

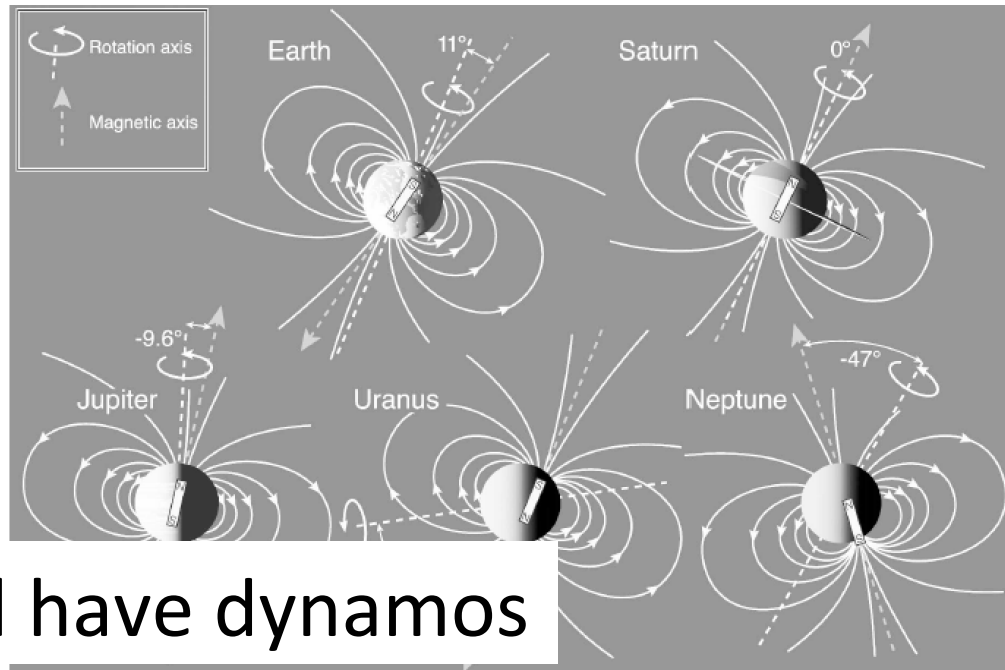
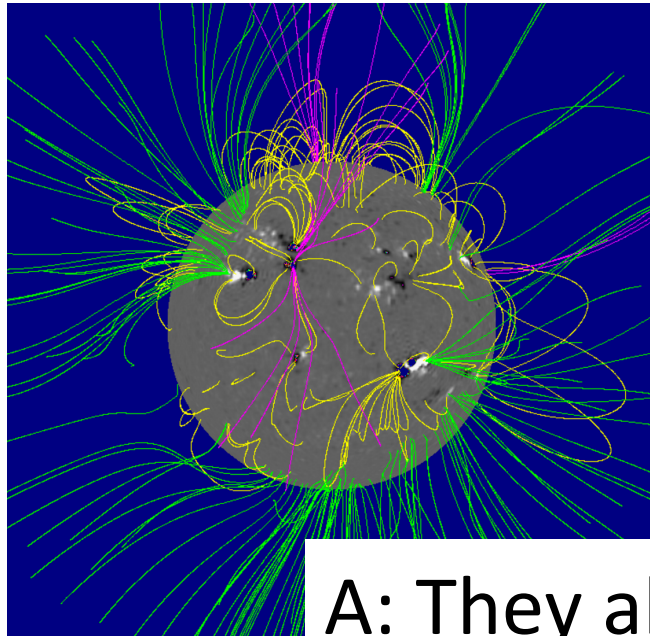
# Q: Why do the Sun and planets have magnetic fields?

Dana Longcope

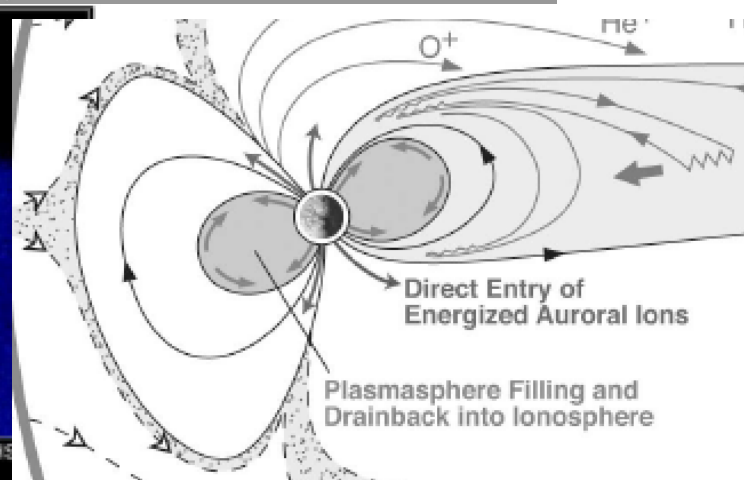
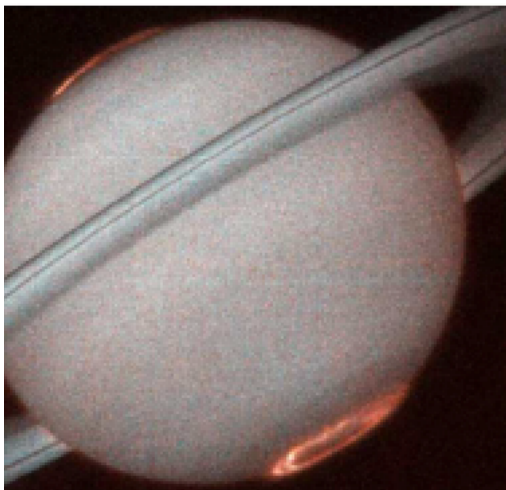
Montana State University

w/ liberal “borrowing” from Bagenal,  
Stanley, Christensen, Schrijver,  
Charbonneau, ...

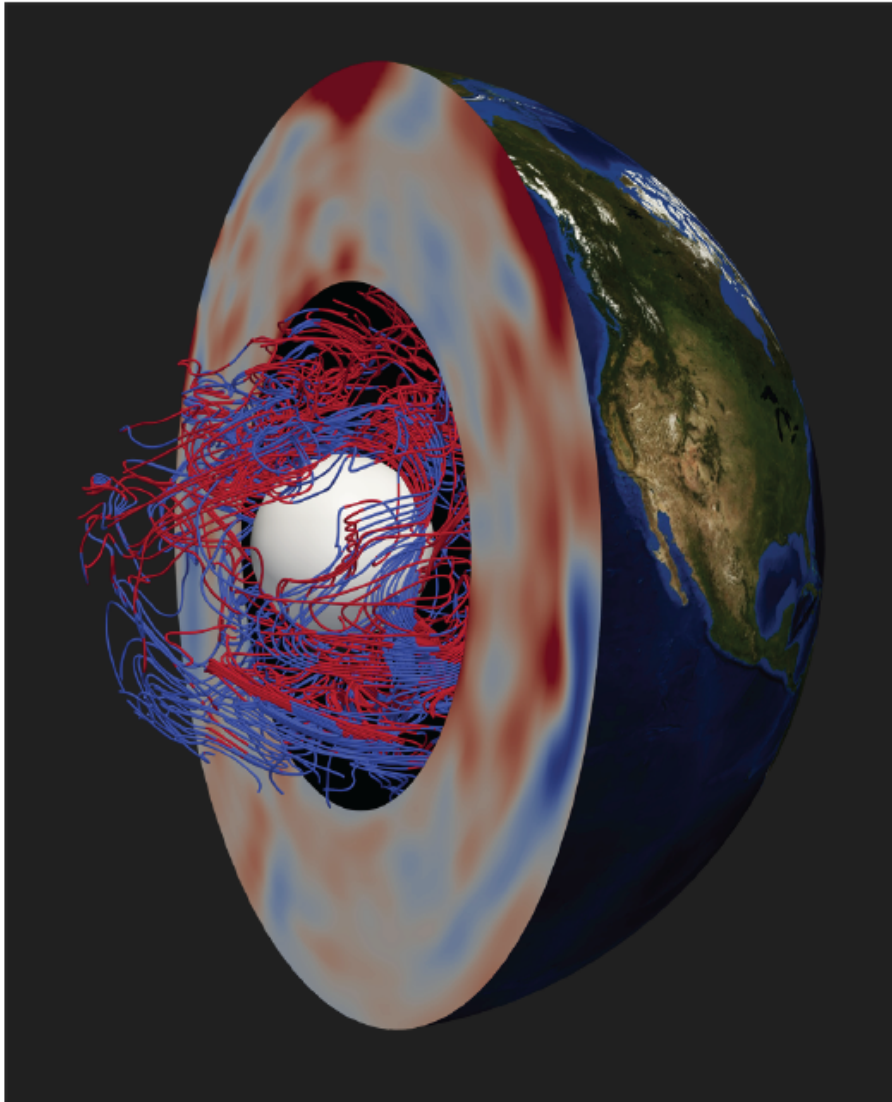
Q: Why do the Sun and planets have magnetic fields?



A: They all have dynamos



# DYNAMO INGREDIENTS



(1) electrically conducting fluid

- Plasma (stars)
- Liquid iron (terrestrial planets)
- Metallic hydrogen (gas giants)
- Ionized water (ice giants)

(2) fluid must have complex motions

- Complex turbulent flows
- Rotation: breaks mirror-symmetry not required, but needed for large-scale, organized fields

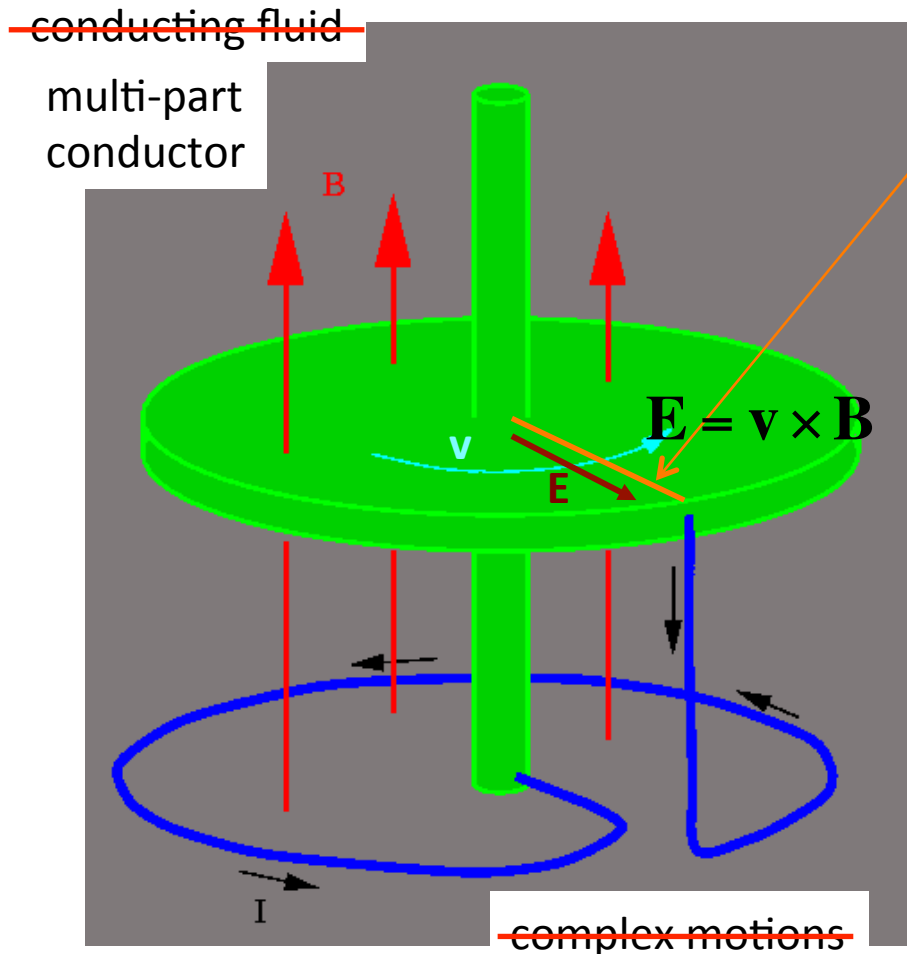
(3) motions must be vigorous enough

- Figure of merit: Magnetic Reynold's #

$$Rm = \text{velocity} \times \text{size} \times \text{conductivity}$$

From Stanley 2013

# A Toy w/ all ingredients



$$V_{\text{disk}} = \int_0^{\ell} vB dr = \int_0^{\ell} (\Omega r) B dr = \frac{1}{2\pi} \Omega \Phi_{\text{disk}}$$

