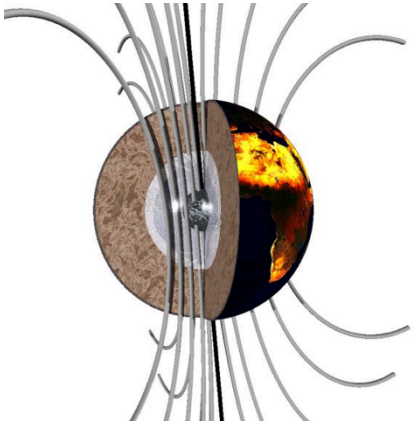
Modeling Planetary Evolution: Perspectives on 1D and 3D Dynamo Predictions



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CIG Workshop 6-22-16

Big Questions

- What do simple thermal evolution models tell us?
- What important physics are necessary/lacking?
- How do magnetic scalings compare to evolving 3D dynamos?
- What geophysical processes are relevant for exoplanets?

Outline

I. Motivation, observations

II. 1D Models: Thermal history, Earth vs Venus

III. 3D Models: Evolving dynamo models ***NEW***, inner core nucleation

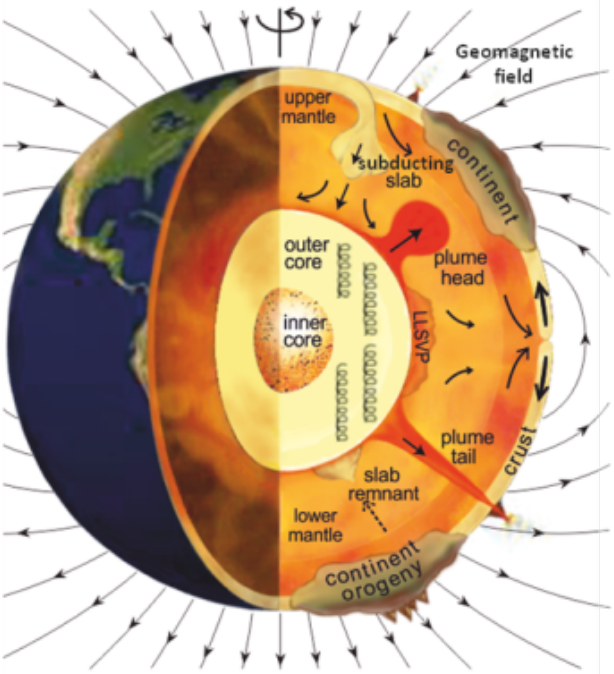
IV. Exoplanets: Exodynamo detectability, tidal dissipation

Why care about Earth's thermal history?

1. Earth as a heat engine: convert internal heat (formation, radiogenic) to useful work (mantle convection, tectonics, volcanoes, earthquakes, magnetic field, …)

2. Earth is unique (plate tectonics, magnetic field, liquid water, life ...)

3. Simplicity*: T(r,t)

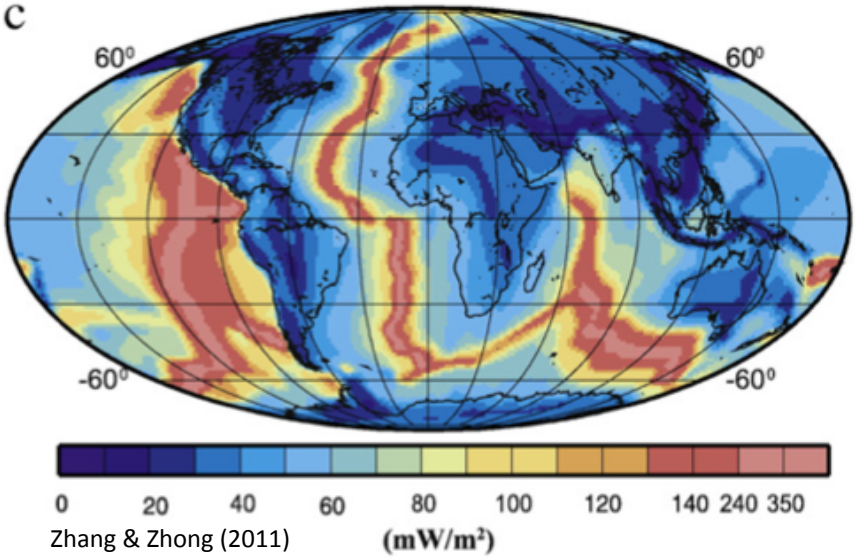


Geomagnetism.org

*Or ignorantly

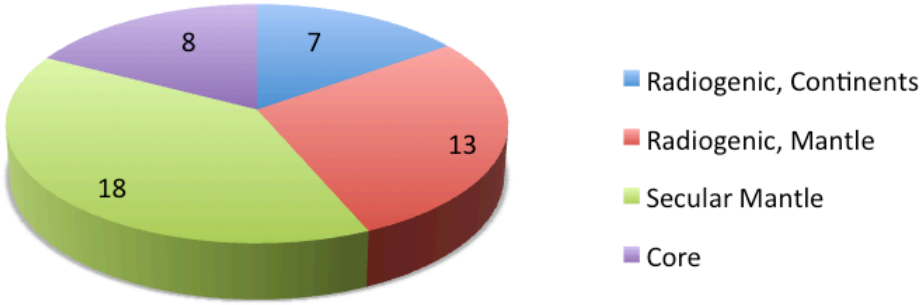
Earth's (nominal) Heat Budget

Surface Heat Flux



Zhang & Zhong (2011)

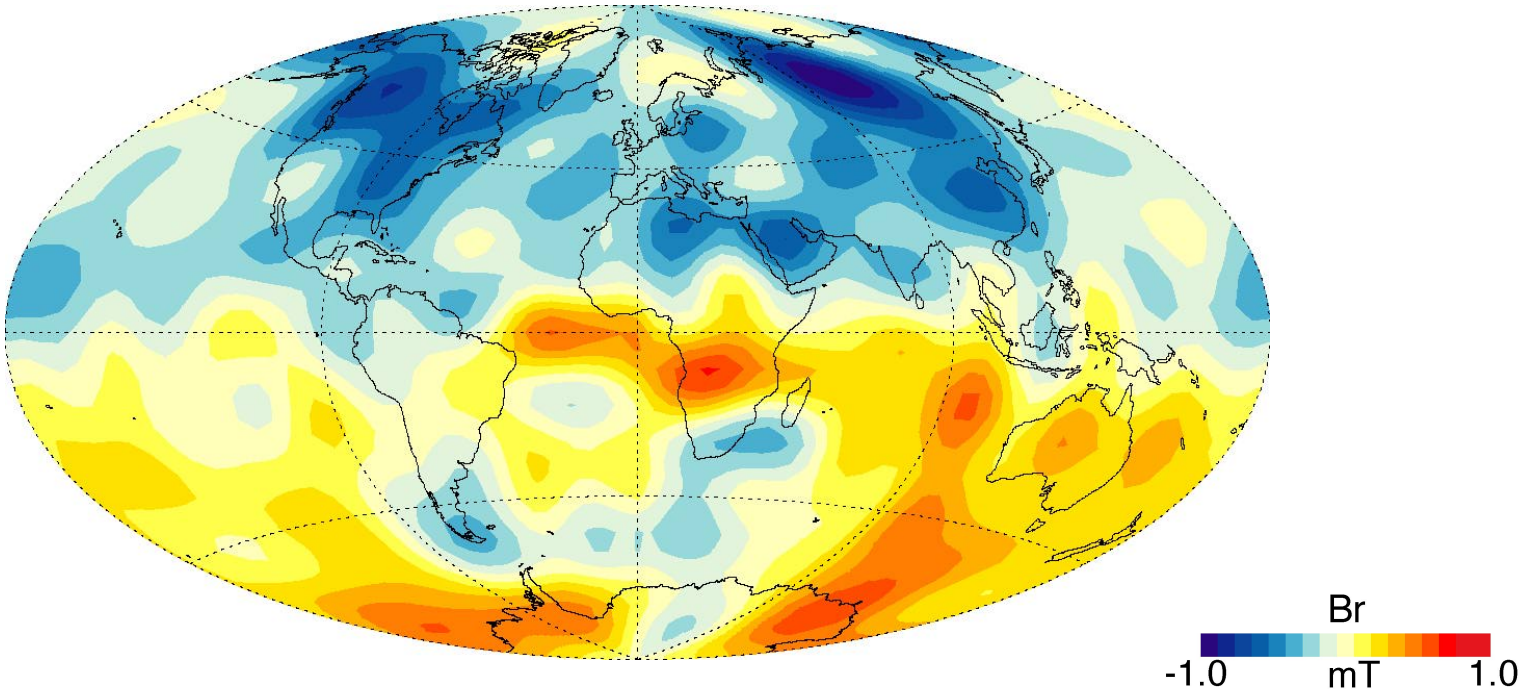
Component	Q [TW]	Fraction
Total surface	46	
Oceanic	32	70%
Continental	14	30%
Radiogenic, Continents	7	15%
Tidal	0.1	<1%
Gravitational (crust)	0.3	<1%
Convecting Mantle	39	85%
Secular, Mantle	18 ??	46%
Radiogenic, Mantle	13 ?	33%
Core	8 ?	17%
Cooling rate [K/Gyr]	~118 ??	
Urey=Rad/Conv=13/39	0.33	33%



Jaupart et al (2007)

Dynamo as Proxy

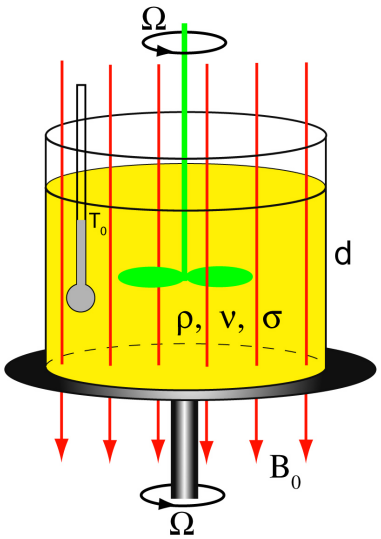
- Planetary magnetic fields rely on convection (thermal or compositional)
- Convection driven by cooling
- Dynamo provides a constraint on the cooling history of a planet
  - Evidence of geodynamo 0 to 3.4-4.2 Ga
  - Venus no dynamo today



How to make a self-sustaining fluid dynamo

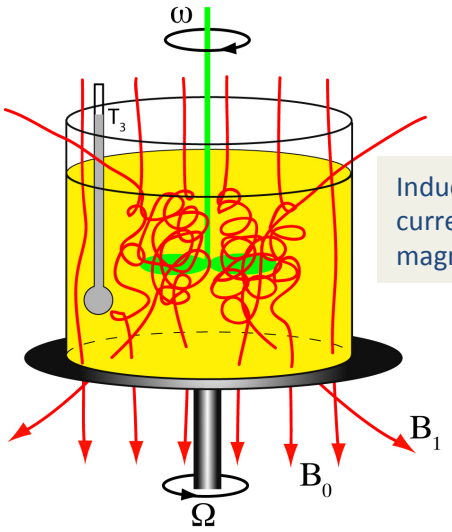
Consider a rotating tank of conducting fluid.

