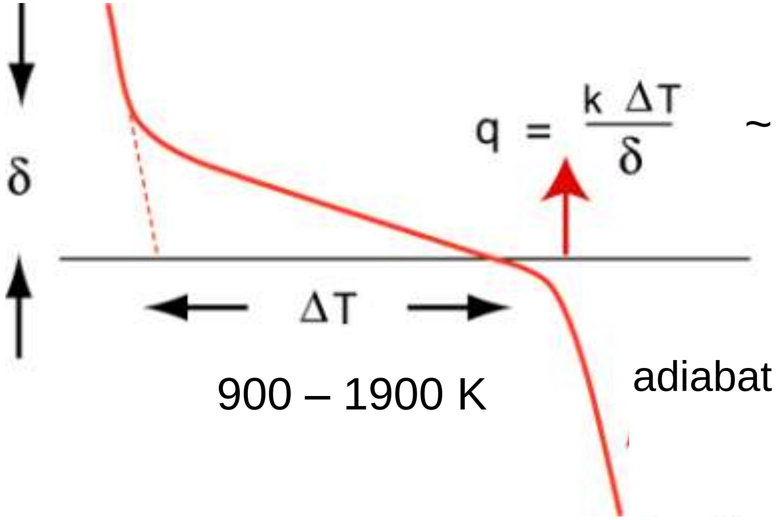
Cooling of the core is controlled by mantle convection

Present-Day Temperature



temperature drop across boundary layer: ΔT = 900 - 1900 K

Core Heat Flow



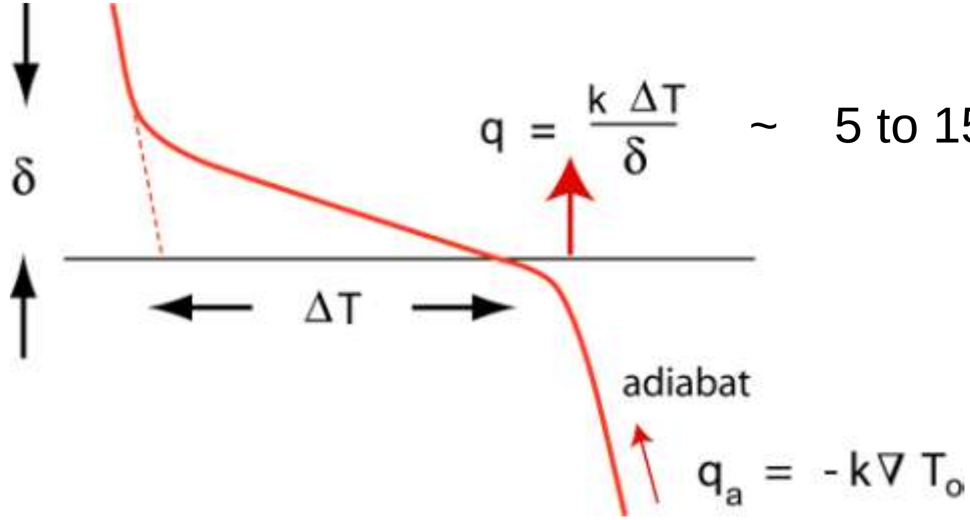
~ 5 to 15 TW

adiabat

900 – 1900 K

thermal boundary layer on the core side?