- No magnets
- No batteries
- No (net) charge

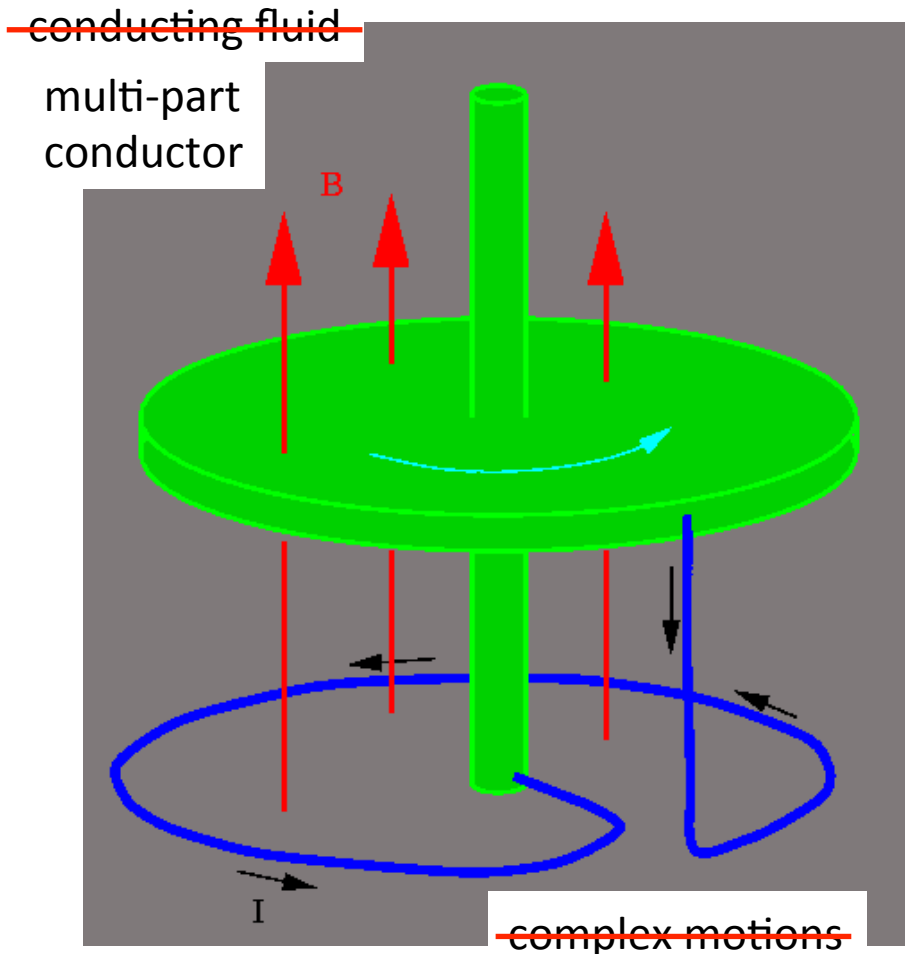
lack of mirror symmetry

differential motion of parts

~~conducting fluid~~  
multi-part conductor

~~complex motions~~

# A Toy w/ all ingredients



lack of mirror symmetry

differential motion of parts

$$V_{\text{disk}} = \int_0^{\ell} vB dr = \int_0^{\ell} (\Omega r) B dr = \frac{1}{2\pi} \Omega \Phi_{\text{disk}}$$

$$IR = \underbrace{\frac{\Omega}{2\pi} \Phi_{\text{disk}}}_{\text{motional EMF}} - \underbrace{L \frac{dI}{dt}}_{\text{back EMF}} = \frac{\Omega}{2\pi} M_{w,d} I - L \frac{dI}{dt}$$

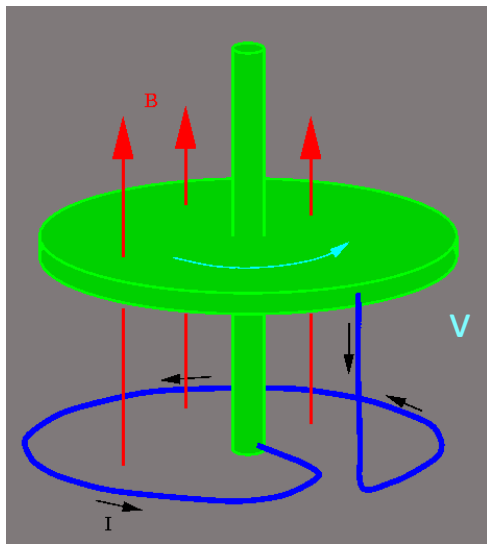
$$\frac{dI}{dt} = \left( \underbrace{\frac{\Omega}{2\pi} \frac{M_{w,d}}{L}}_{\text{generation}} - \underbrace{\frac{R}{L}}_{\text{dissipation}} \right) I = \gamma I \quad I(t) = I_0 e^{\gamma t}$$

$$\text{Growth: } \gamma > 0 \Leftrightarrow \Omega > 2\pi \frac{R}{M_{w,d}}$$

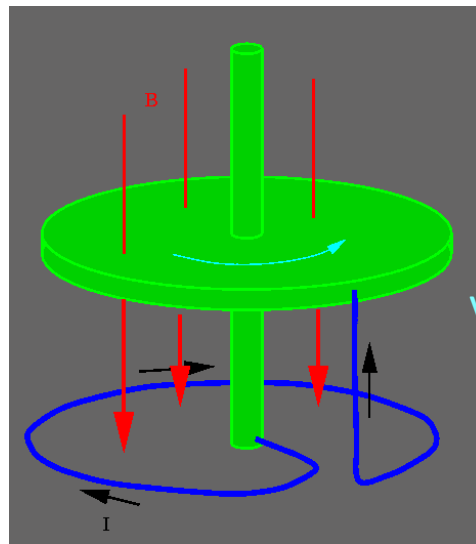
$$\frac{v}{\ell} > 2\pi \frac{1/\sigma \ell}{\mu_0 \ell} = \frac{2\pi}{\mu_0 \sigma \ell^2}$$

Growth:  $Rm = \mu_0 \sigma \ell v > 2\pi$

Toy dynamo amplifies fields of either sign:  
two attracting states



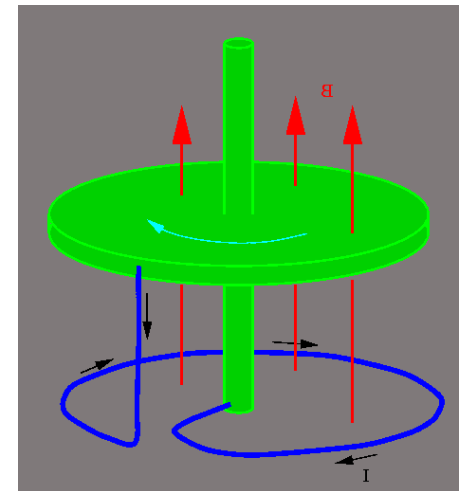
$I_0 > 0$



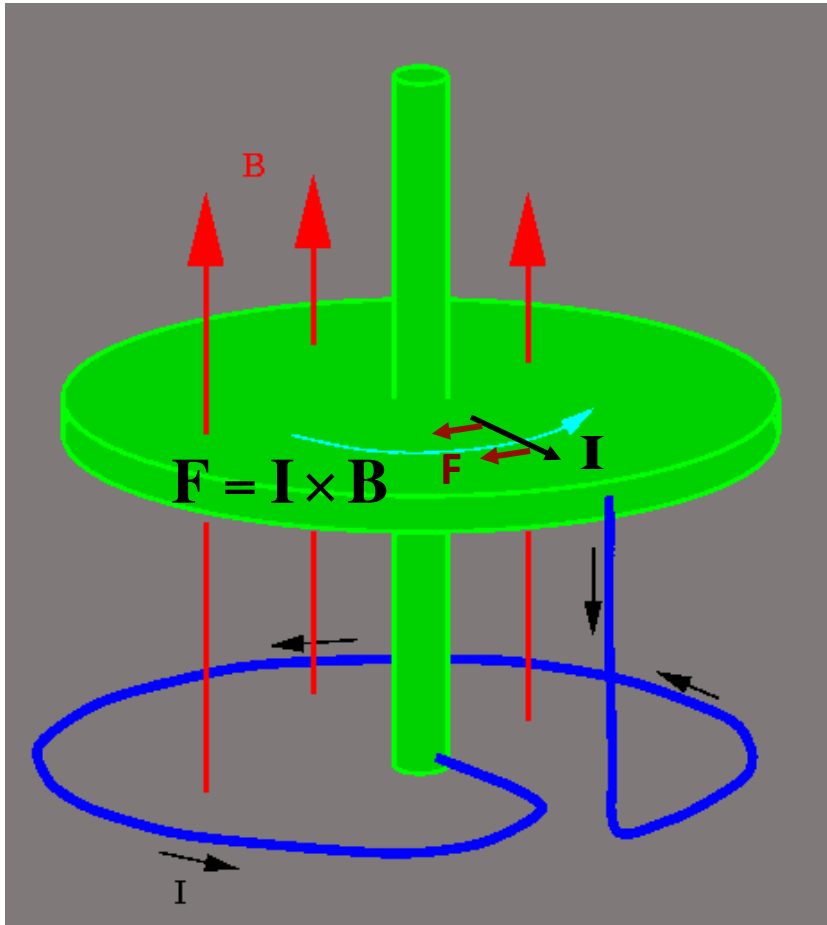
$I_0 < 0$

$$I(t) = I_0 e^{\gamma t}$$

- Reverse velocity AND reflect in mirror → still amplifies
- Do one and not the other → no amplification



# Will $I$ grow forever?



Torque on disk carrying current:

$$\tau = \int_0^{\ell} Fr \, dr = \int_0^{\ell} IBr \, dr = \frac{1}{2\pi} I\Phi_{\text{disk}} = \frac{M_{w,d}}{2\pi} I^2$$

Power needed to turn disk:

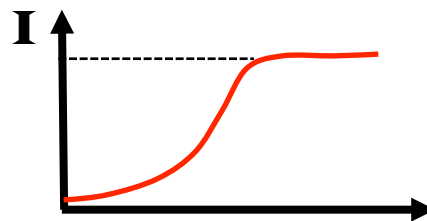
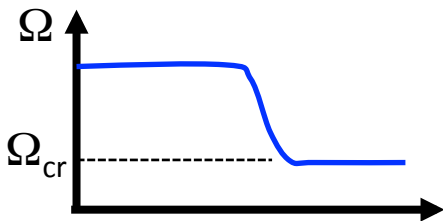
$$P_{\Omega} = \Omega\tau = \frac{\Omega}{2\pi} M_{w,d} I^2$$

Subtracting Ohmic losses

$$P_{\Omega} - I^2 R = \left( \frac{\Omega}{2\pi} M_{w,d} - R \right) I^2 = \gamma LI^2$$

$$= \frac{d}{dt} \left( \frac{1}{2} LI^2 \right)$$

Stored in energy of **B**



# Reality: Conducting fluid – MHD

Effect of **B** on conducting fluid

Fluid dynamics

$$\left\{ \begin{array}{l} \frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{v}) \\ \rho \frac{\partial \mathbf{v}}{\partial t} + \rho (\mathbf{v} \cdot \nabla) \mathbf{v} = -\nabla p + \rho \mathbf{g} + \nabla \cdot \vec{\sigma} + \mathbf{J} \times \mathbf{B} \\ \rho c_v \left( \frac{\partial T}{\partial t} + \mathbf{v} \cdot \nabla T \right) = -\frac{2}{3} T \nabla \cdot \mathbf{v} + \nabla \mathbf{v} : \vec{\sigma} + \dot{Q} + \frac{1}{\sigma} |\mathbf{J}|^2 \end{array} \right.$$