1. Apply external magnetic field.



Solid body rotation:
Propeller and fluid rotate with table.
No convection.

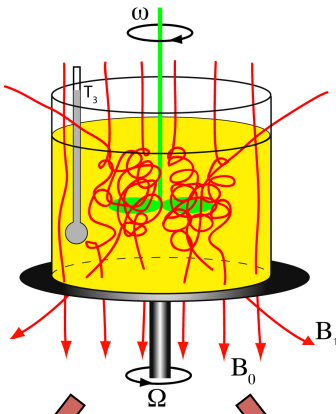
2. Stir.

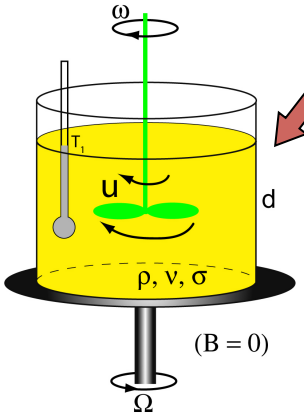


MHD:
Propellor ω driven opposite to table Ω.

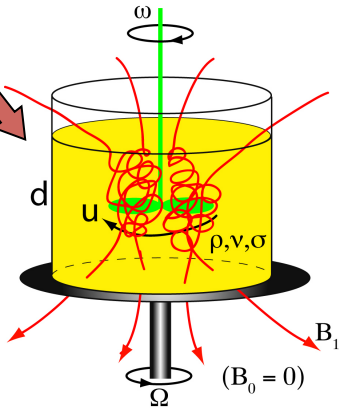
Induced electric currents & magnetic fields

3. Remove external field and wait.





Subcritical:
B decays.



Supercritical Dynamo! **B** generation balances decay.

Dynamo parameter

$$Rm = \frac{Ud}{\eta} \geq 40$$

$$B_1 \approx \sqrt{\rho\Omega/\sigma}$$

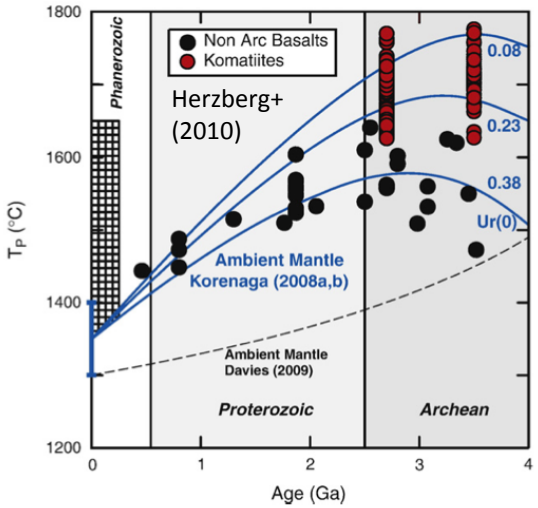
Adapted from P. Olson

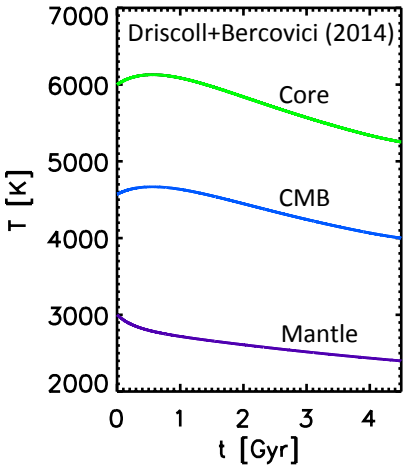
Observations

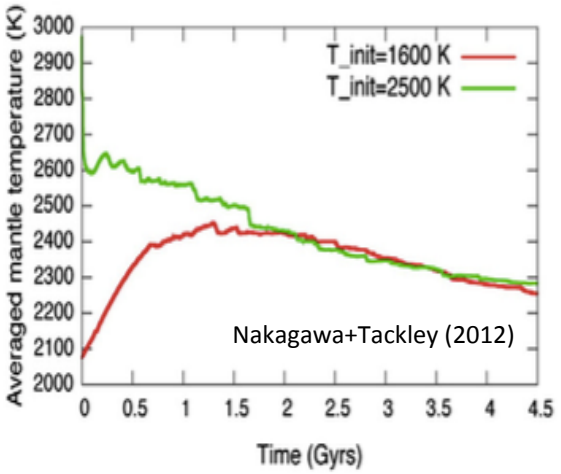
1D Model

3D Model

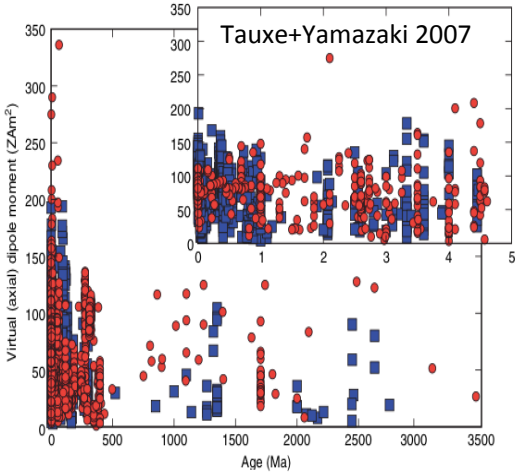
Mantle

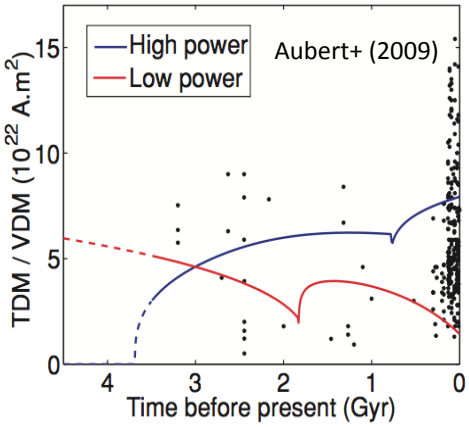


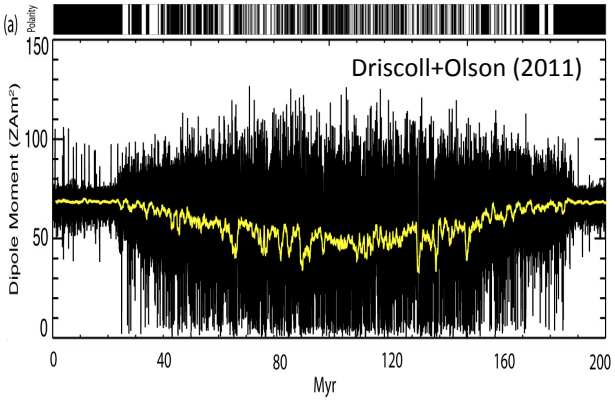




Core







Thermal History Model

Secular cooling

$$Q_{(m,c)} = -M_{(m,c)} c_{(m,c)} \dot{T}_{(m,c)}$$

Mantle

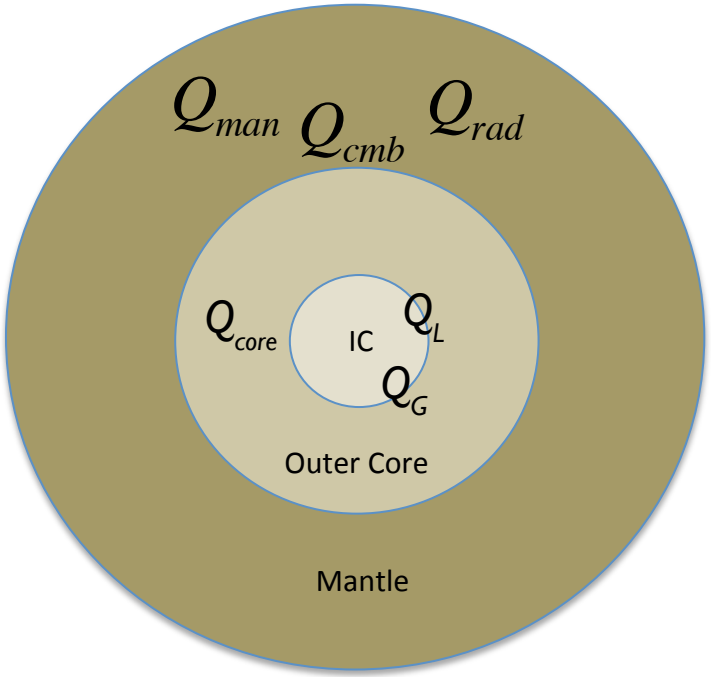
$$\dot{T}_m = \frac{Q_{cmb} + Q_{rad} - Q_{conv} - Q_{melt}}{M_m c_m}$$