Core Heat Flow

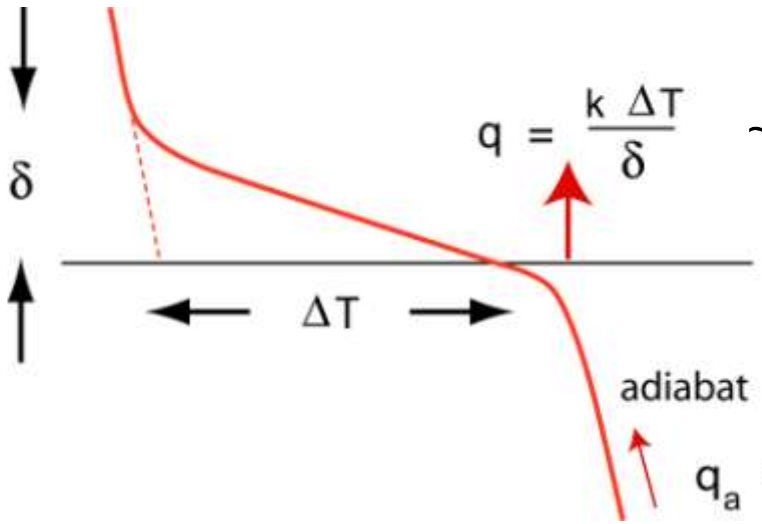


~ 5 to 15 TW

~ 5 to 8 TW

conduction along adiabat is comparable to total heat flow

Core Heat Flow



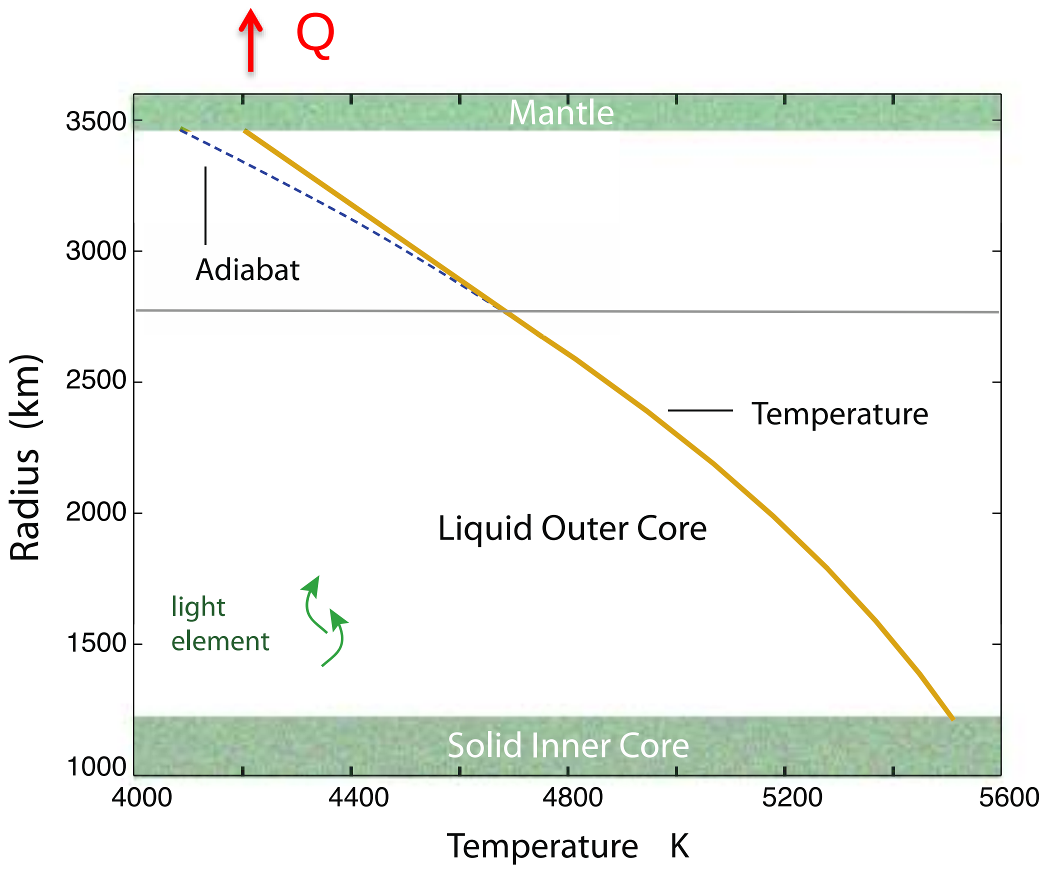
~ 5 to 15 TW

~ 5 to 8 TW

10 to 16 TW

conduction along adiabat is comparable to total heat flow

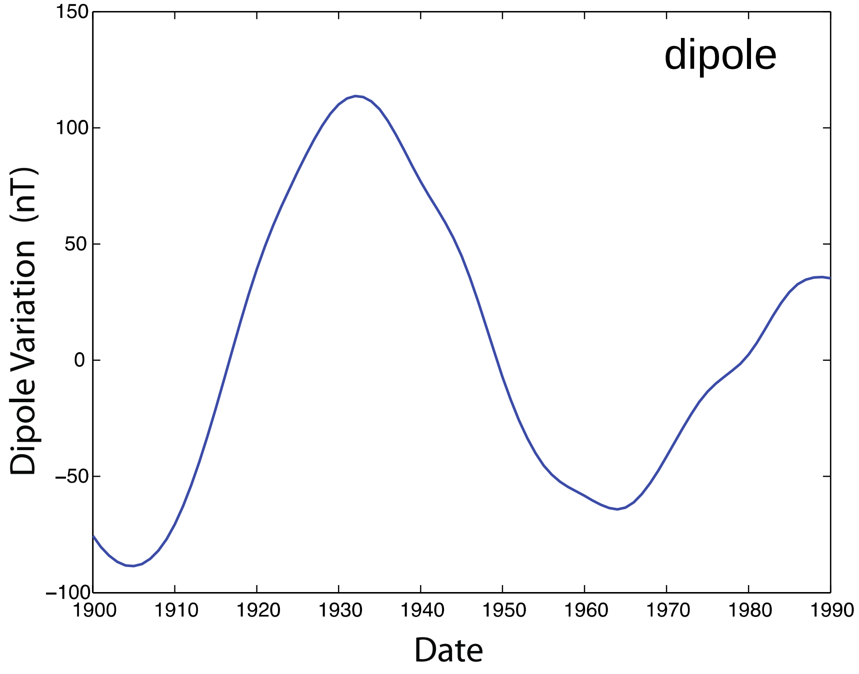