$\mathbf{J} = \frac{1}{\mu_0} \nabla \times \mathbf{B}$

Lorentz force

Ohmic heat

Faraday's  
+ Ohm's laws

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} = \nabla \times \left[ \mathbf{v} \times \mathbf{B} - \frac{1}{\sigma} \mathbf{J} \right]$$

$$\nabla \times \left[ -\frac{1}{\sigma} \mathbf{J} \right] = \nabla \times \left[ -\frac{1}{\sigma \mu_0} \nabla \times \mathbf{B} \right] = \eta \nabla^2 \mathbf{B} \quad \eta = \frac{1}{\mu_0 \sigma} \quad \text{magnetic diffusivity}$$



# Reality: Conducting fluid – MHD

If  $\mathbf{B}$  is weak: kinematic equations

Fluid dynamics

$$\left\{ \begin{array}{l} \frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{v}) \\ \rho \frac{\partial \mathbf{v}}{\partial t} + \rho (\mathbf{v} \cdot \nabla) \mathbf{v} = -\nabla p + \rho \mathbf{g} + \nabla \cdot \vec{\sigma} \\ \rho c_v \left( \frac{\partial T}{\partial t} + \mathbf{v} \cdot \nabla T \right) = -\frac{2}{3} T \nabla \cdot \mathbf{v} + \nabla \mathbf{v} : \vec{\sigma} + \dot{Q} \end{array} \right.$$

Traditional  
(neutral) fluid –  
solve first

Faraday's  
+ Ohm's laws

$$\frac{\partial \mathbf{B}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{B} = (\mathbf{B} \cdot \nabla) \mathbf{v} - \mathbf{B} (\nabla \cdot \mathbf{v}) + \eta \nabla^2 \mathbf{B}$$

Linear equation for  $\mathbf{B}(\mathbf{x}, t)$  – solve w/ known  $\mathbf{v}(\mathbf{x}, t)$

# Dynamo action in MHD

$$\underbrace{\frac{D\mathbf{B}}{Dt}}_{\frac{\partial \mathbf{B}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{B}} \quad \underbrace{\mathbf{B} \cdot [\nabla \mathbf{v} - \mathbf{I}(\nabla \cdot \mathbf{v})]}_{(\mathbf{B} \cdot \nabla)\mathbf{v} - \mathbf{B}(\nabla \cdot \mathbf{v})} = \mathbf{B} \cdot \mathbf{M}$$

$$\frac{\partial \mathbf{B}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{B} = (\mathbf{B} \cdot \nabla)\mathbf{v} - \mathbf{B}(\nabla \cdot \mathbf{v}) + \eta \nabla^2 \mathbf{B}$$

If  $\mathbf{M}$  has a positive eigenvalue  $\lambda > 0$

$\mathbf{B}$  can grow exponentially: **DYNAMO ACTION**

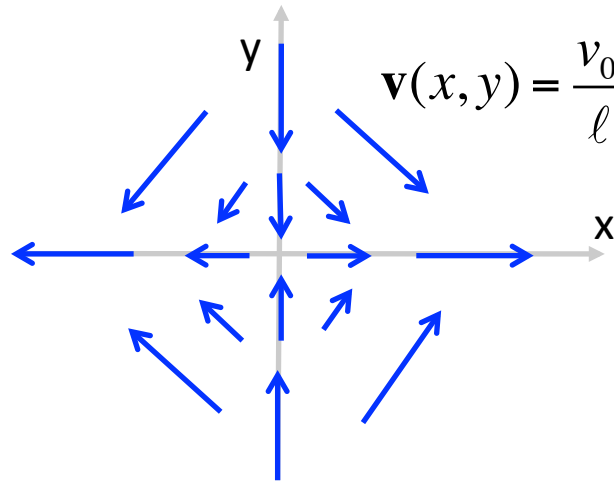
- $\mathbf{B} \rightarrow -\mathbf{B}$  : same e-vector  $\rightarrow$  same  $\lambda$
- Reverse velocity AND reflect in mirror  $\rightarrow \lambda \rightarrow \lambda$
- Do one and not the other  $\rightarrow \lambda \rightarrow -\lambda$

$$\gamma \sim \frac{v}{\ell} - \frac{\eta}{\ell^2} = \frac{v}{\ell} \left( 1 - \frac{\eta}{lv} \right)$$

↙  $\lambda$        $\eta \nabla^2$  ↘

Growth:  $Rm = \frac{lv}{\eta} = \mu_0 l v \sigma > 1$

Q: What kind of flow has  $\lambda > 0$ ?

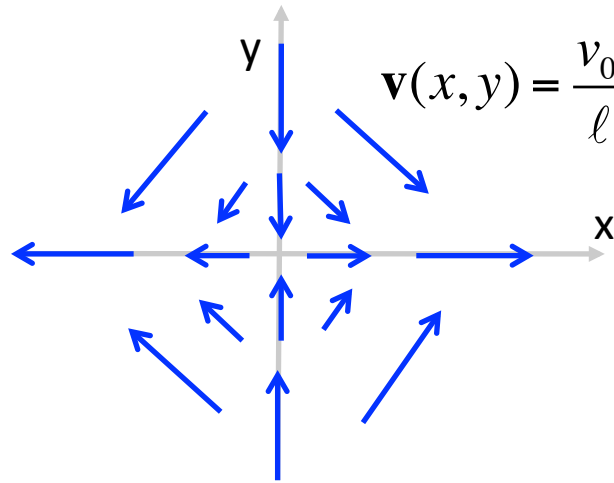


$$\mathbf{v}(x, y) = \frac{v_0}{\ell} (x\hat{\mathbf{x}} - y\hat{\mathbf{y}})$$

$$\mathbf{M} = \begin{bmatrix} \partial v_x / \partial x & \partial v_x / \partial y \\ \partial v_y / \partial x & \partial v_y / \partial y \end{bmatrix} = \frac{v_0}{\ell} \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

$$\mathbf{M} \cdot \begin{bmatrix} B_0 \\ 0 \end{bmatrix} = \frac{v_0}{\ell} \cdot \begin{bmatrix} B_0 \\ 0 \end{bmatrix} \quad \lambda = +\frac{v_0}{\ell}$$

Q: What kind of flow has  $\lambda > 0$ ?

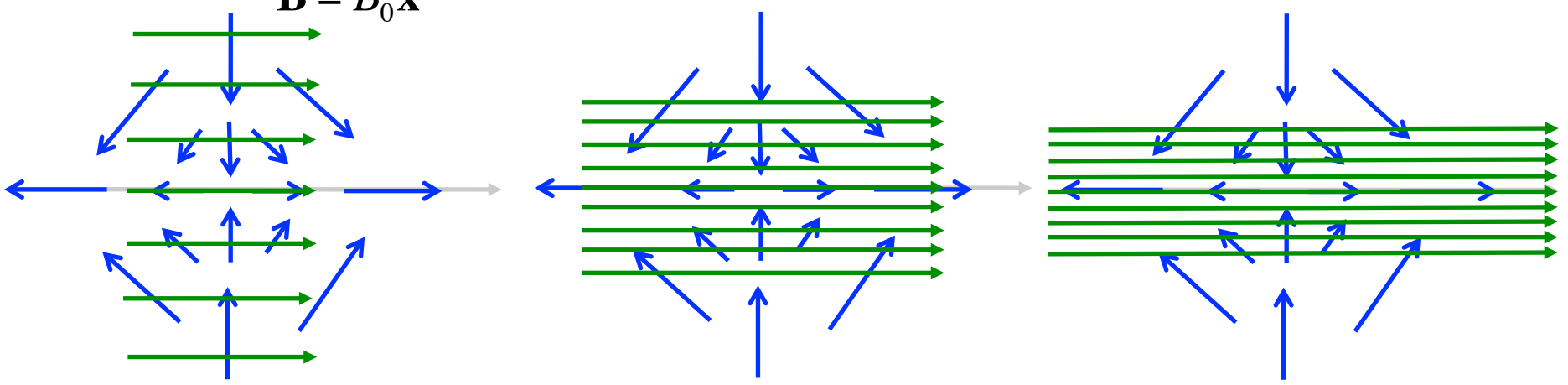


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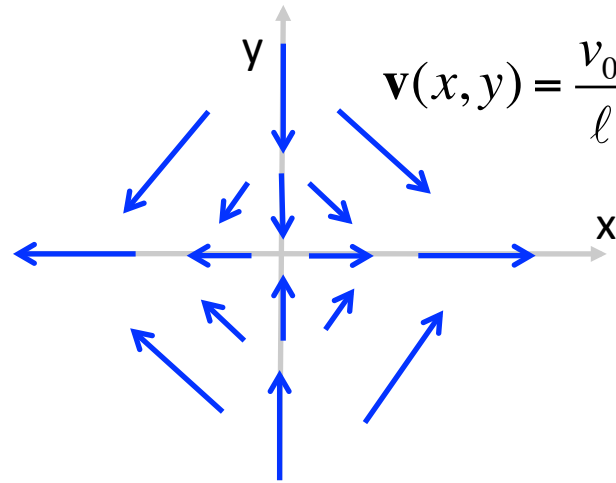
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$$\mathbf{B} = B_0 \hat{\mathbf{x}}$$



A: stretching flow

Q: What kind of flow has  $\lambda > 0$ ?



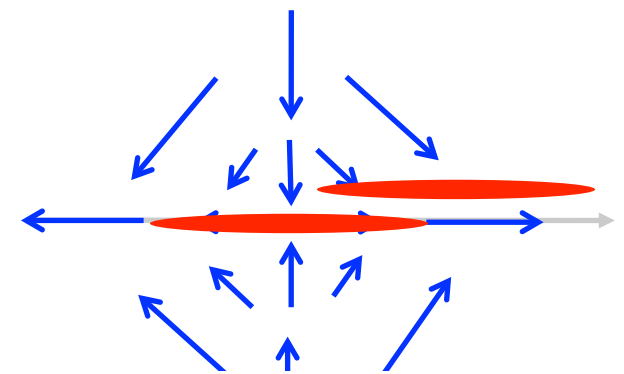
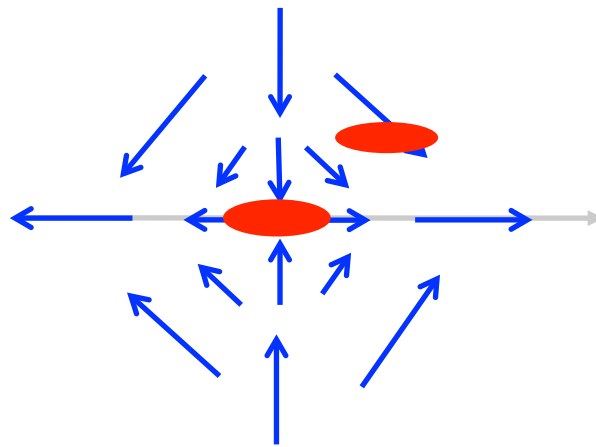
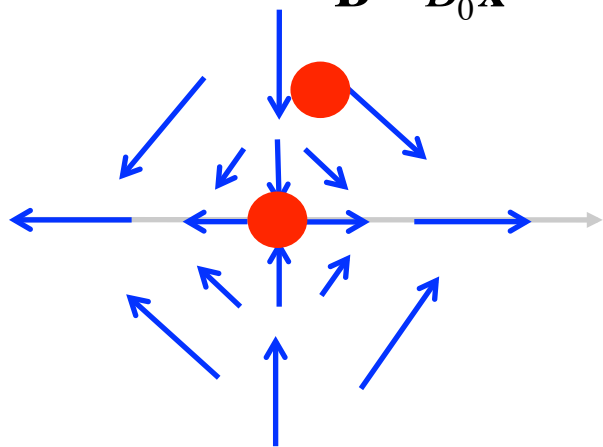
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$$\mathbf{M} \cdot \begin{bmatrix} B_0 \\ 0 \end{bmatrix} = \frac{v_0}{\ell} \cdot \begin{bmatrix} B_0 \\ 0 \end{bmatrix}$$

$$\lambda = +\frac{v_0}{\ell}$$

$$\mathbf{B} = B_0 \hat{\mathbf{x}}$$



Aspect ratio growth  
 $\sim$  Lyapunov exponent

A: stretching flow

# Q: What kind of flow has $\lambda > 0$ ?

- Turbulent flows have pos. Lyapunov exponent:  $\lambda > 0$

- tend to stretch balls into strands 
- tend to amplify fields

- Conditions for turbulence:

- driving: e.g. Rayleigh-Taylor instability
- viscosity fights driving – must be small

$$Re = \frac{\ell v}{\nu} \gg 1$$

- Rotation can organize turbulence:

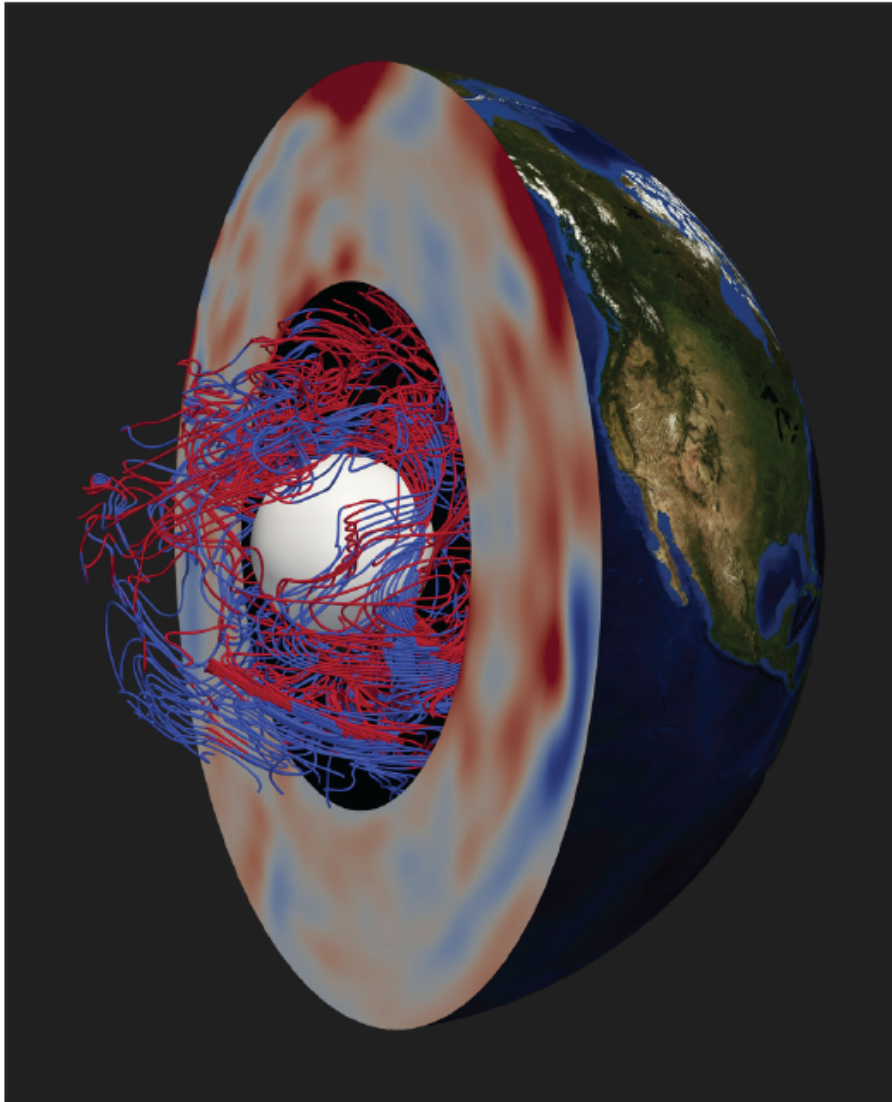
align stretching direction  $\rightarrow$  azimuthal  
(toroidal) – known as  $\Omega$ -effect

– must be significant w.r.t. fluid motion

$$Ro = \frac{v}{\ell \Omega} \ll 1$$

	$\eta$ [m <sup>2</sup> /s]	$\nu$ [m <sup>2</sup> /s]	L [m]	v [m/s]	$\Omega$ [rad/s]	Rm	Re	Ro
Sun (CZ)	1	10 <sup>-2</sup>	10 <sup>8</sup>	1	10 <sup>-6</sup>	10 <sup>8</sup>	10 <sup>10</sup>	10 <sup>-2</sup>
Earth (core)	1	10 <sup>-5</sup>	10 <sup>6</sup>	10 <sup>-4</sup>	10 <sup>-4</sup>	10 <sup>2</sup>	10 <sup>7</sup>	10 <sup>-6</sup>

# DYNAMO INGREDIENTS



(1) electrically conducting fluid

- Plasma (stars)
- Liquid iron (terrestrial planets)
- Metallic hydrogen (gas giants)
- Ionized water (ice giants)

(2) fluid must have complex motions

- Complex turbulent flows
- Rotation: breaks mirror-symmetry not required, but needed for large-scale, organized fields

(3) motions must be vigorous enough

- Figure of merit: Magnetic Reynold's #

$$Rm = \text{velocity} \times \text{size} \times \text{conductivity}$$

From Stanley 2013

# How this works for Earth

Non-conducting mantle

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} = 0$$

$$\mathbf{B} = -\nabla \chi \quad \nabla \cdot \mathbf{B} = -\nabla^2 \chi = 0$$

$$\chi(r, \theta, \phi) = \sum_{\ell, m} \tilde{g}_{\ell, m} Y_{\ell}^m(\theta, \phi) \left( \frac{R_{\oplus}}{r} \right)^{\ell+1}$$

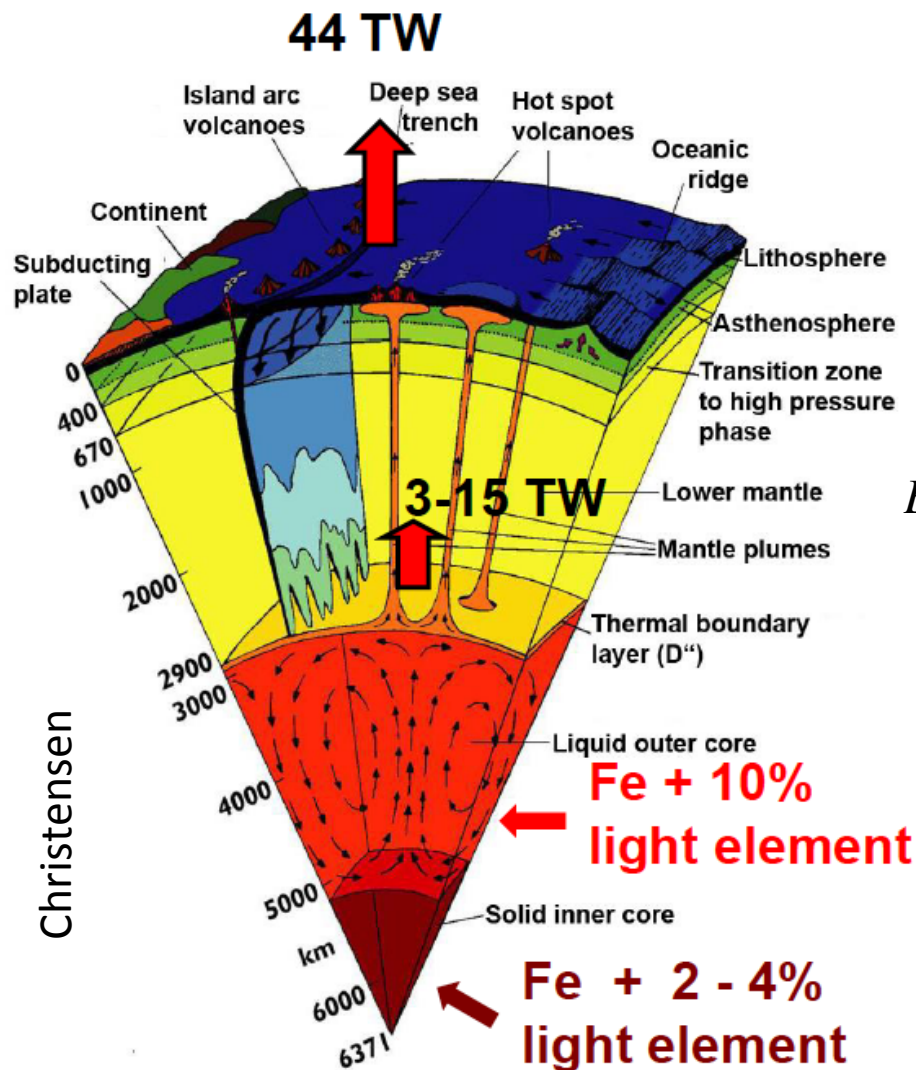
$$B_r(r, \theta, \phi) = -\frac{\partial \chi}{\partial r} = \sum_{\ell, m} (\ell+1) \tilde{g}_{\ell, m} Y_{\ell}^m(\theta, \phi) \left( \frac{R_{\oplus}}{r} \right)^{\ell+2}$$

simplifies w/ increasing r

Turbulent conducting fluid:  
**DYNAMO**

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} \neq 0$$

Complex flows – complex field





# A Spherical Harmonic Refresher

$\ell = 1$   
dipole

$$Y_1^0(\theta, \varphi) \sim \cos \theta \quad Y_1^{\pm 1}(\theta, \varphi) \sim \sin \theta e^{\pm i\varphi}$$


$$\tilde{g}_{1,\pm 1} \sim g_{1,1} \mp ih_{1,1} \quad (g_{1,0}, g_{1,1}, h_{1,1}) \leftrightarrow \vec{\mu} \quad \text{dipole moment}$$


---

$\ell = 2$   
quadrupole

$$Y_2^0(\theta, \varphi) \sim \frac{3}{4} \cos 2\theta + \frac{1}{4} \quad Y_2^{\pm 2}(\theta, \varphi) \sim \sin^2 \theta e^{\pm 2i\varphi}$$

$\ell=2$



$$(g_{2,0}, g_{2,1}, h_{2,1}, g_{2,2}, h_{2,2}) \leftrightarrow \vec{Q} \quad \text{quadrupole tensor}$$

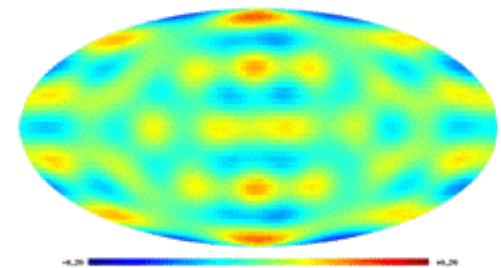
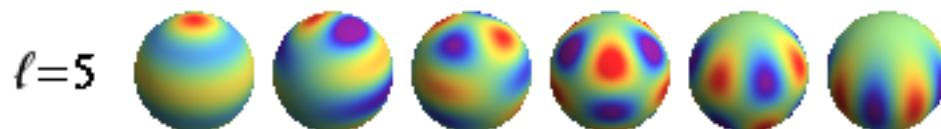

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higher  $\ell$ :

$$Y_\ell^0(\theta, \varphi) \sim \cos \ell \theta + \dots \quad Y_\ell^{\pm \ell}(\theta, \varphi) \sim \sin^\ell \theta e^{\pm \ell i\varphi}$$