Core

$$\dot{T}_c = \frac{Q_{rad,c} - Q_{cmb}}{M_c c_c - A_i \rho_i \eta_c \frac{dT_i}{dT_{cmb}} (L_{Fe} + E_G)}$$

Heat Flow

$$Q_{surf} = Q_{conv} + Q_{melt}$$



Parameterized Physics

1. Mantle and core well mixed
2. Conductive solution in thermal boundary layers
3. Anchors: T_{UM}≈1625 K, T_{ICB}≈5500 K

Thermal boundary layer conductive solution:

$$T(z) = T_s + \Delta T_{UM} \mathrm{erf}\left(\frac{\sqrt{\pi}}{2}\frac{z}{\delta_{UM}}\right)$$

Heat flow:

$$Q_{UM} = Ak\frac{dT}{dz} = Ak\frac{\Delta T_{UM}}{\delta_{UM}}$$

Critical BL depth:

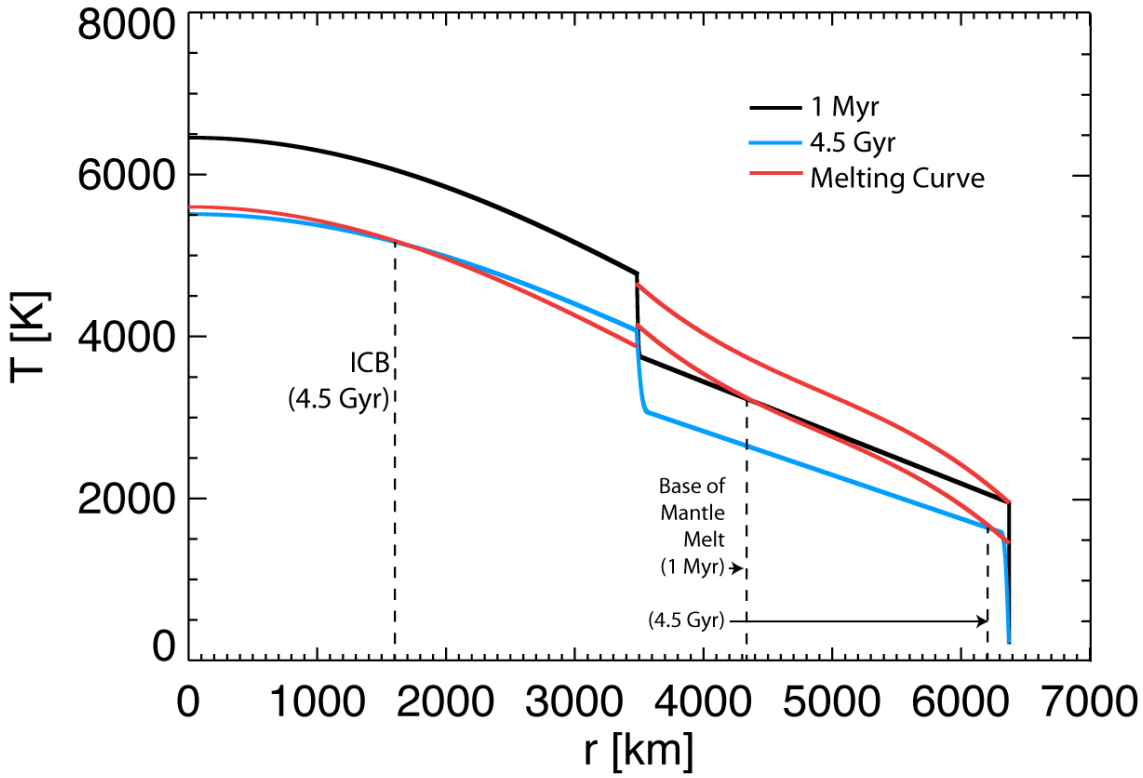
$$Ra(\delta) = Ra_{crit}$$

$$\delta_{UM} = \left(Ra_c \frac{\nu_{UM}\kappa}{\alpha g \Delta T_{UM}}\right)^{1/3}$$

Magmatic heat loss:

$$Q_{melt} \sim a_m f_{melt} \nu^{-\beta} T_m^{\beta} \Delta T_{melt}$$

Whole Planet Geotherm



Magnetic Field Scaling Law

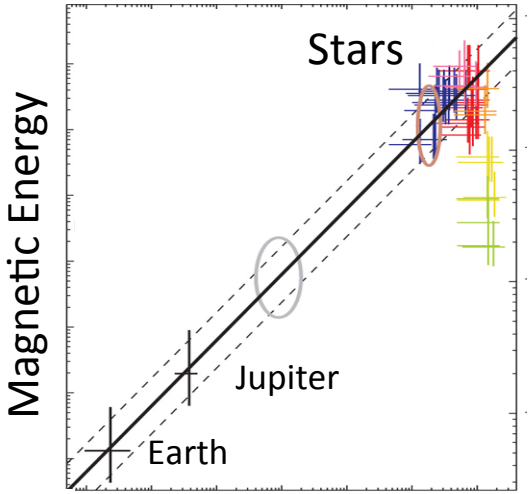
Convective Heat Flux (available to do work): $q_{c,conv} = q_{cmb} - q_{ad}$

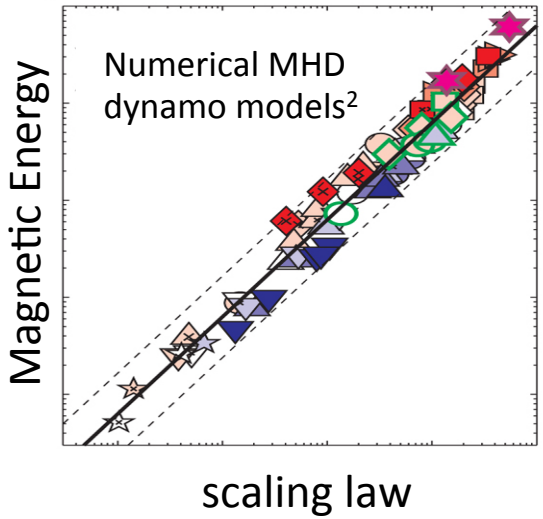
Core Buoyancy Flux: $F_c = \frac{\alpha_c g_c}{\rho_c c_c} q_{c,conv}$

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

Core Thermal Conductivity: $k_c = \sigma_c L T_{cmb}$

$$k_c = 100 \text{ W/m/K}$$





*All dipolar

[1] Olson and Christensen (2006)
[2] Christensen *et al.* (2009)

Earth's Thermal and Magnetic Paradoxes

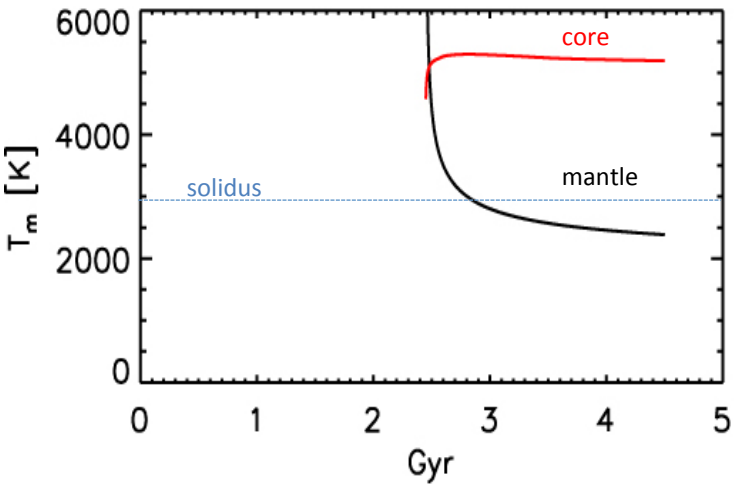
Present Heat Budget: Mantle Q_{surf}=40 TW, radiogenic Q_{rad}=13 TW, core Q_{CMB}=8 TW, mantle cooling Q_M=18 TW

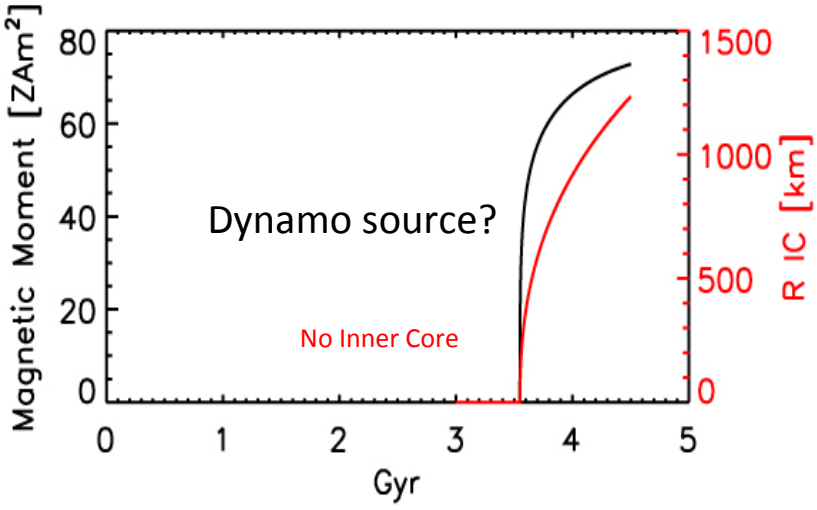
Thermal Catastrophe:

- Present-day heat flows & temperatures predict molten mantle only 2 Gyr ago!