Thermal Stratification



stratification supports waves with periods of several decades

Long-Period Fluctuations

A dominant 60-year period in magnetic field

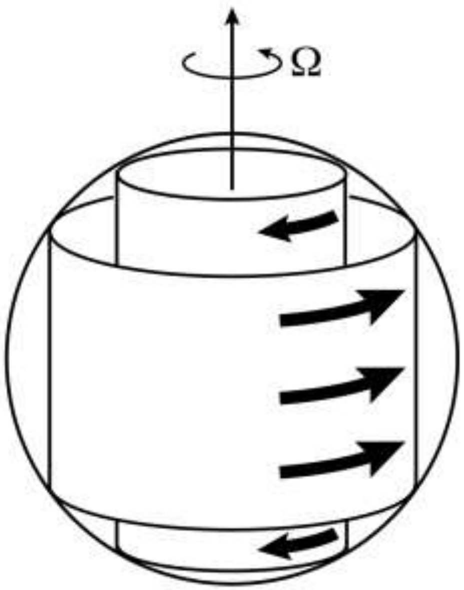


60-year signal also detected in magnetic declination

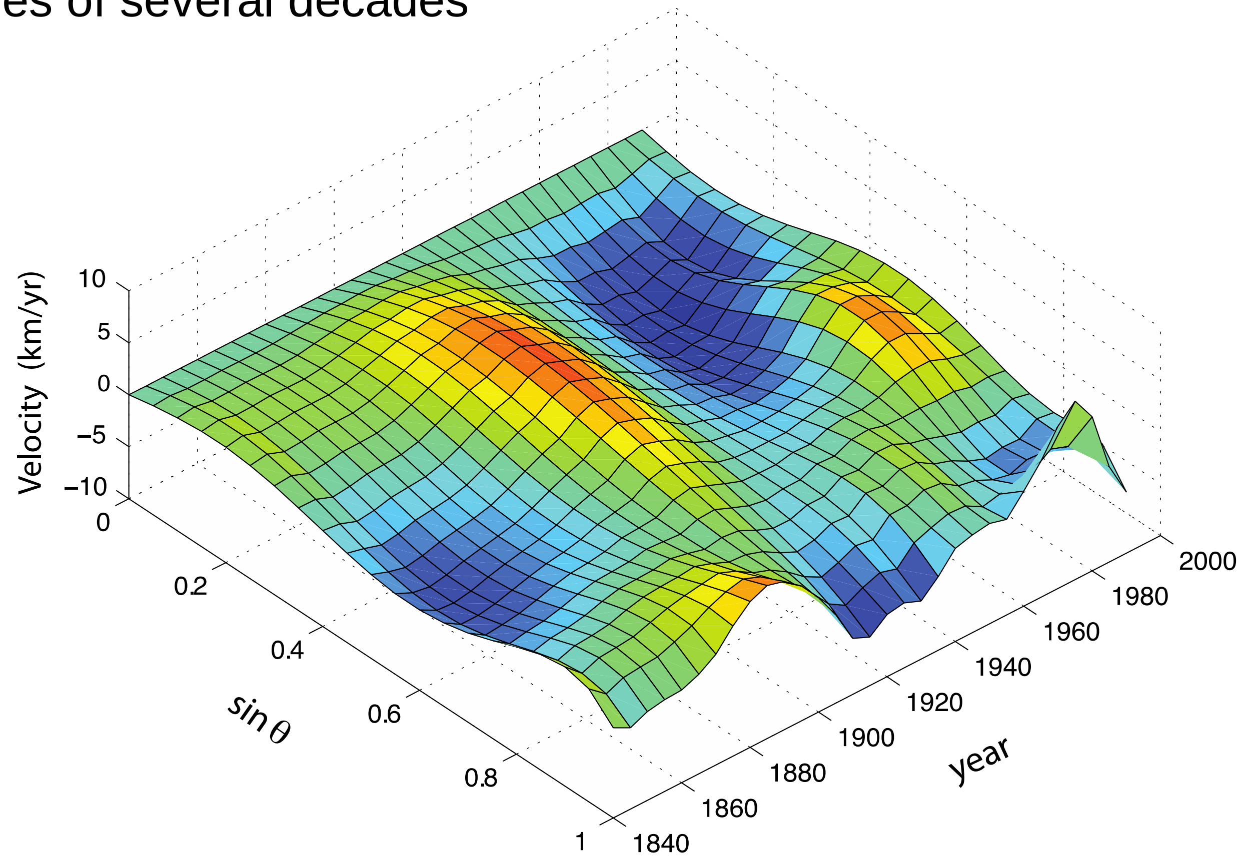
(e.g. Roberts et al. 2007)

