Planetary dynamos: Dipole-multipole transition and dipole reversals

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The geodynamo

- Thermal/compositional convection in liquid outer iron core
- Electromagnetic induction by motion through the existing magnetic field sets up electrical current
- Currents produce magnetic field as needed for induction

⇒ Selfsustained dynamo
Dipole reversals

A few reversals per million years

Stochastic (vs. periodic at Sun)

Low magnetic field strength during reversal (but non-zero)

Field during reversal dominated by multipole components
Field morphology

Earth, Mercury, Jupiter and Saturn have dipole-dominated magnetic fields.

Uranus and Neptune have multipolar fields.
Outline of geodynamo models

Solve equations of thermal / compositional convection and magnetic induction in a rotating and electrically conducting spherical shell

😊 Direct numerical simulation of fundamental equations of magnetohydrodynamics

😊 Some parameters not Earth-like
Governing equations

\[ \frac{\partial u}{\partial t} + u \cdot \nabla u + 2e_z \times u + \nabla P = \nabla^2 u + \frac{Ra^*}{r_o} T + (\nabla \times B) \times B \]

\[ \frac{\partial T}{\partial t} + u \cdot \nabla T = \frac{E}{Pr} \nabla^2 T \]

\[ \frac{\partial B}{\partial t} + u \cdot \nabla B = B \cdot \nabla u + \frac{E}{Pm} \nabla^2 B \]

- Inertia
- Coriolis
- Viscosity
- Buoyancy
- Lorentz

\[ \nabla \cdot u = 0 \]
\[ \nabla \cdot B = 0 \]
Magnetic field morphology

\[ \frac{a}{Ra_c} = 114 \quad E = 10^{-5} \quad Pm = 0.8 \]

\[ \frac{Ra}{Ra_c} = 161 \quad E = 10^{-5} \quad Pm = 0.5 \]

\[ Rm = 914 \quad Ro_\ell = 0.12 \]

\[ Rm = 917 \quad Ro_\ell = 0.21 \]

Earth

Dipole

Multipolar dynamo
Selection of dynamo regime

Ratio inertia / Coriolis measured by Rossby number

$$\text{Ro}_\ell = \frac{U}{\Omega \ell}$$

critical point $$\text{Ro}_\ell \approx 0.12$$

reversing dynamos near transition point
Simulated reversals

\[ \sim 2.5 \text{ million years} \]
Geomagnetic reversal

Magnetic field of dynamo model at Earth’s surface
Generation of dipole field

\( \Omega \)-effect

poloidal field

\( \alpha \)-effect

toroidal field

Helical flow elements
Differential rotation

Reynolds stress: inverse inertial cascade from small eddies

Thermal wind: Coriolis force acting on flow driven by temperature variation with latitude

Zonal flow change passive reaction to different magnetic field? or Different zonal flow pattern causes breakdown of dipole field?
Forced zonal flow

- Manipulate zonal flow in dynamo by imposing velocity condition on outer boundary
- Shape of forced flow similar to that driven by Reynolds stress.
By forcing geostrophic differential rotation, an intrinsically dipolar dynamo can be turned multipolar.

Undoing the differential rotation by inverse forcing, an intrinsically multipolar dynamo turns dipolar.
Change in Omega effect

\[ \partial B_\varphi / \partial t = s B_{\text{pol}} \cdot \nabla (U_\varphi / s) + \]

Omega-effect in forced dynamo (while field is still dipolar)

versus

Omega - effect in free dynamo

Geostrophic differential rotation: Omega-effect counterproductive for generating toroidal flux tubes
Forcing of reversing synamo

Reversal frequency increased by forcing differential rotation

Reversal frequency decreased by suppressing differential rotation
Dynamo models suggest reversals are sensitive to small change in parameters

Is there evidence from geomagnetic field that this is so?

Change of reversal frequency on 100 Mill.year time scale

Possibly change in core heat flow by changes in mantle
In other dynamo models, bistability of dipolar and multipolar solutions found over significant parameter range. For such dynamos, rapid dipole reversals by an excursion into the multipolar mode would not be possible.
Conclusions

- Geodynamo probably close to phase transition between strongly dipolar and multipolar regime
- Dipole reversals due to instability of dipolar dynamo. Fluctuations lead to brief lapse into multipolar phase.
- Phase transition occurs where inertial force relative to Coriolis force reach a critical limit
- Inverse inertial cascade transfers energy from small eddies to geostrophic differential rotation
- Anti-$\Omega$-effect eliminates toroidal flux tubes of dipolar dynamo
- Open question: is Earth by chance near critical point, or is it self-organized criticality?
Hazard for satellites

- Geomagnetic field particularly weak over South Atlantic and South America (South Atlantic Anomaly)
- Disruption of electronics on satellites by MeV protons
- Field intensity in SAA anomaly decreasing by 2% in 10 years