Finer scale:  $\ell$  periods around circle

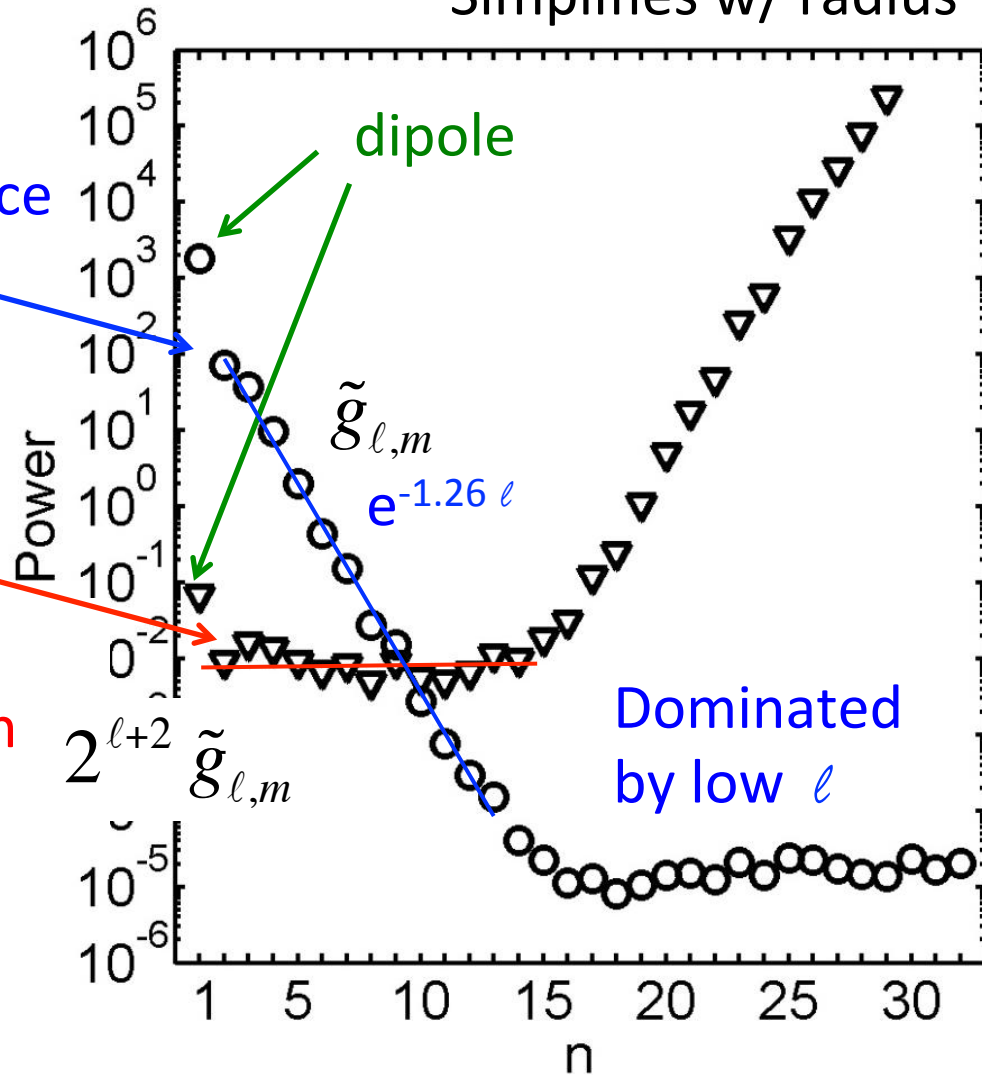
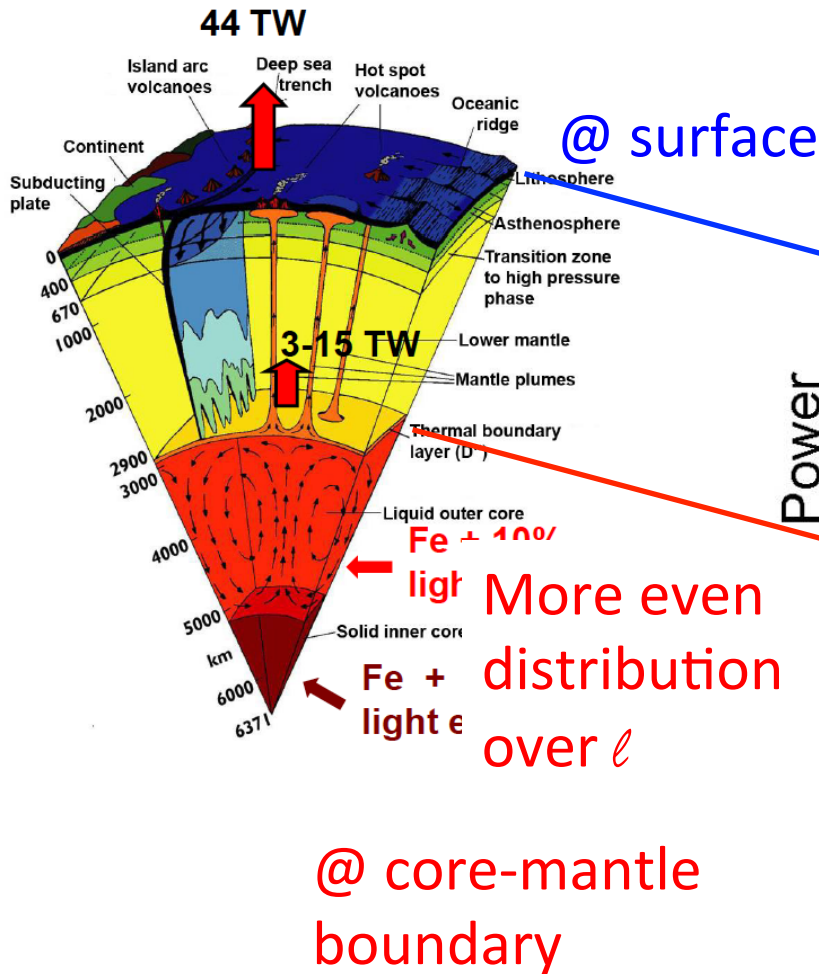
More components:  $2\ell + 1$  real coefficients



$\ell = 9$

$$B_r(r, \theta, \phi) = \sum_{\ell, m} (\ell + 1) \tilde{g}_{\ell, m} Y_{\ell}^m(\theta, \phi) \left( \frac{R_{\oplus}}{r} \right)^{\ell+2}$$

Simplifies w/ radius



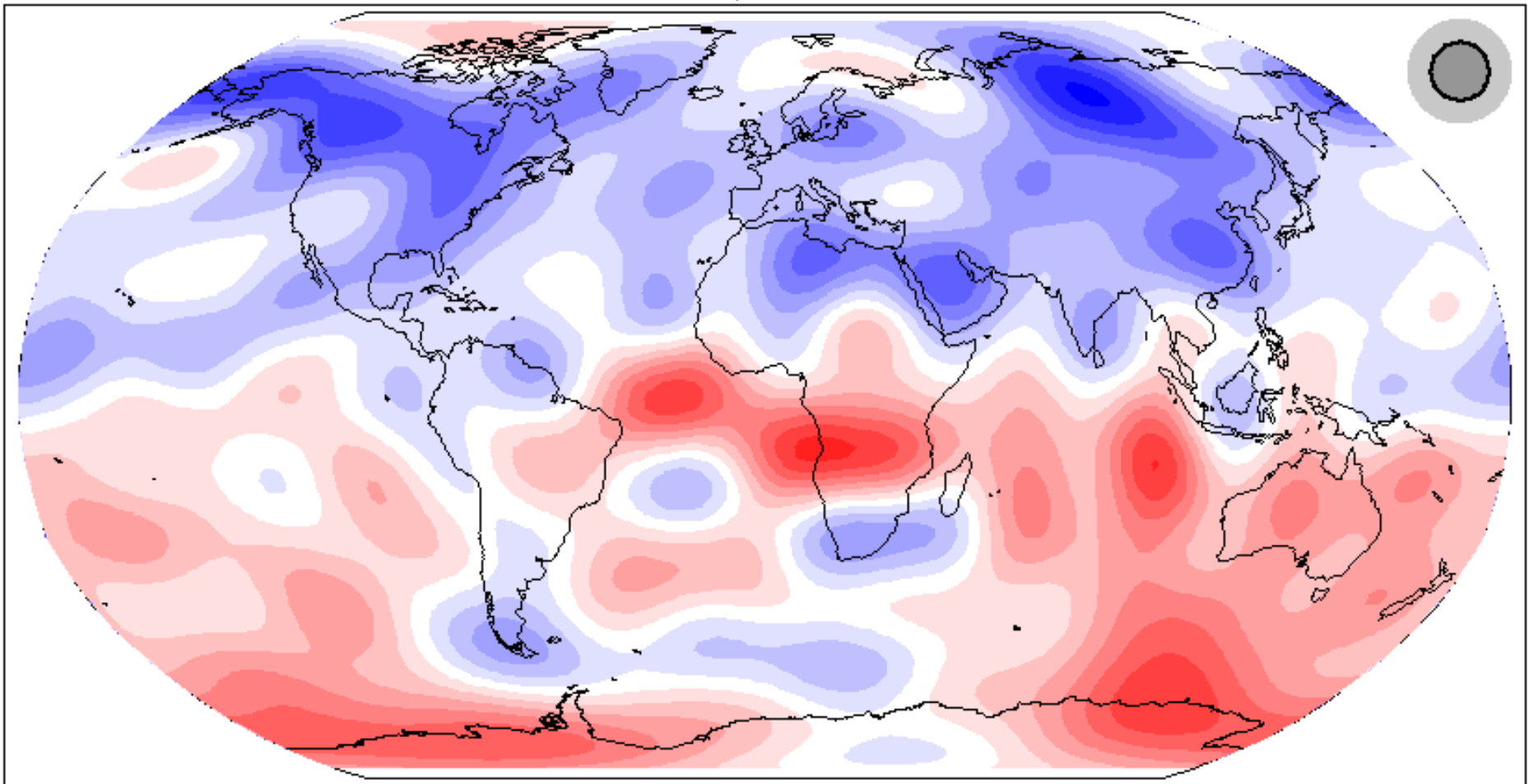
Christensen

# Observation: what $B_r$ looks like today

@ core-mantle boundary: lower boundary of potential region

$l < 14$

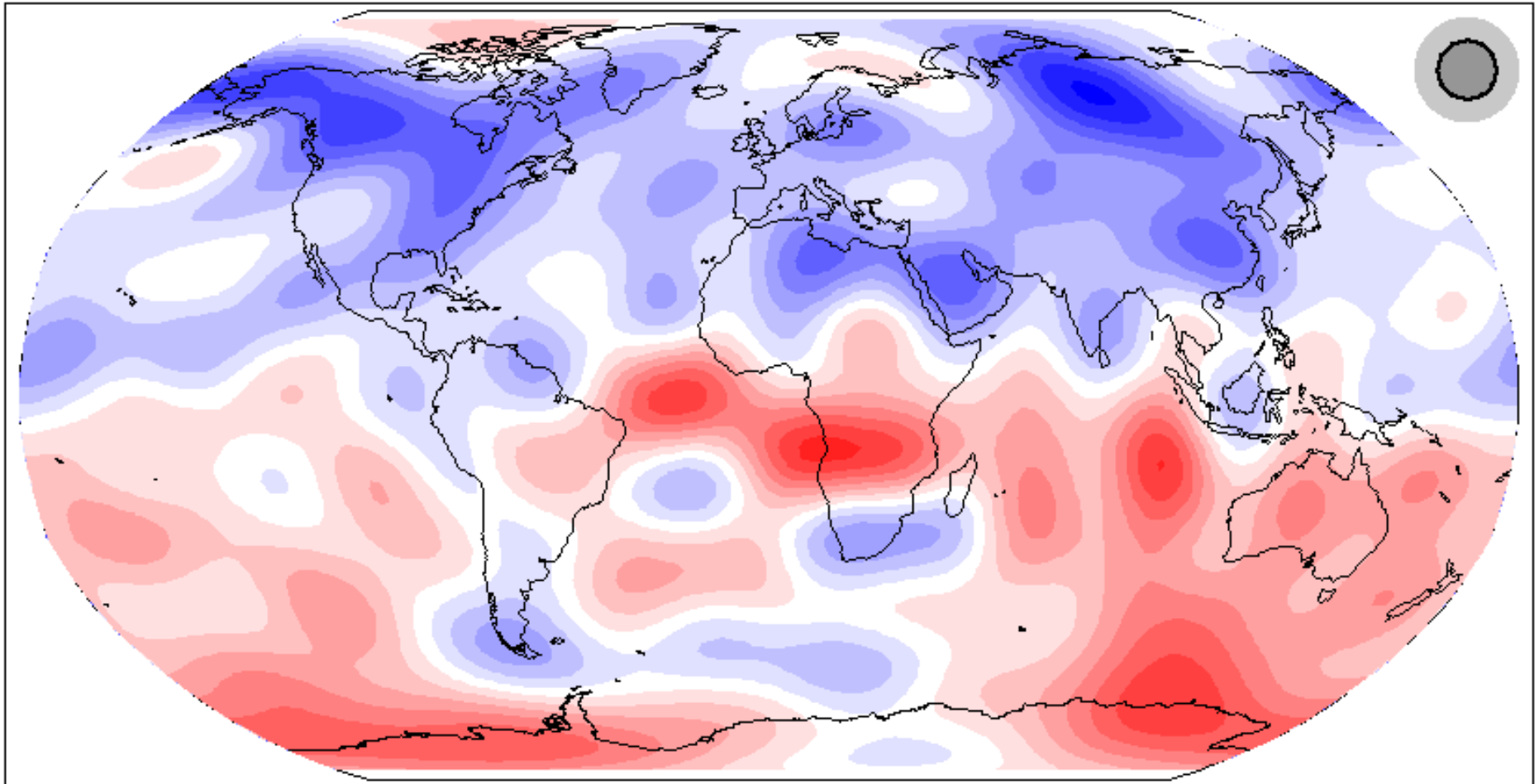
2010:  $B_r$  @  $r = 0.55$



# Simplifies w/ increasing r

$$B_r(r, \theta, \phi) = -\frac{\partial \chi}{\partial r} = \sum_{\ell, m} (\ell + 1) \tilde{g}_{\ell, m} Y_{\ell}^m(\theta, \phi) \left( \frac{R_{\oplus}}{r} \right)^{\ell+2}$$