Surface Core Flow

Fluctuations on timescales of several decades



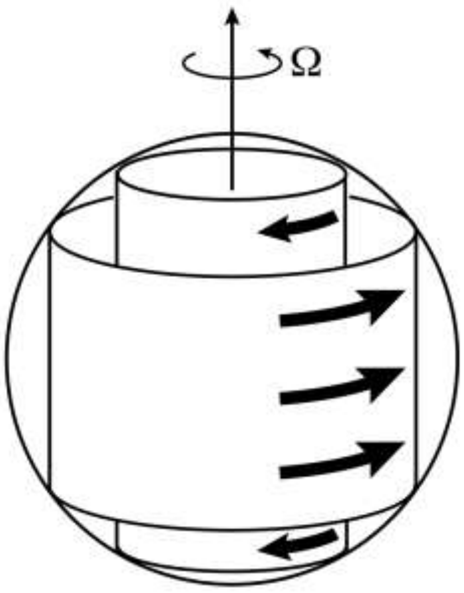
geostrophic flow



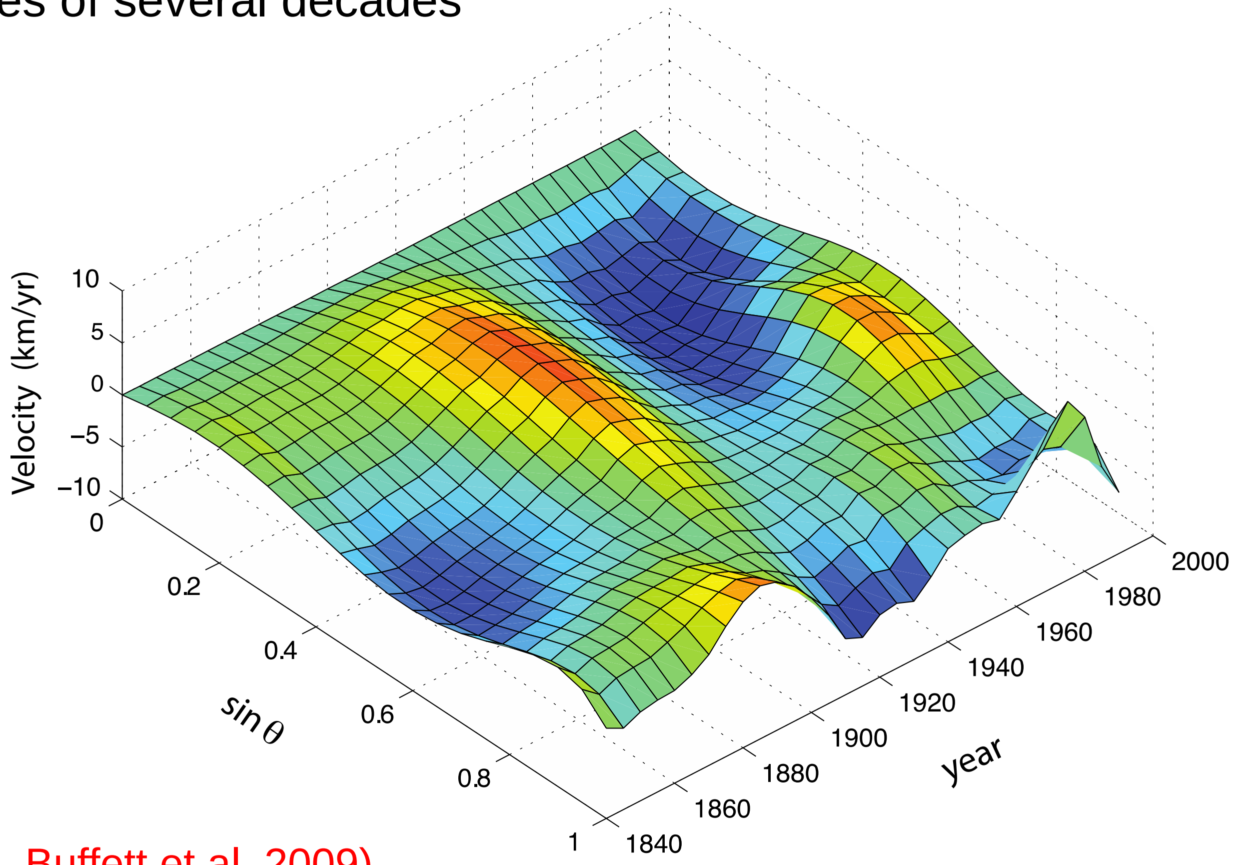
Jackson (1997)