Core Paradox:

- High core thermal conductivity implies no dynamo source prior to inner core





Examples with Q_{cmb}=8 TW

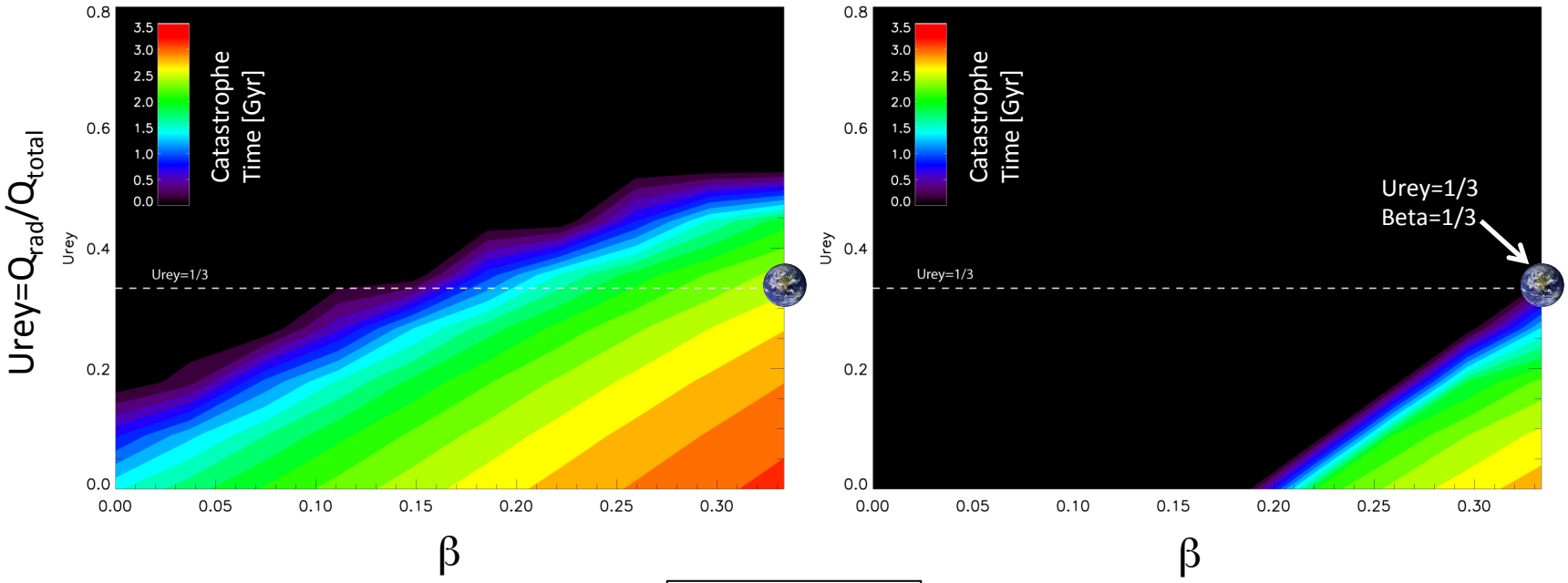
Avoiding the Paradoxes

Driscoll + Bercovici (2014)

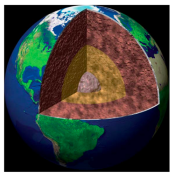
- Geochemically preferred Urey=0.3
- Geodynamically preferred β=1/3
- Mantle secular cooling rate uncertain: 18±10 TW

✧ Q_{cmb}=8 TW
✧ Q_{man}=18 TW

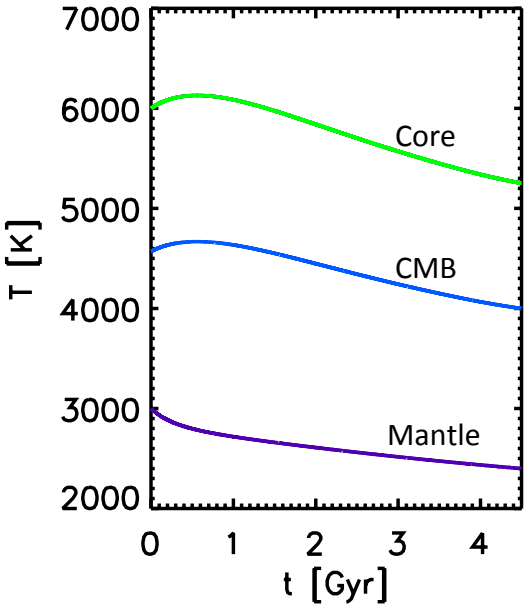
✧ Invoke higher Q_{cmb}=15 TW (+7)
✧ Lower Q_{man}=11 TW (-7)

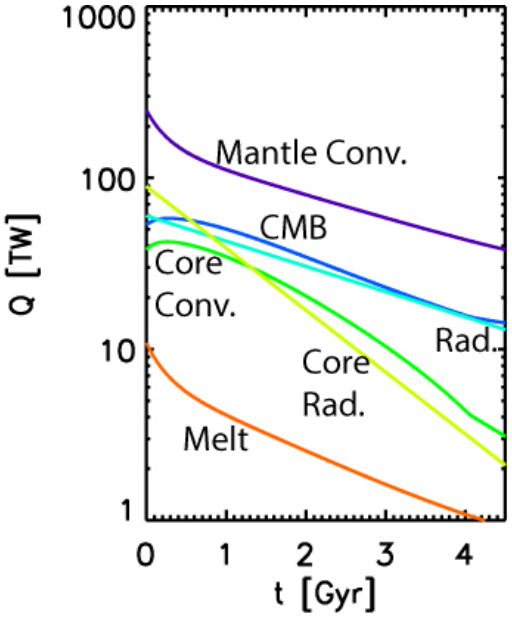


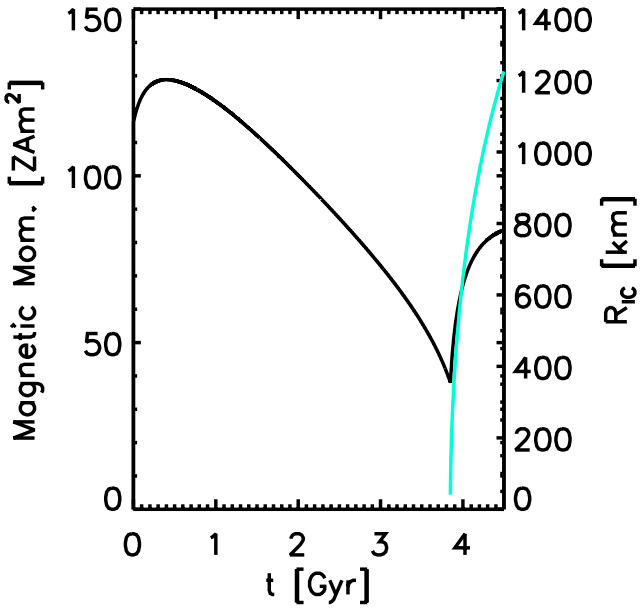
$Q_{surf} \sim (T_M)^{\beta+1}$



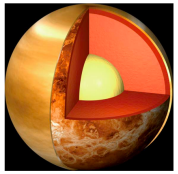
Preferred Solution







- Core is thermally convective for all times
- Inner core 650 Myr old
- Alternative solutions (exotic dynamics, non-chondritic Earth) unnecessary
- Invoking ~2 TW K^{40} in core is high, but uncertain
- Note: magnetic scaling law assumes strong-field, misleading?



Stagnant Lid (Venus)

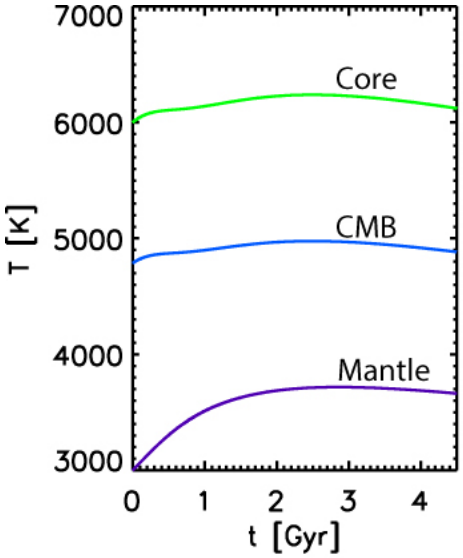
Venus useful test case

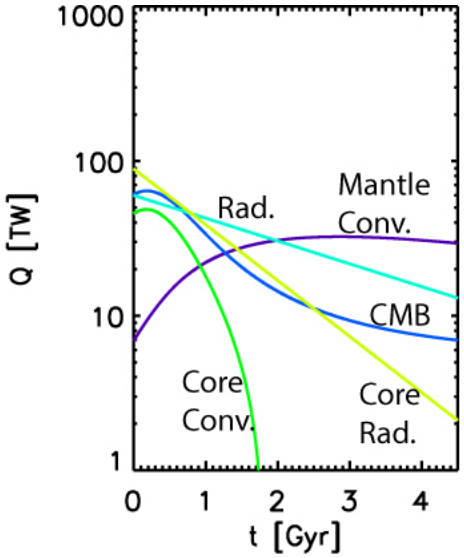
- Similar mass and bulk composition as Earth
- Has stagnant lid and no dynamo today
- Probably began with similar initial conditions