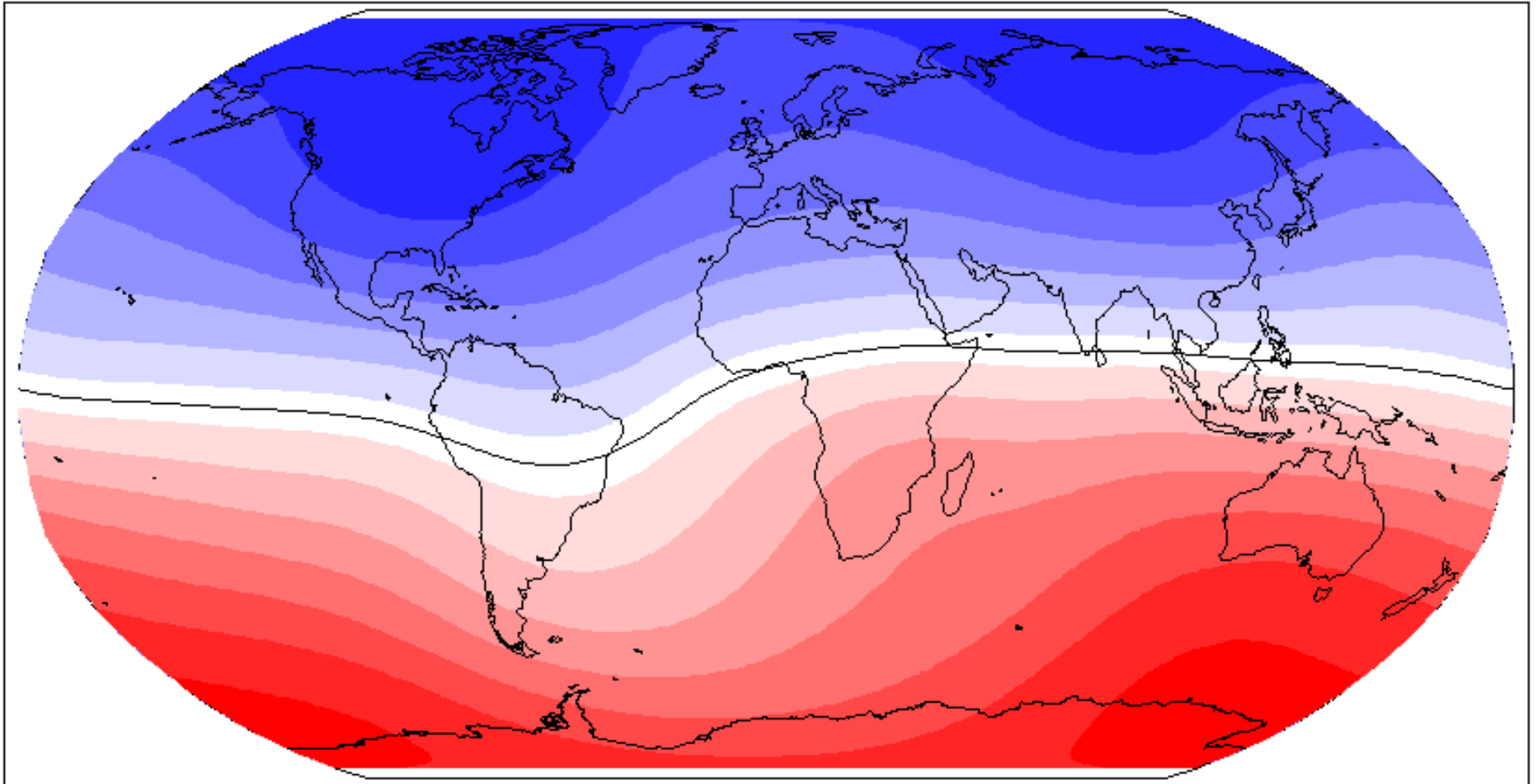
2010:  $B_r$  @  $r = 0.55$



# Evolution of field

@ surface for 100 years

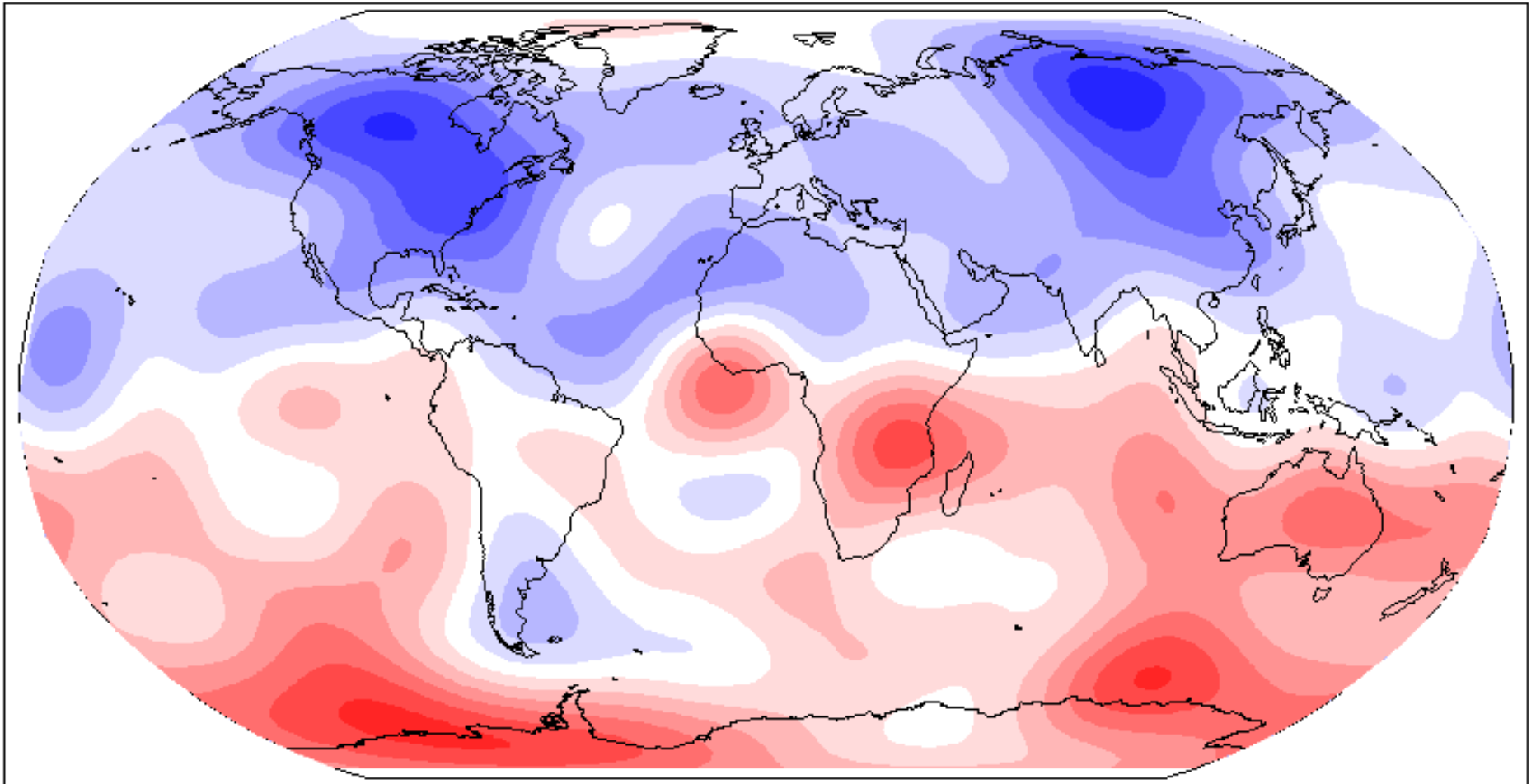
B, 1900



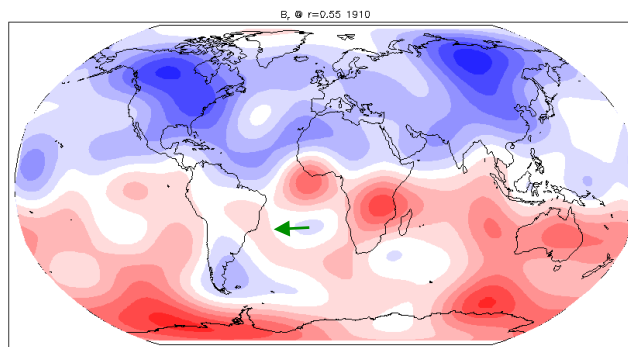
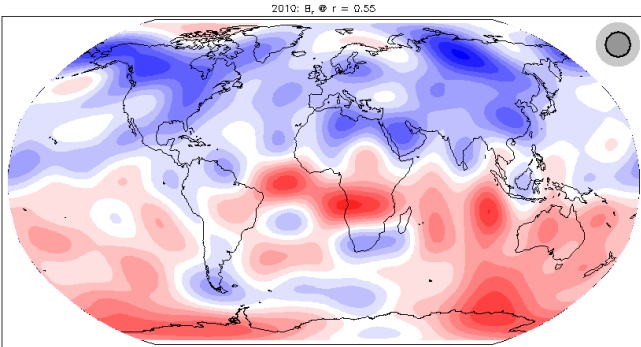
# Evolution of field

@ core-mantle boundary for 100 years

$B_r$  @  $r=0.55$  1900



# Use evolution to infer fluid velocity

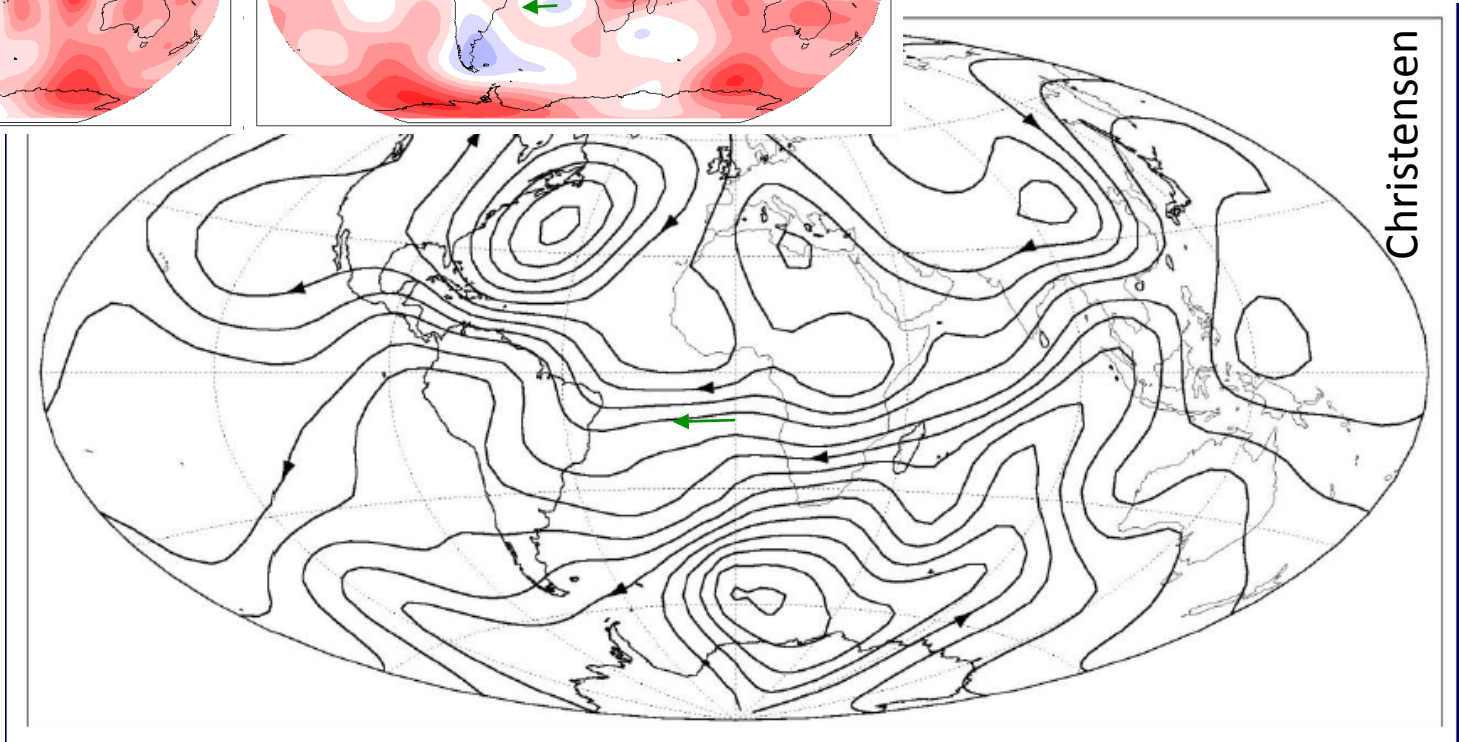


$v \sim 3 \times 10^{-4}$  m/s  
 $\rightarrow \Delta x = 1,000$  km  
 $\rightarrow$  in 100 years