Time-Dependent Flow

Fluctuations on timescales of several decades



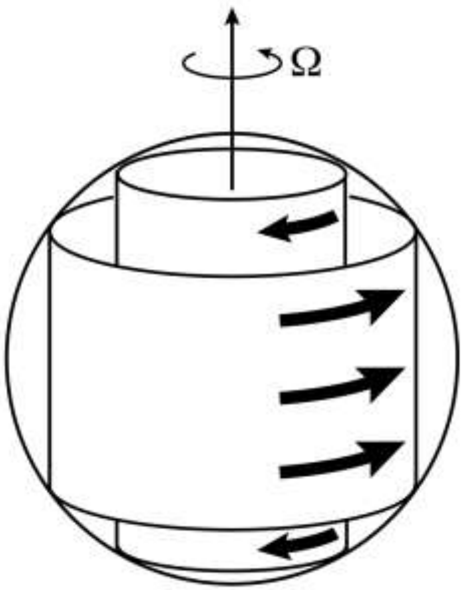
geostrophic flow



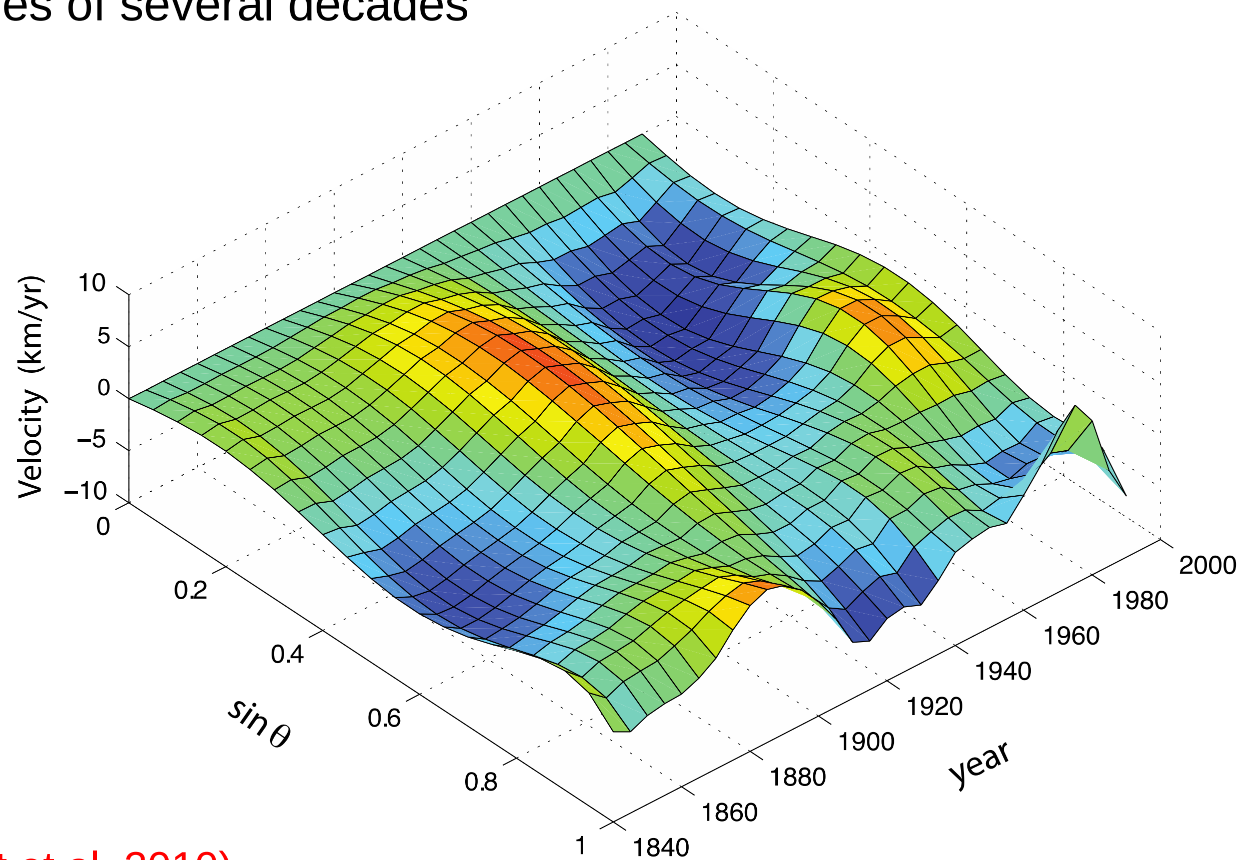
⇨ B ~ 0.3 mT (e.g. Buffett et al. 2009)

Time-Dependent Flow

Fluctuations on timescales of several decades

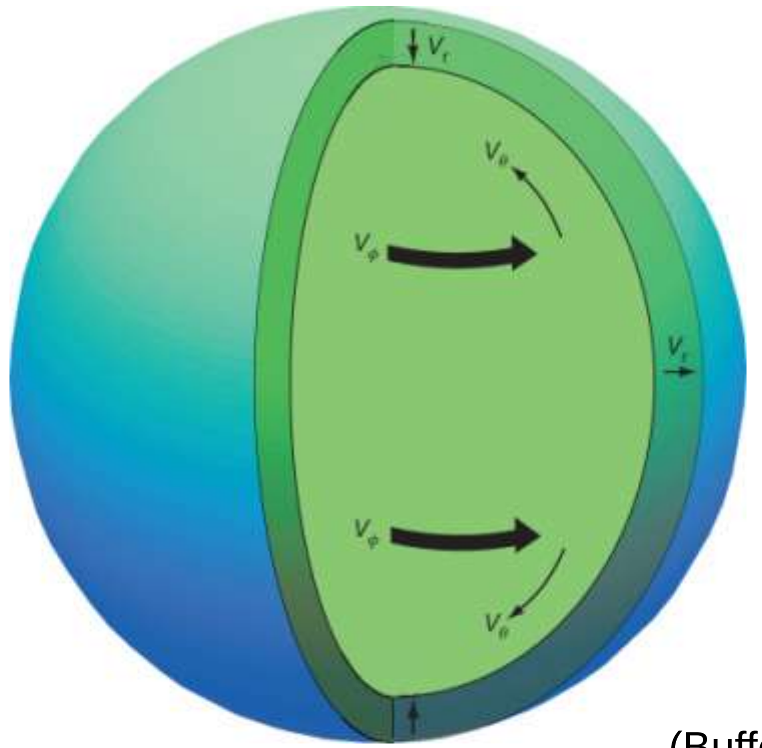


geostrophic flow



B > 2 mT (Gillet et al. 2010)