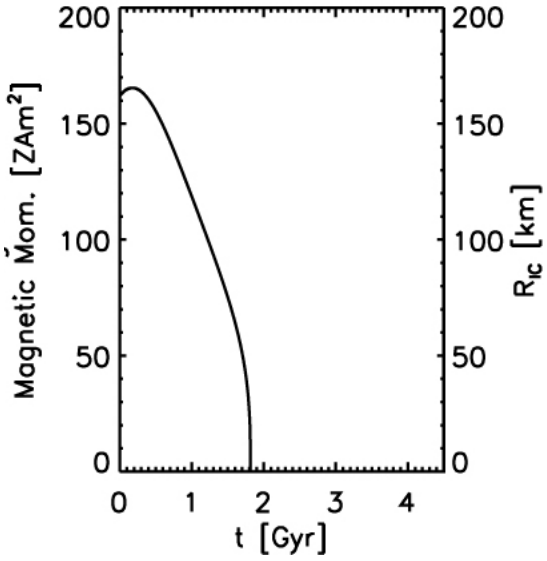
$$Q_{stag} = Q_{surf}/25$$

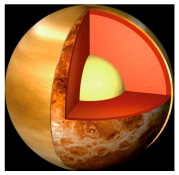
No melting: $\epsilon_{erupt} = 0$

- Mantle heats up ~500 K
- Thermal dynamo dies ~1.8 Gyr
- No IC solidification



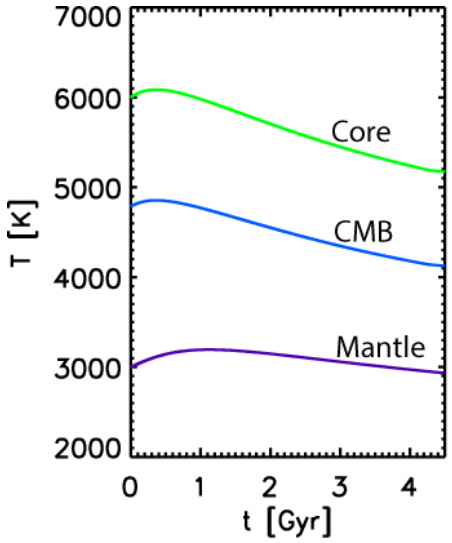


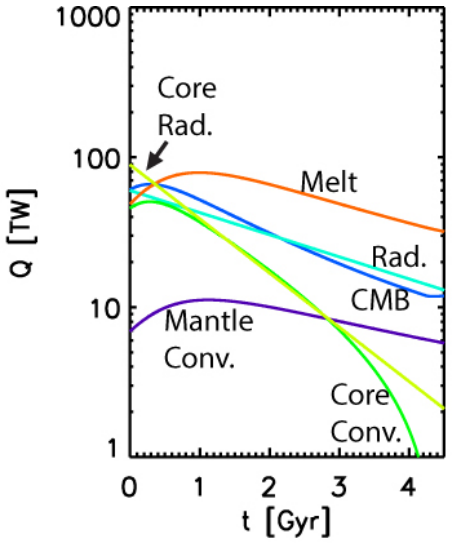


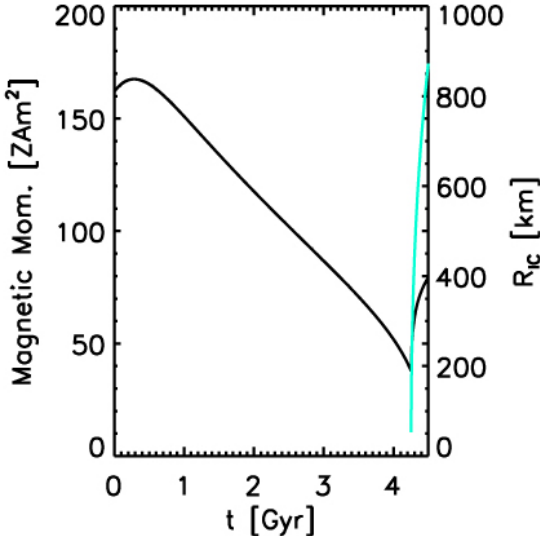


Stagnant Lid with Melting

$$\epsilon_{erupt} = 1$$







- Melting cools mantle and core like a mobile lid planet!
- Continuous dynamo, and late ICN

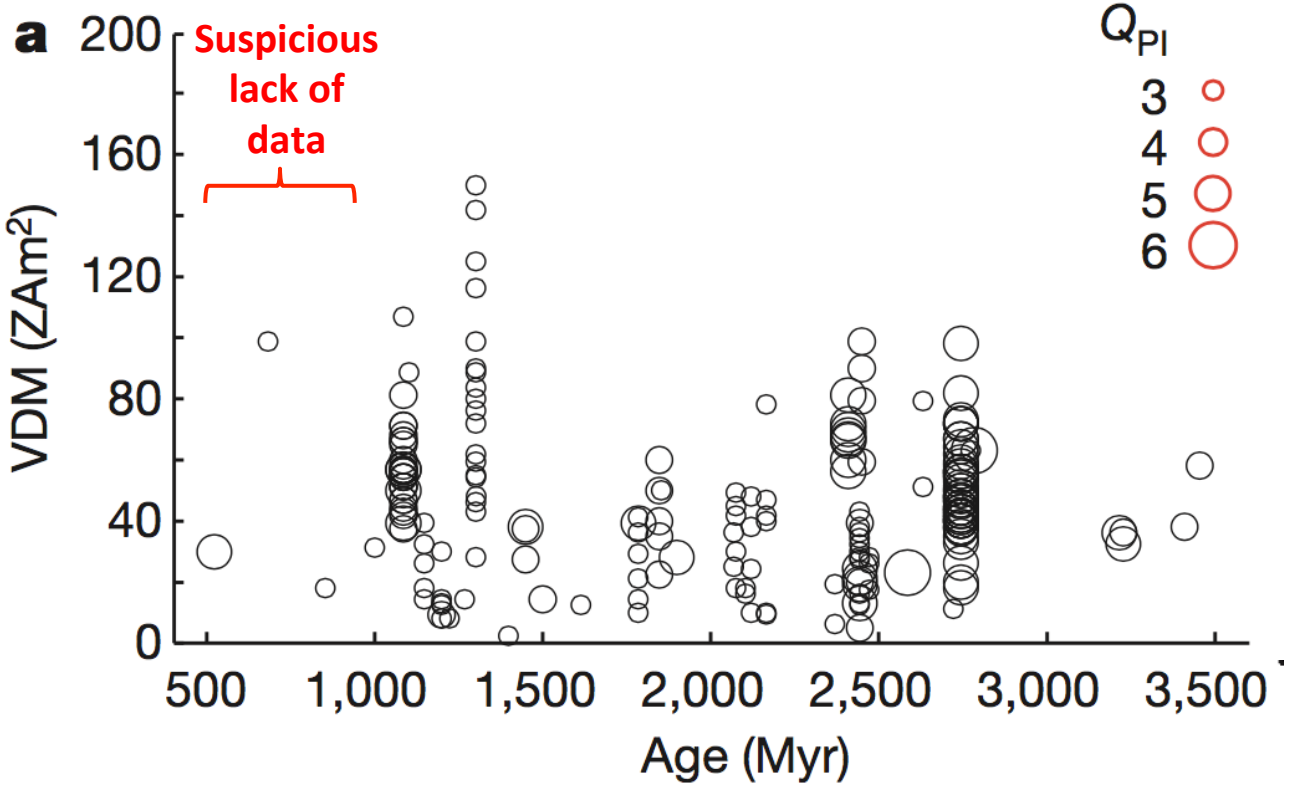
Venus take away:

- Only a fraction of magma erupted to surface over recent history (~ 1 Ga?) , or else we should see a magnetic field today

Evolving 3D Dynamos

Earth example

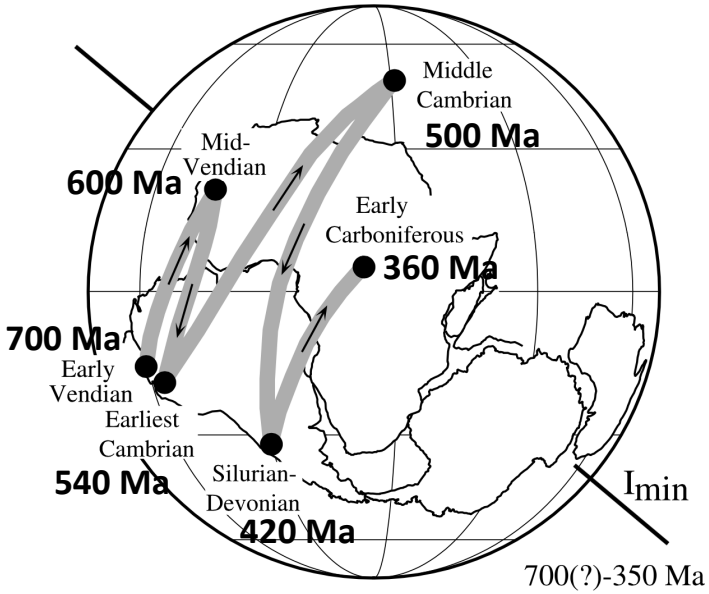
Signature of Inner Core Nucleation?

