Extrapolating from the Geodynamo to Exodynamos

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Motivation
• How do we make predictions for terrestrial exodynamos?
• Can we extrapolate from the geodynamo?
• What do we know about the geodynamo through time?

Outline
1. Magnetic scaling laws
2. Dynamo regimes
3. Paleomagnetic observations
4. Numerical geodynamo evolution
5. Mantle effects
Cyclotron Radio Emission Spectrum

\[ \Phi \text{ Scaling law (Farrell, 1999)} \]

Driscoll+Olson 2011
Numerical Limitations

Optimistically, $E=10^{-9}$ with 54k processors requires 35.6 years to compute $t_{mag}$ (Davies+ 2010)
Dynamic Similarity

- “Earth-like” dynamo criteria (Christensen+ 2010): AD/NAD, O/E, Z/NZ, Flux concentration (FCF)
- Derived from 0-7 kyr time average
- But ... is modern field typical?
- Look at paleomagnetic record

How to extrapolate?
Magnetic Scaling Laws

Dipole Moment Scaling Law\(^1\)
\[
\mathcal{M} = 4\pi R_c^3 \gamma_{dip} \sqrt{\frac{\rho_c}{2\mu_0}} \left( D_c F_c \right)^{1/3}
\]

Buoyancy Flux
\[
F_c = \frac{\alpha_c g_c}{\rho_c c_c} q_{\text{conv}} + g_i \frac{\Delta \rho}{\rho_c} \left( \frac{R_i}{R_c} \right)^2 \dot{R}_i
\]

Convective Heat Flux
\[
q_{c, \text{conv}} = q_{\text{cmb}} - q_{\text{ad}}
\]

But... all dipolar!
At high \( F_c \) expect:
\[
\gamma_{dip} \propto F_c^{-\alpha}
\]

Is a dipolar dynamo expected?

1 Olson and Christensen (2006)
2 Christensen et al. (2009)
Magnetic Regimes

Maximum dipole intensity & Earth-like field structure & Magnetic field reversals!

Olson and Christensen (2006)

Driscoll+Olson (2009)
Dynamo Regimes

Dynamo regimes:
- Weak-field: steady/oscillating
- Strong-field: chaotic
- Dipolar
- Multipolar

Has the geodynamo moved through regimes over time?

Driscoll and Olson, 2009
Geodynamo Timescales

- Viscous mantle ($\tau \approx 100$ Myr) controls core cooling rate
- Dipole decay time scale $\sim 50$ kyr
- Geodynamo contains both mantle (imposed) and core (intrinsic) timescales
- Maintained for 3-4 Gyr!
- Thousands of polarity reversals

geomagnetism.org
Probing Geodynamo Evolution:

1. Magnetic field intensity ("paleointensity")

![Graph showing paleointensity over time](image)

- Brunhes
- Jaramillo
- Matuyama
- Olduvai

Polarity:
- Normal
- Reversed


2. Morphology, reversal frequency

![Diagram showing reversal rate over time](image)

- Cretaceous Normal Superchron
- Kiaman Reverse Superchron
- No data
- Moyero Reverse Superchron
Paleointensity Record

- Oldest 4.2 Ga! (possibly older than plate tectonics)
- Up to > 3x stronger than modern field
- Trend ~ flat?
- Inner core nucleation effects?

Is the mean paleointensity stationary??
PINT Paleointensity

Biggin et al. 2015, 2009

Proterozoic (>1 Ga): 268
Neoproterozoic: 10
Phanerozoic: 3664

- Highest quality data
- 100 Myr bins
- Size proportional to N
- Error bar = stdev

Is there a signature of inner core nucleation?
Driving the Geodynamo

1. Thermal convection:
   - CMB heat flow is super-adiabatic ($Q_{cmb} > Q_{ad}$)
   - CMB heat flow determined by lower mantle
   - High Fe thermal conductivity implies $Q_{ad} \sim 14$ TW

2. Compositional convection:
   - Phase change (e.g. inner core growth) releases buoyancy (latent heat + light elements)
   - Requires cooling and must overcome any stratification

3. Driving Forces
   a. Top driven: secular cooling, favors small scales
   b. Bottom driven: inner core growth, favors large scales
1D Thermal Evolution

- Invoke 3.5 TW radioactivity in core
- Core is thermally convective for 4.5 Gyr
- Inner core ~650 Myr old

New problems:
1. Observations inconsistent with model prediction
2. Magnetic scaling assumes dipolar dominant field

Thermal Evolution

Magnetic Scaling Prediction

\[ M \propto F^{1/3} \]

Dipole moment scaling
Evolving Numerical Dynamos

- Every 80 Myr, compute numerical dynamo for 1-2 Myr
- Energetics from thermal history model
- 500 Myr long regimes

Paleointensity

- Highest quality data
- 100 Myr bins
- Gap 0.5-1.0 Ga
Equatorial co-density (temperature+light element)

Surface Magnetic Field (time ave)

680 Ma Pre-IC

Strong Multipolar

580 Ma Post-ICN

Strong Dipolar

Weak Non-axial

Strong Multipolar

0 Ma Present

Strong

Strong Dipolar

Weak

Strong Dipolar

Strong
680 Ga, Prior to ICN

Present-day

$B_r^{\text{SUR}}$
Mantle Control

How is core affected by

1. Volcanic cooling of mantle
2. Radioactivity
3. Tidal heating in mantle
For mobile lid mantle

- Mobile lid little dependence on volcanic cooling

Driscoll+Bercovici (2014)
Stagnant lid mantle (e.g. Venus)

Driscoll+Bercovici (2014)
Stagnant Lid, Radioactive Core

Driscoll+Bercovici (2014)
Tidal heating in mantle:
How long is inner edge of HZ tidally dominated?

- Tidal dissipation is stronger function of orbital distance ($\alpha a^{-15/2}$) than stellar mass ($\alpha M_*^{+5/2}$)
- So inner edge around low mass stars experiences stronger tides, fast circularization
- Tides are stronger function of $M_{\text{star}}$ and $a$ than circularization rate
- Tides dominate for 0.15-0.4 $M_{\odot}$ and $e>0.1$!
Terrestrial Exodynamo Speculation

Multiple regimes
Time variable

Magnetic Energy

Energy Flux

Dipolar dominant
Summary

1. Scaling laws predict dipole dominated dynamos depend only on energy flux
2. Multiple *dynamo regimes* exist around dipolar state
3. Geodynamo may have passed through *weak-field* state
4. Long-lived dynamo may rely on *compositional convection*
5. *Volcanic heat loss* can power a core dynamo beneath a stagnant lid
6. *Tidal heating* in mantle can stymie dynamos around 0.3 \(M_s\) stars
7. Expect *exodynamos* to occupy a myriad of dynamo states, difficult to infer tectonics