Subsonic flow,  
 Ignore  
 stratification

$$\nabla \cdot \mathbf{v} = 0$$

Ignore diffusion

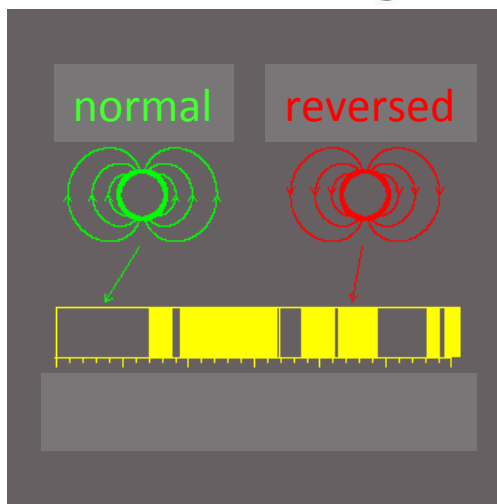
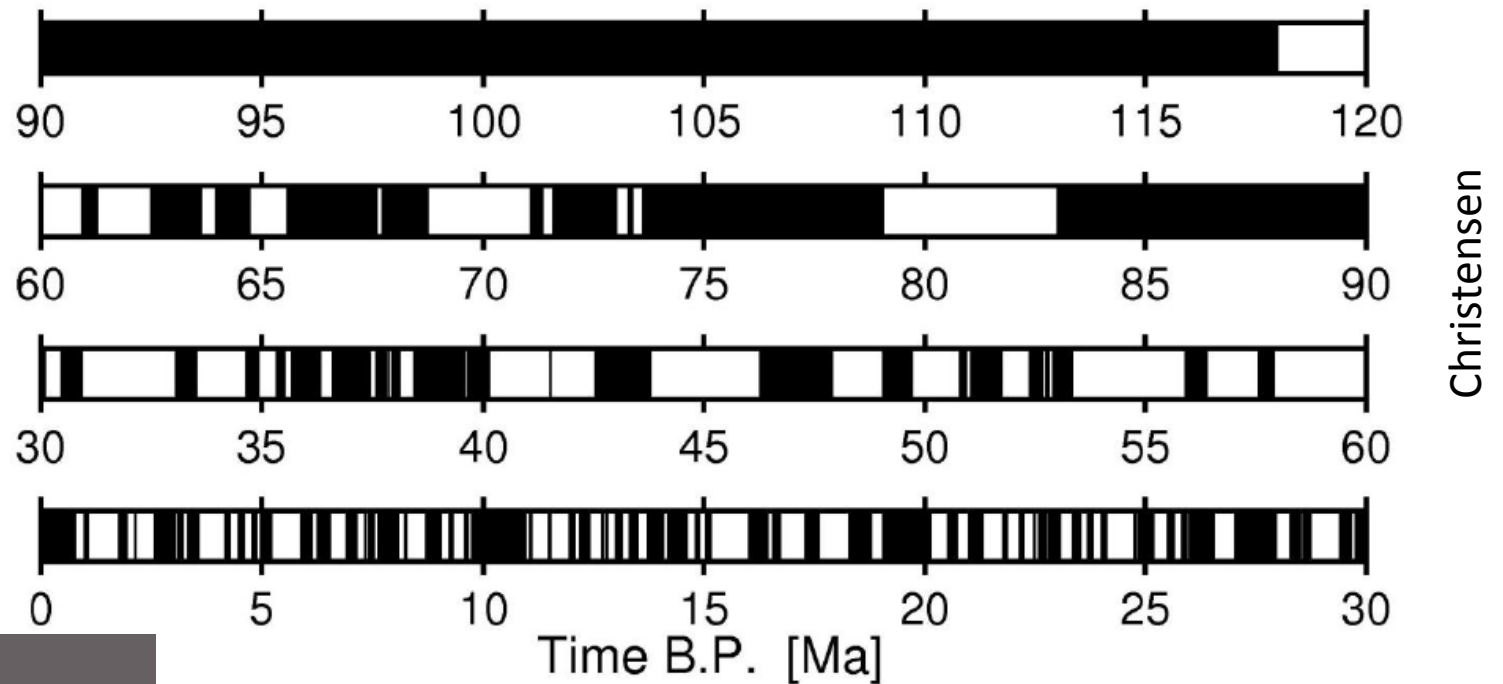


$$\frac{\partial \mathbf{B}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{B} = (\mathbf{B} \cdot \nabla) \mathbf{v} - \mathbf{B}(\nabla \cdot \mathbf{v}) + \eta \nabla^2 \mathbf{B}$$

known

$$\frac{\partial B_r}{\partial t} + \nabla \cdot (\mathbf{v} B_r) = 0$$

# Longer-term evolution

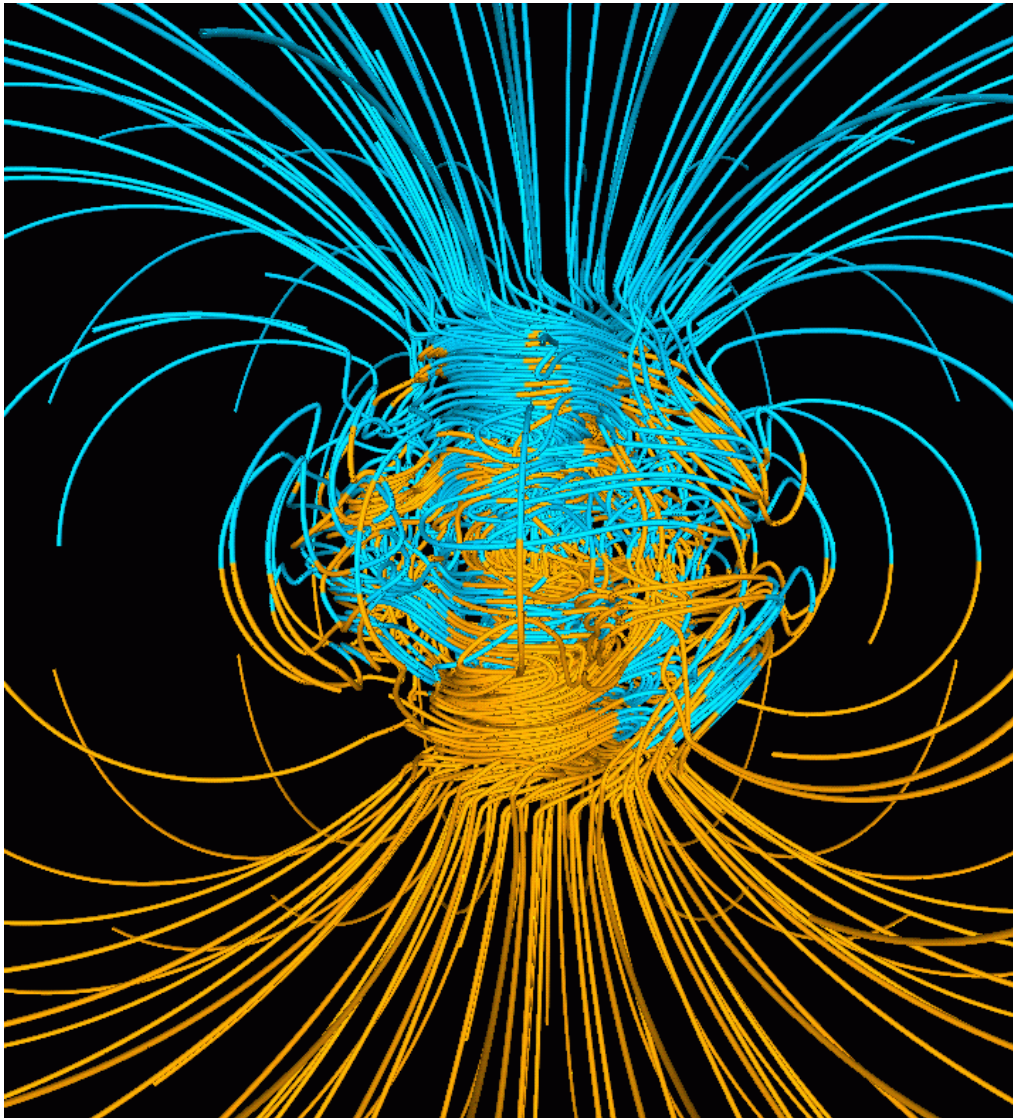


Like toy dynamo, Earth works in 2 modes. Flips between them seemingly at random



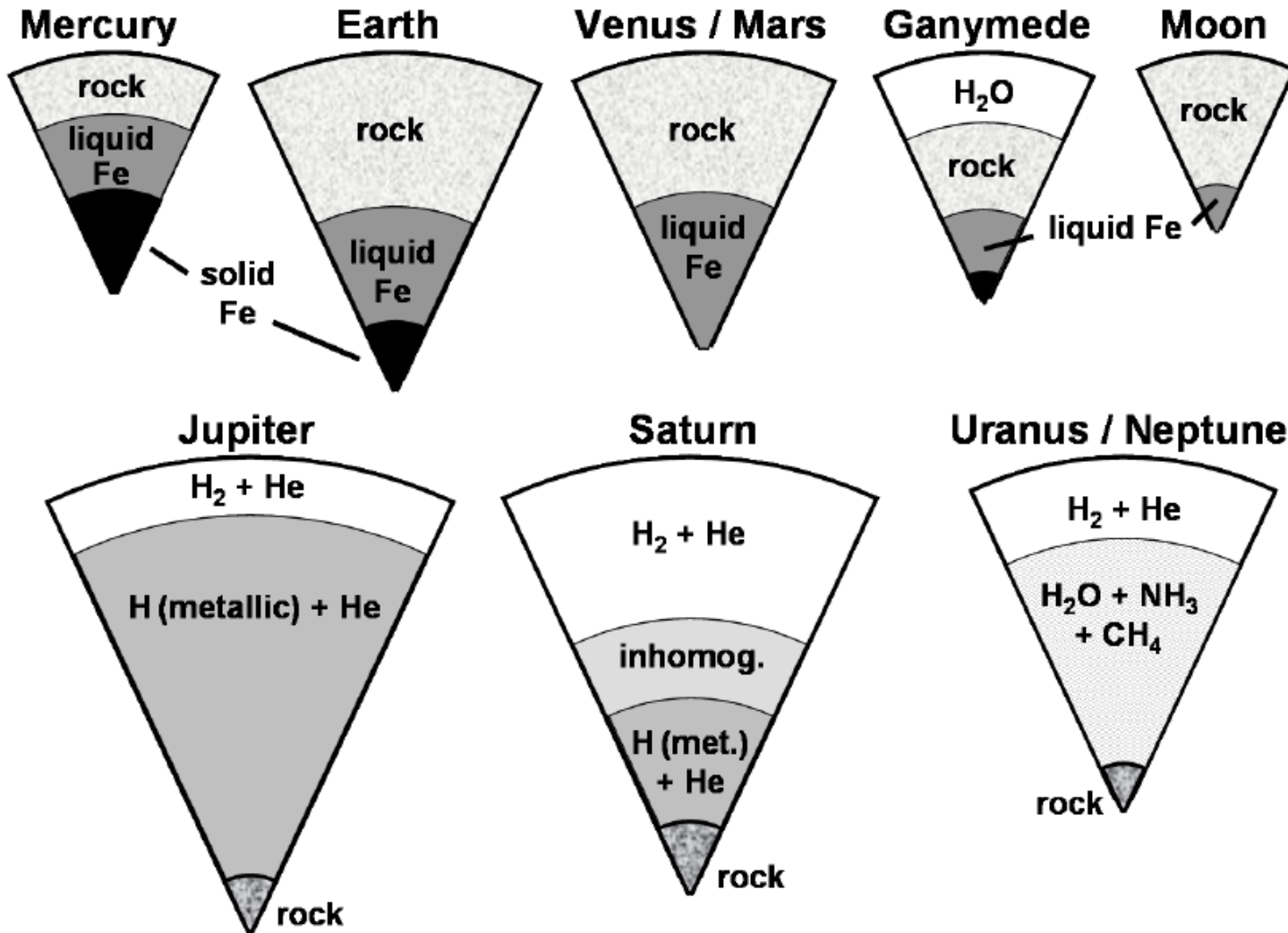
# Model geodynamo

<http://www.es.ucsc.edu/~glatz/geodynamo.html>



- Glatzmaier & Roberts 1995
- Numerical solution of MHD
- Toroidal structure inside convecting core