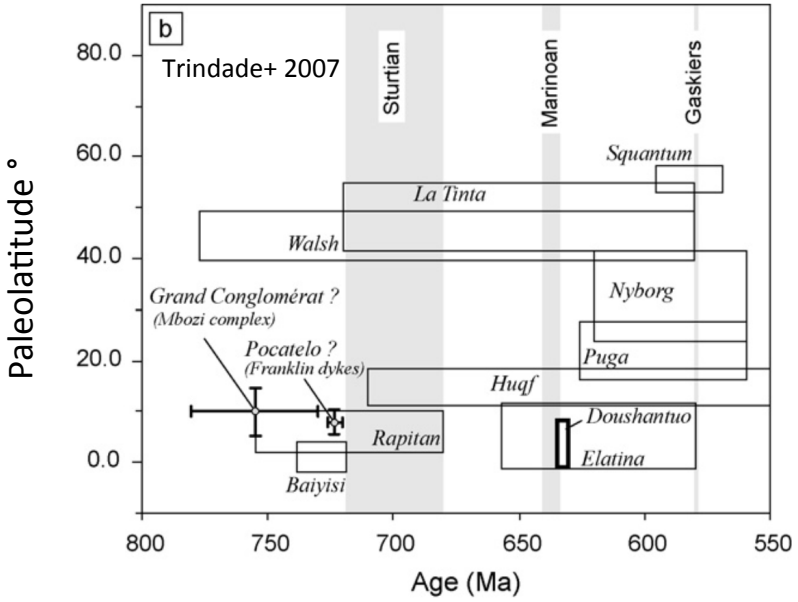


Biggin+ 2015
PINT database

Neoproterozoic "Weirdness"

Gondwanaland Apparent Polar Wander Path (Evans, 2003)





Anomalous magnetic poles

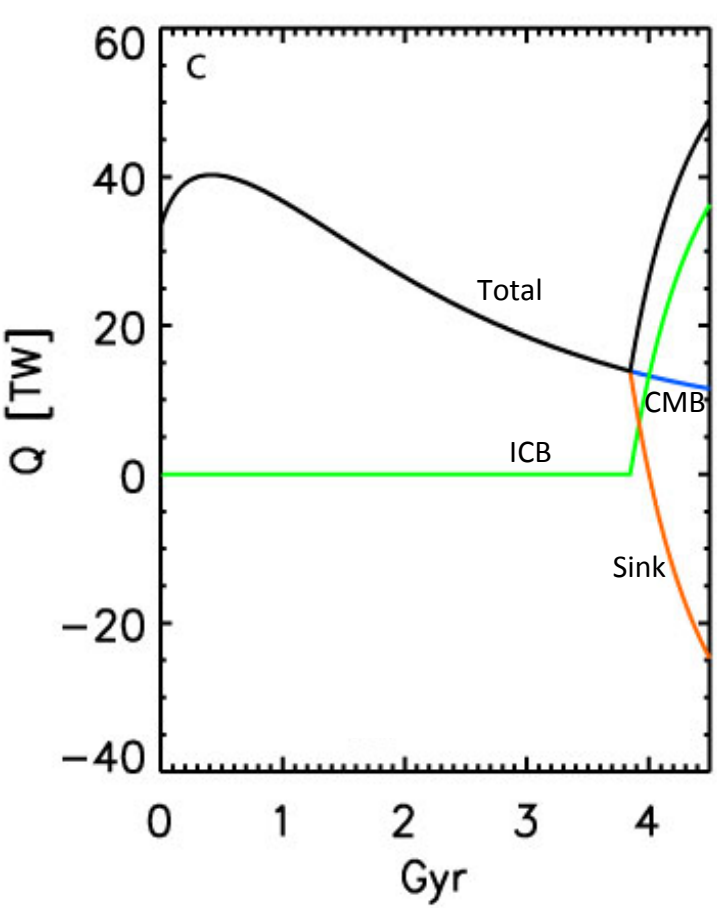
- Ediacaran (540-630 Ma) [*Kirschvink et al.*, 1997; *Abrajevitch and Van der Voo*, 2010; *Halls et al.*, 2015; *Bono and Tarduno*, 2015; *Klein et al.*, 2015; *Bazhenov et al.*, 2016]
- Cryogenian (630-720 Ma) [*Maloof et al.*, 2006; *Swanson-Hysell et al.*, 2012].

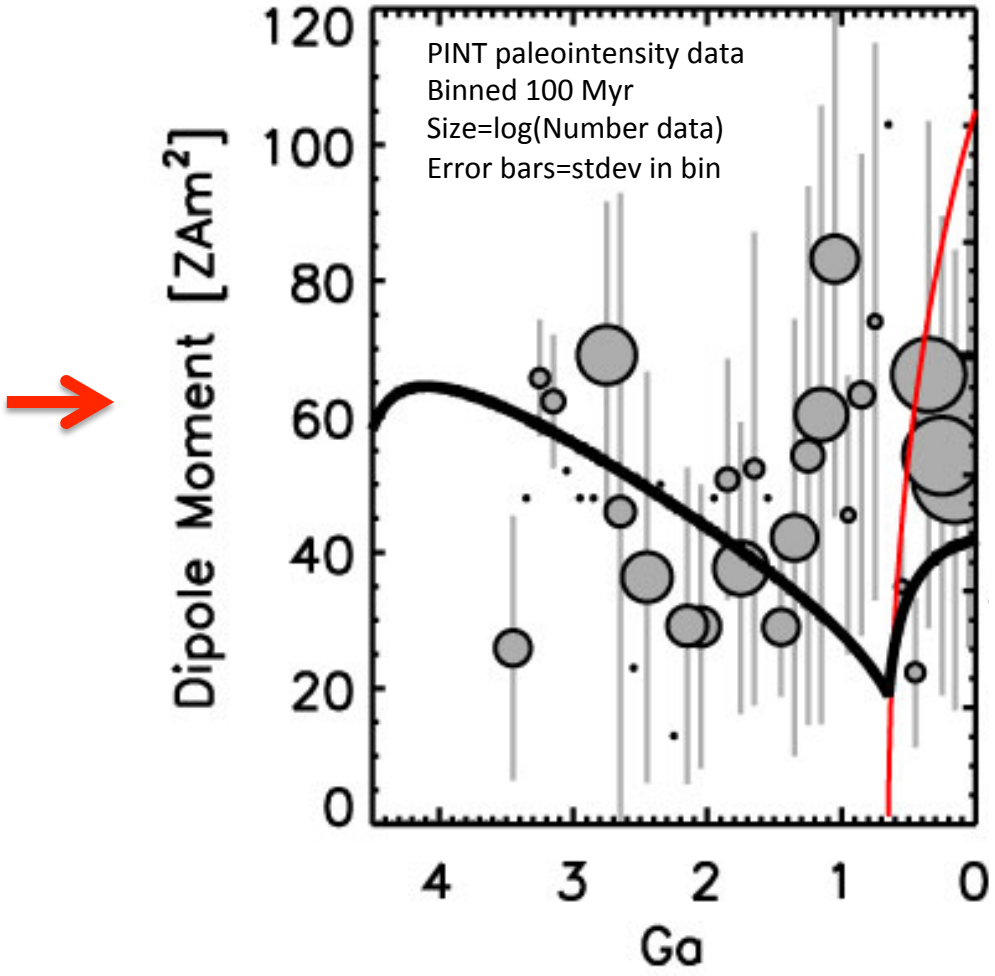
Interpretations

1. rapid plate motions
2. true polar wander (TPW) due to change in global moment of inertia
3. absence of a stable GAD field, equatorial dipole, and/or "hyper" frequent reversals

Neoproterozoic paleolatitudes could be unreliable if non-axial dipole components were important