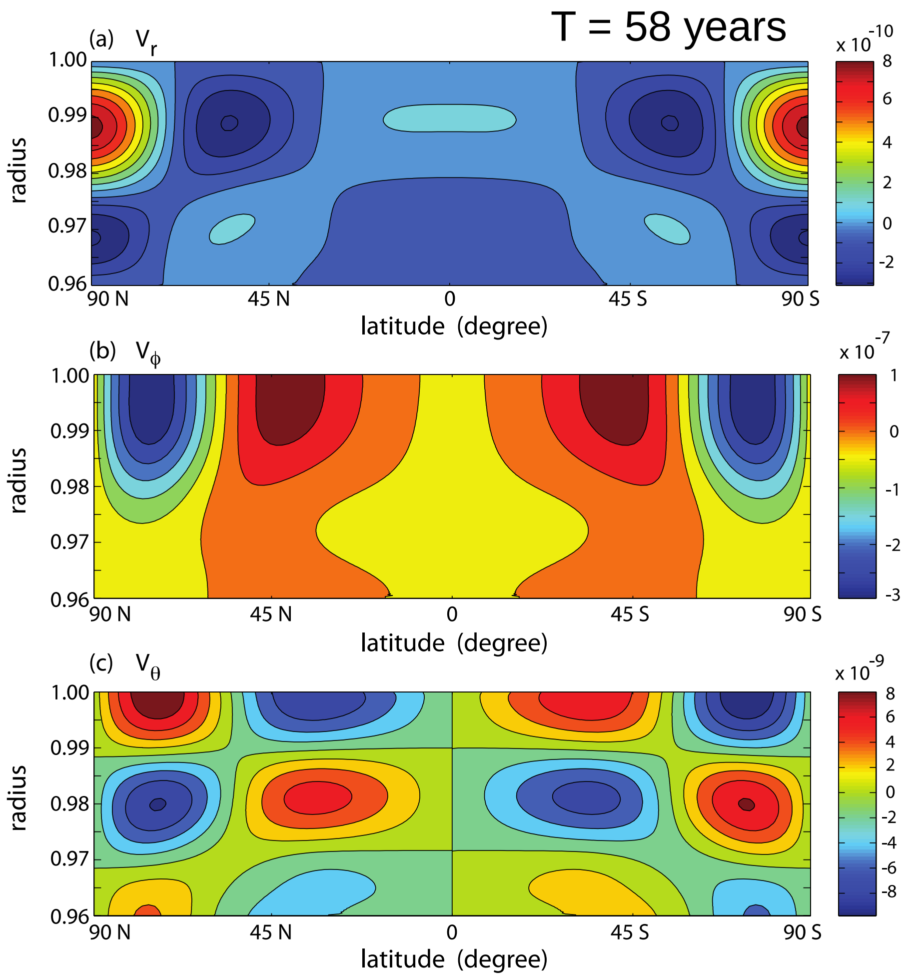
MAC Waves



(Buffett,2014)

A combination of Magnetic, Archimedes and Coriolis forces

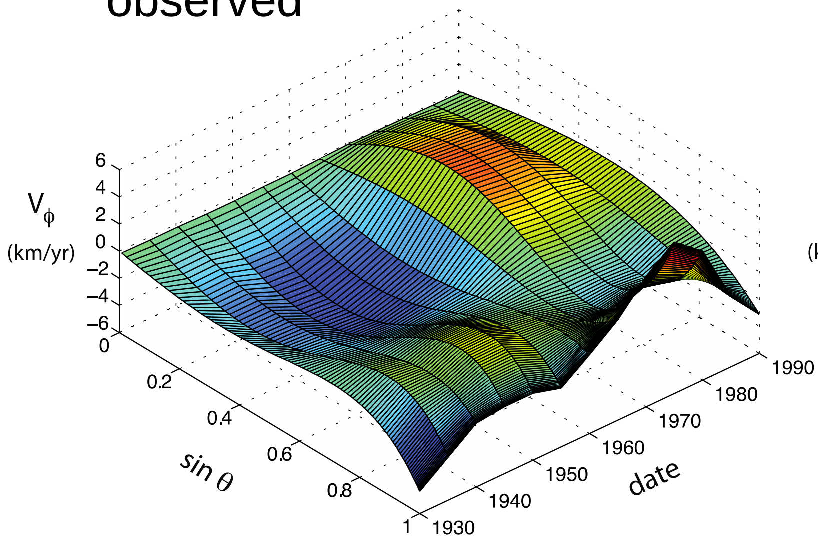
Representative Wave



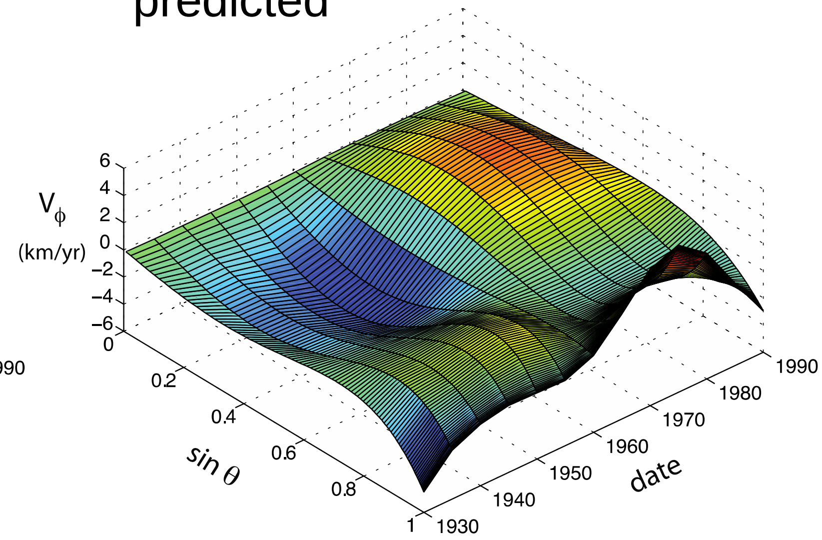
model parameters: thickness H and buoyancy frequency N

Fit to Observations

observed



predicted



Vary H and N_{max} to fit estimates of v_ϕ using linear combination of 6 modes

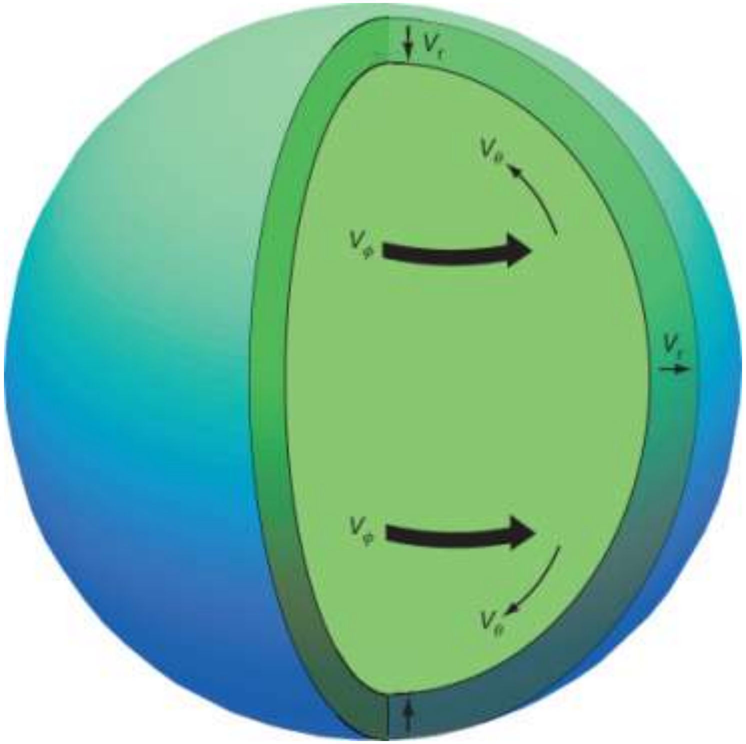
best-fitting model parameters: H ~ 140 km $N_{max} \sim \Omega$

Consequences of Zonal Flow

Simple scaling suggests

$$\frac{\mathbf{v}_\theta}{\mathbf{v}_\phi} \approx \frac{V_a^2\,\pi^2}{H^2\Omega\,\omega} \approx 0.08$$

where $V_a = B_r/\sqrt{\mu\rho}$



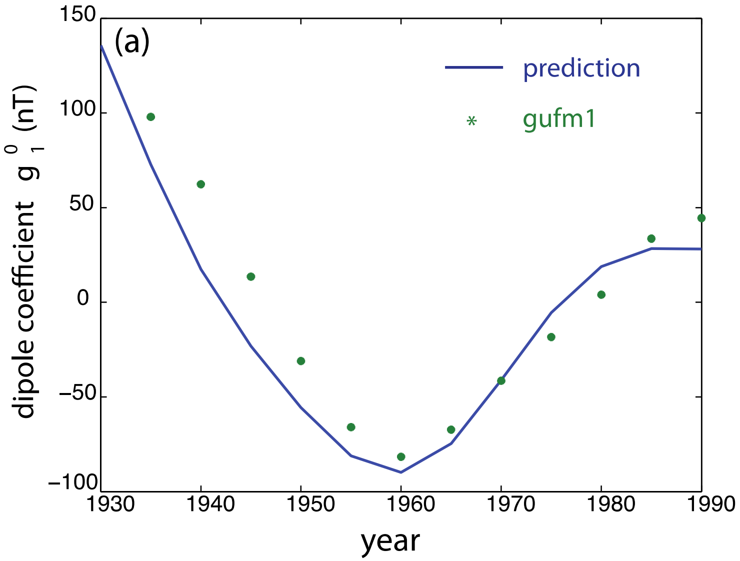
Secular Variation of Magnetic Field

$$\partial_t\, b_r = -\nabla_H \cdot (\mathbf{v} B_r)$$

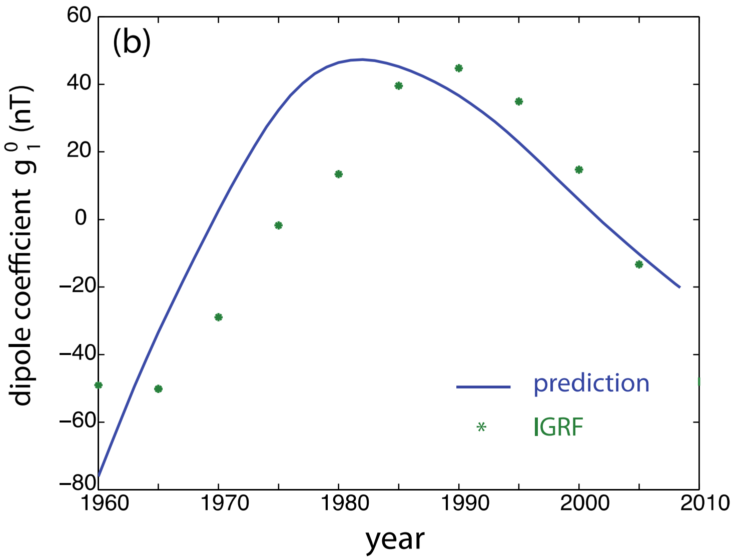
use waves to predict dipole fluctuations

Dipole Fluctuations

Fit to V_ϕ of Jackson (1997)