Thermal History & Magnetic Scaling Law Predictions

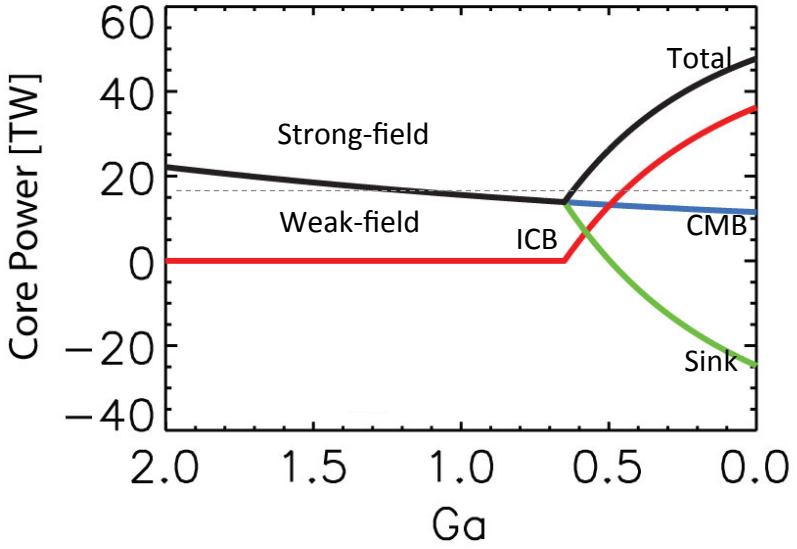


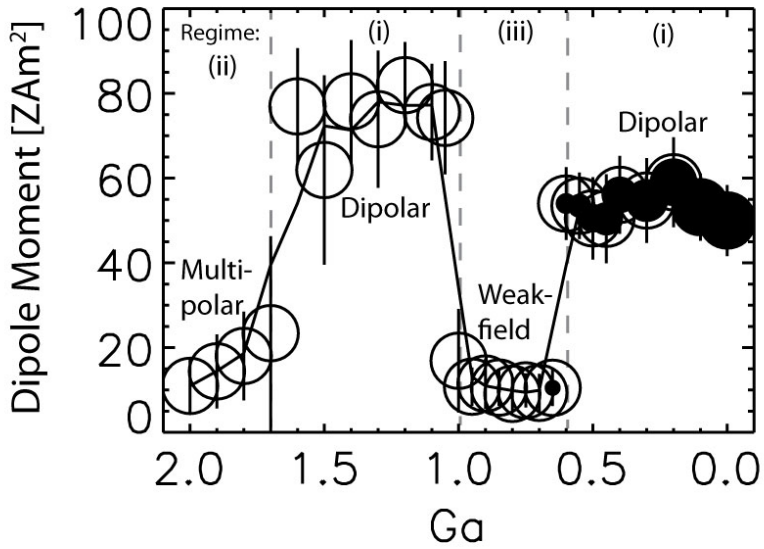


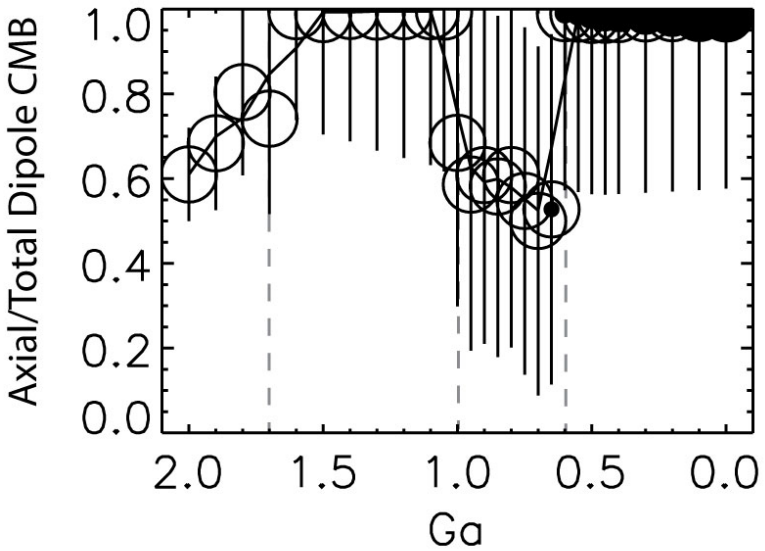
3D Dynamo Model Evolution

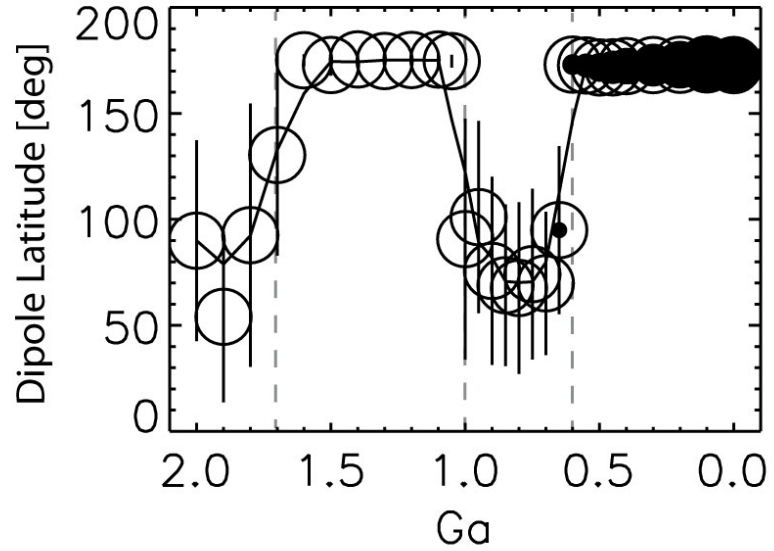
(Driscoll 2016, GRL)

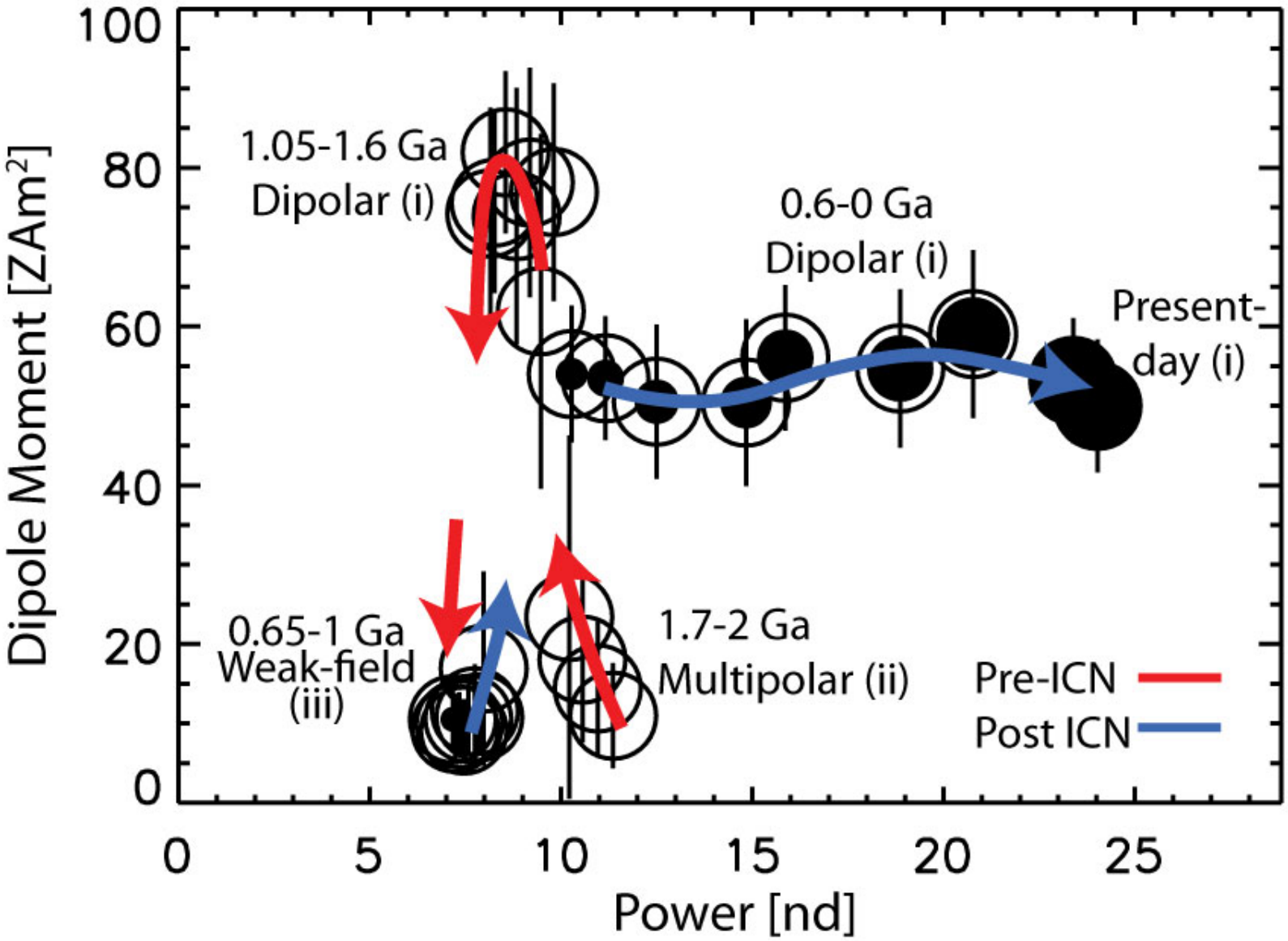
Ek=3e-4
Ra=5e6
Pr=1
Pm=10









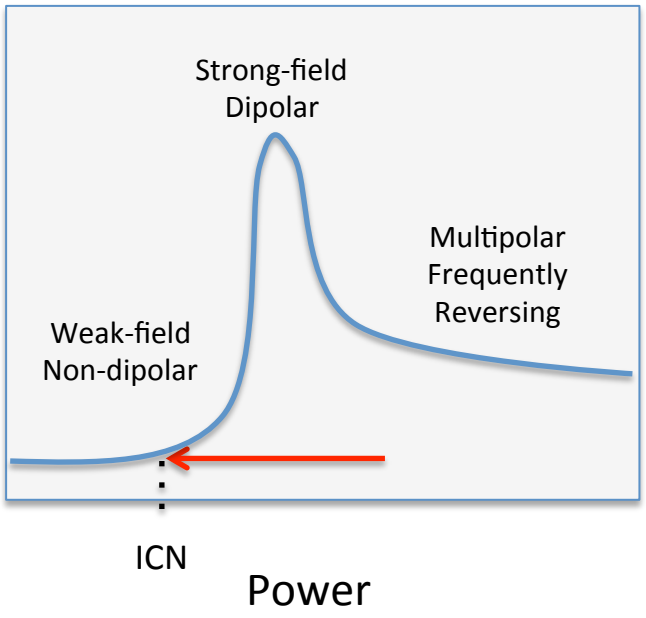

100
80
60
40
20
0
Dipole Moment [ZAm²]
0
5
10
15
20
25
Power [nd]
1.05-1.6 Ga
Dipolar (i)
0.6-0 Ga
Dipolar (i)
Present-
day (i)
0.65-1 Ga
Weak-field
(iii)
1.7-2 Ga
Multipolar (ii)
Pre-ICN
Post ICN

Dynamo Regimes

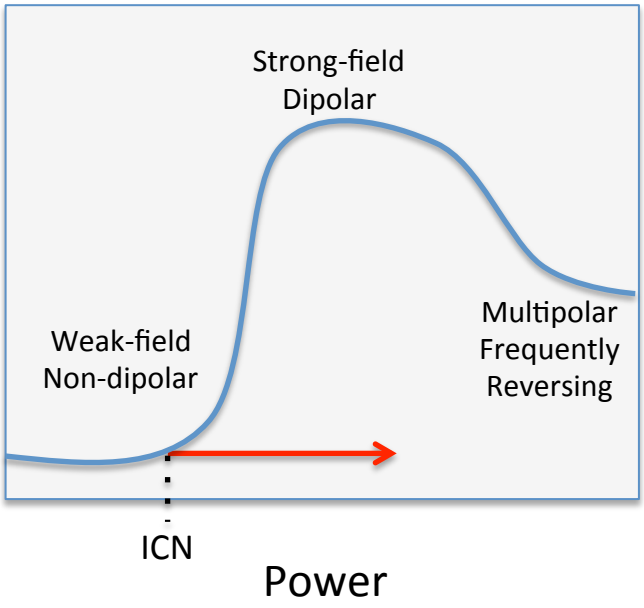
- Top-driven dynamo favors small scale convection, multi-polar field
- Bottom-driven dynamo favors large scale, dipole