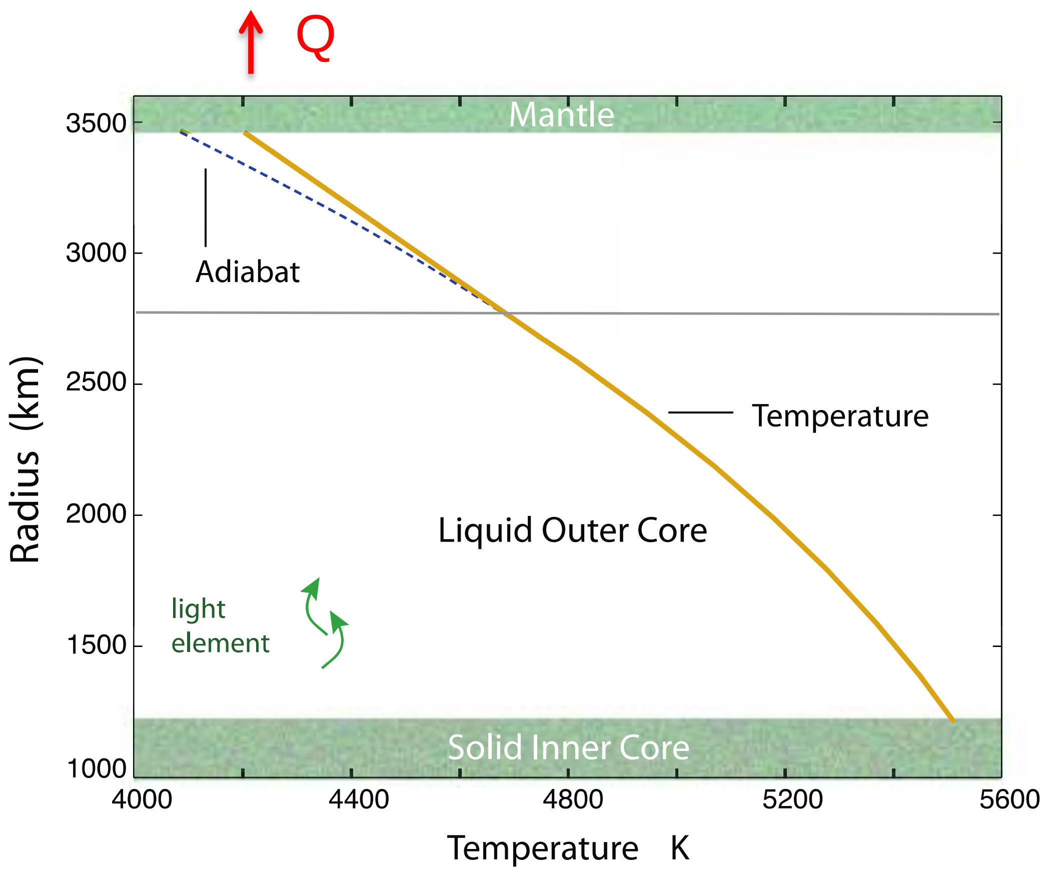
Fit to V_ϕ of Wardinski and Lesur (2013)



Good fit to flow and dipole fluctuation requires $\sigma \sim 10^6$ S m^{-1}

$$\frac{\mathbf{v}_\theta}{\mathbf{v}_\phi} \approx \frac{V_a^2 \pi^2}{H^2 \Omega \, \omega} \approx 0.08$$

Thermal Stratification



Model of Lister & Buffett (1998)

$Q = 13$ TW

$Q_a = 15$ TW

yields

$H = 140$ km

$N = 1.5\ \Omega$

(waves suggest $H = 140$ km and $N = 1.0\ \Omega$)

Conclusions

1. Energy for geodynamo depends on core cooling

    - thermal and chemical buoyancy today
    - thermal buoyancy prior to 500 Ma ?
    - existence of field at 3.4 Ga requires plate tectonics?

2. Field variations provide important constraints on dynamics

    - evidence for MAC waves at top of core
    - mantle heat flow is approximately Q = 13 TW
    - higher Q is required to sustain field before 500 Ma

Conclusions

3. Wave motion offers a new probe of core dynamics

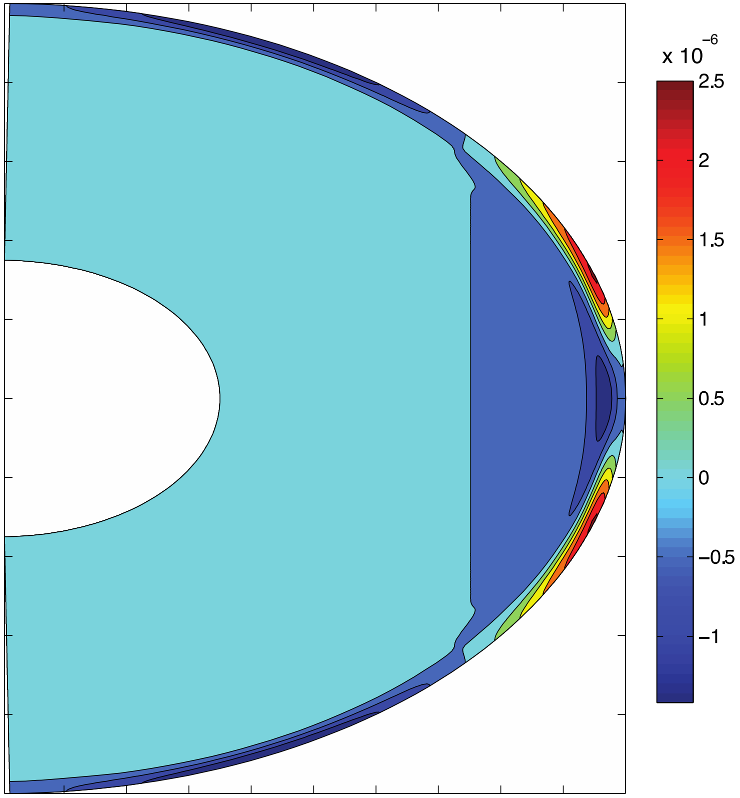
   - non-zonal modes contribute to field variations

   - how are the modes excited ?

   - coupling to deeper flow required to explain LOD

Flow in Interior

Azimuthal velocity v_ϕ



wave motion in stratified layer couples to geostrophic flow in interior