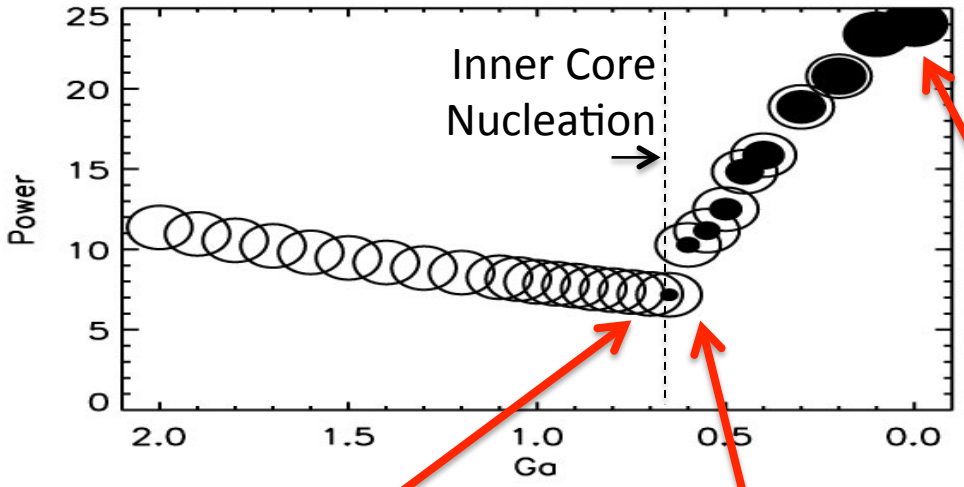
Dipole

Top-driven
Thermal Dynamo
Pre-Inner Core



Bottom-driven
Thermo-chemical Dynamo
Inner Core Growing





Boundary Conditions:

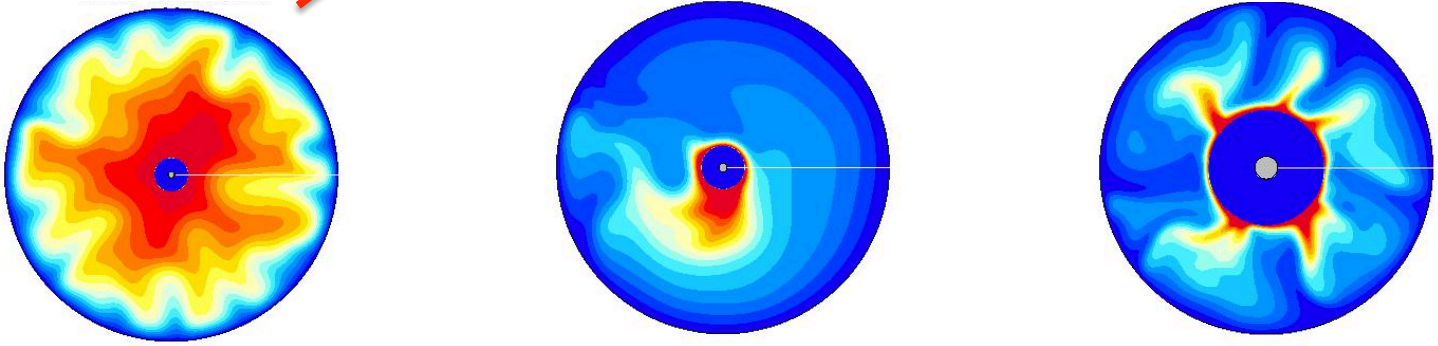
- Fix Q_{icb}
- Fix heat source/sink
- Isothermal CMB

680 Ma

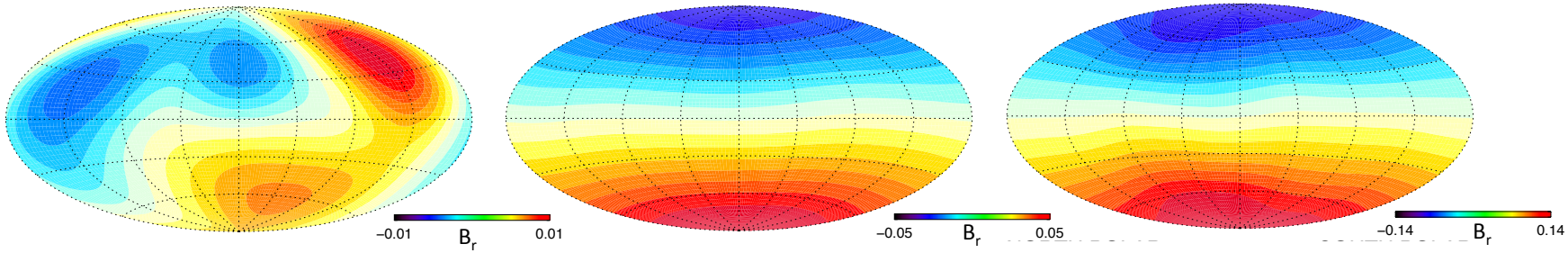
580 Ma

0 Ma

Equatorial Temperature

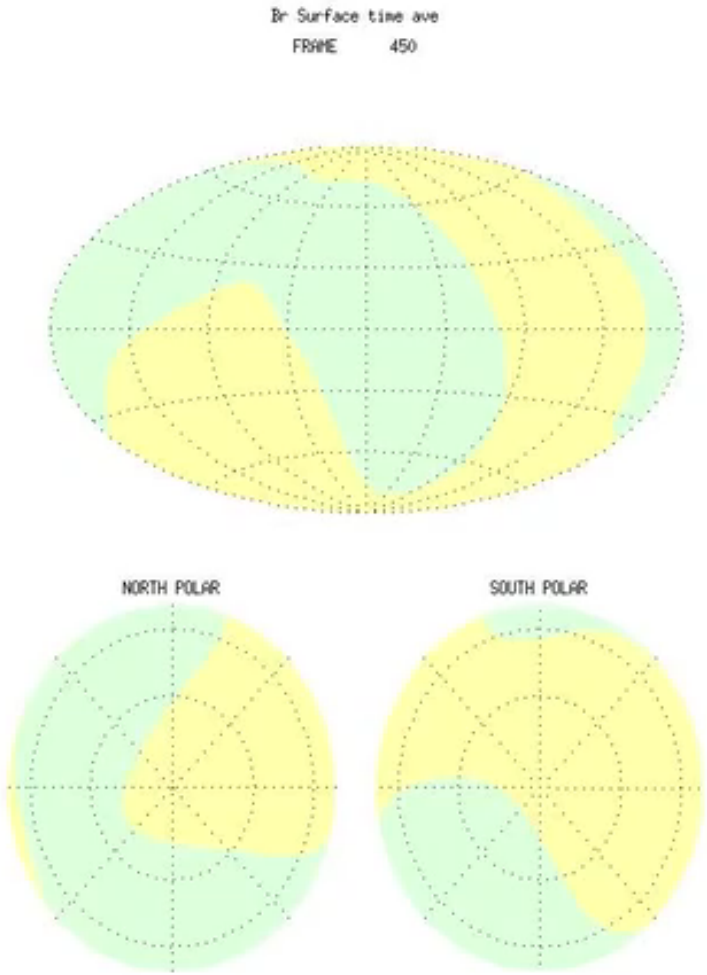


Surface Magnetic Field (time ave)

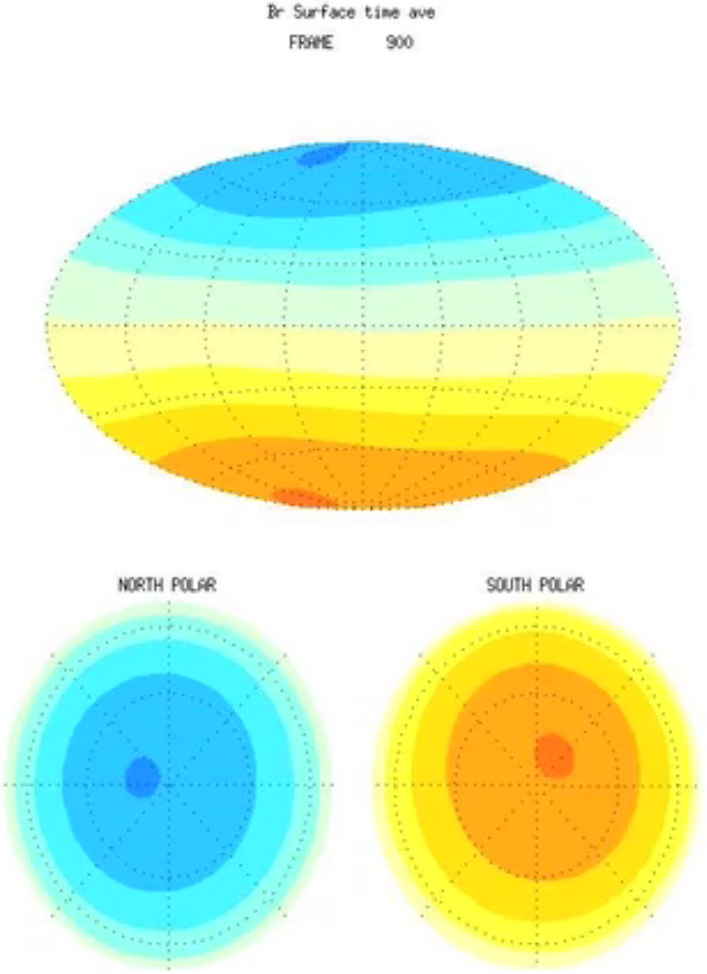


Models of B_r at Surface

Prior to Inner Core
680 Ma



Present-day



Summary

1. Thermal and magnetic *paradoxes* avoidable with Q_{cmb}=15 TW
2. Magmatic cooling can overcome a stagnant lid, drive dynamo
3. Inner core nucleation could drive weak to strong-field transition
4. Neoproterozoic (550-1000 Ma) plate reconstructions and paleointensities may support inner core nucleation around 650 Ma
5. 1D and 3D dynamo predictions differ – dynamo regimes have sharp boundaries
6. Uncertainties: heat budget, core conductivity, high Ek dynamos …