# Other planets

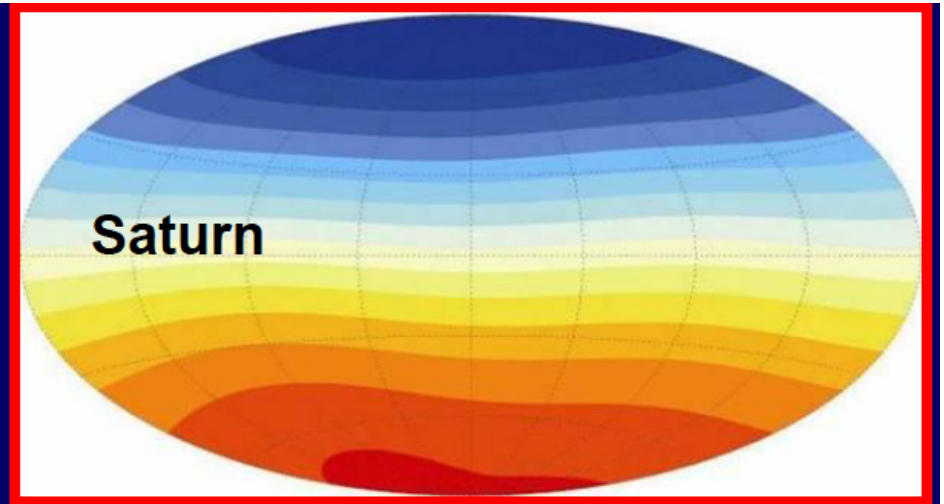
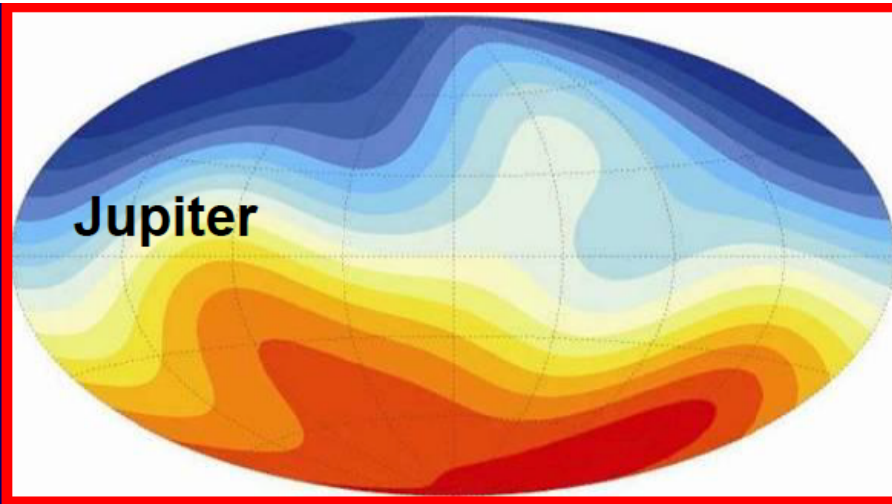


# Other planets

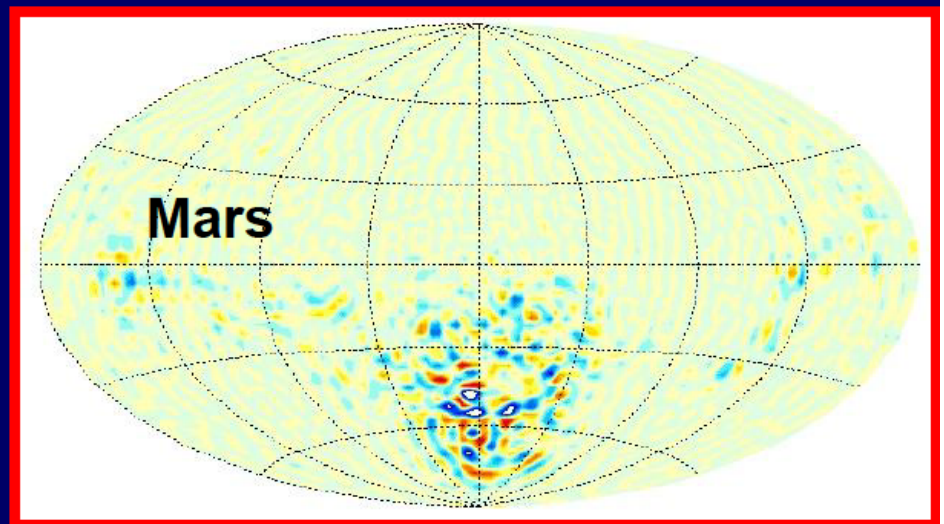
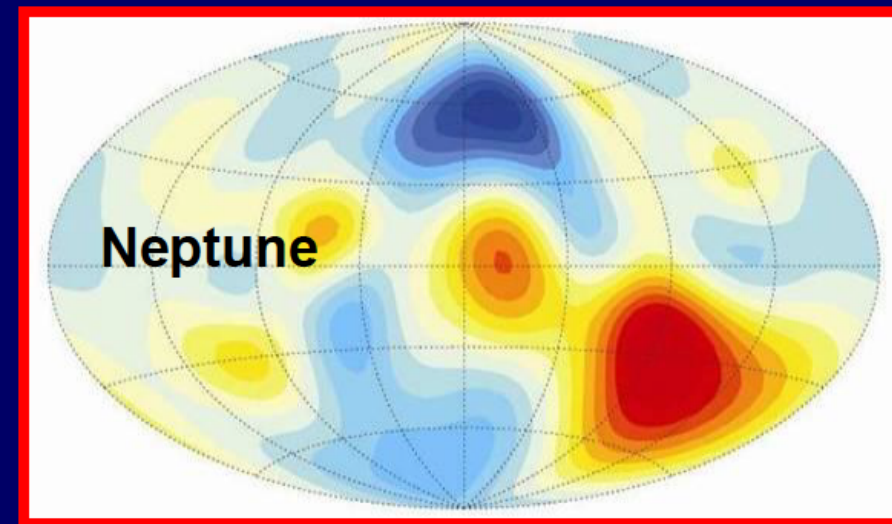
Christensen

Planet	Dynamo	$R_c/R_p$	$B_s$ [ $\mu$ T]	Dip. tilt	<u>Quadr</u> Dipole
Mercury	Yes (?)	0.75	0.35	<5° ?	0.1-0.5
Venus	No	0.55			
Earth	Yes	0.55	44	10.4°	0.04
Moon	No	0.2 ?			
Mars	No, but in past	0.5			
Jupiter	Yes	0.84	640	9.4°	0.10
Saturn	Yes	0.6	31	0°	0.02
Uranus	Yes	0.75	48	59°	1.3
Neptune	Yes	0.75	47	45°	2.7
Ganymede	Yes	0.3 ?	1.0	< 5° ?	?

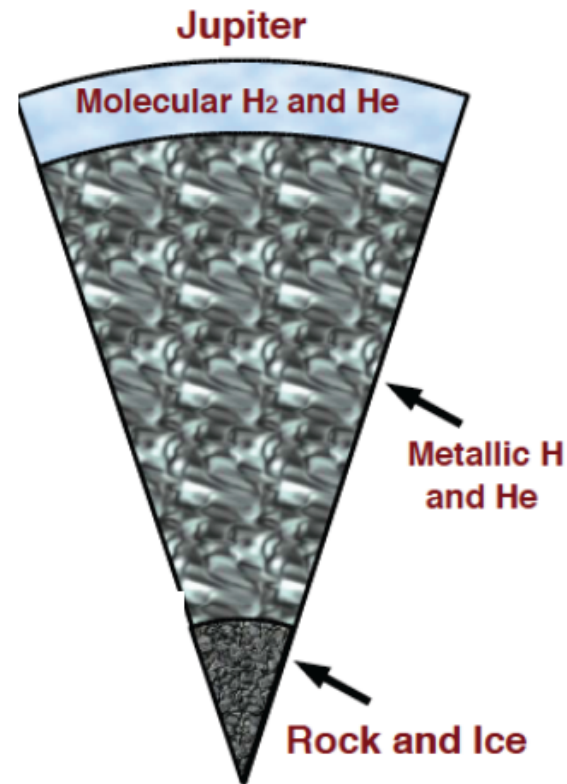
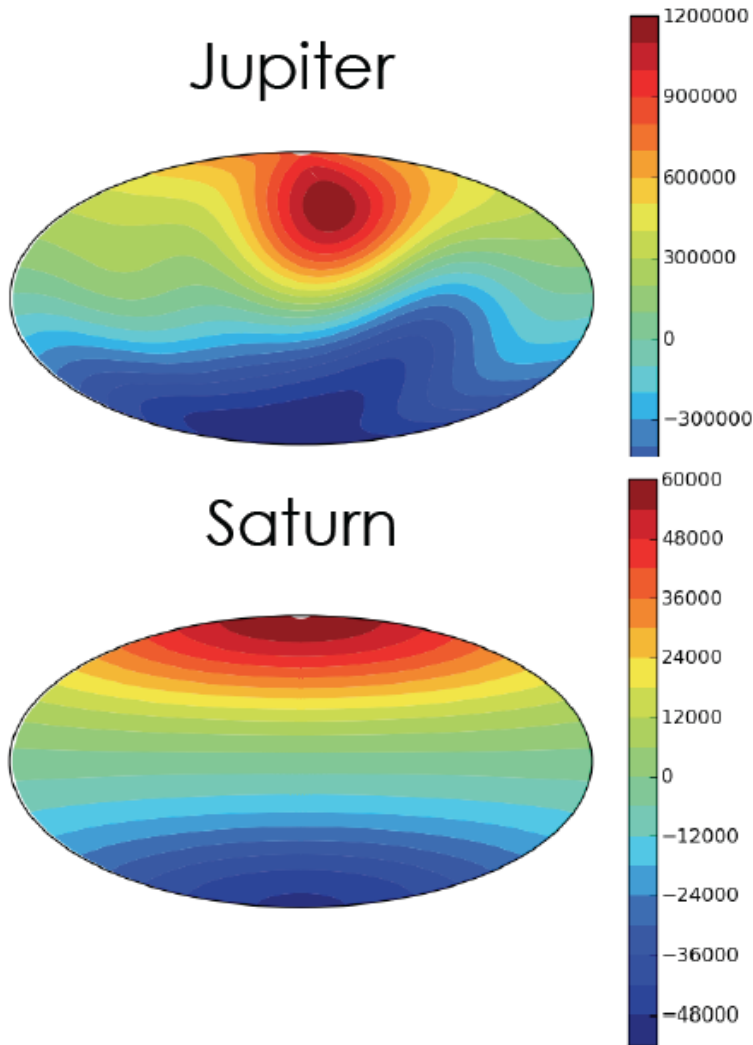
# What that means



Christensen



# GAS GIANTS



Stanley

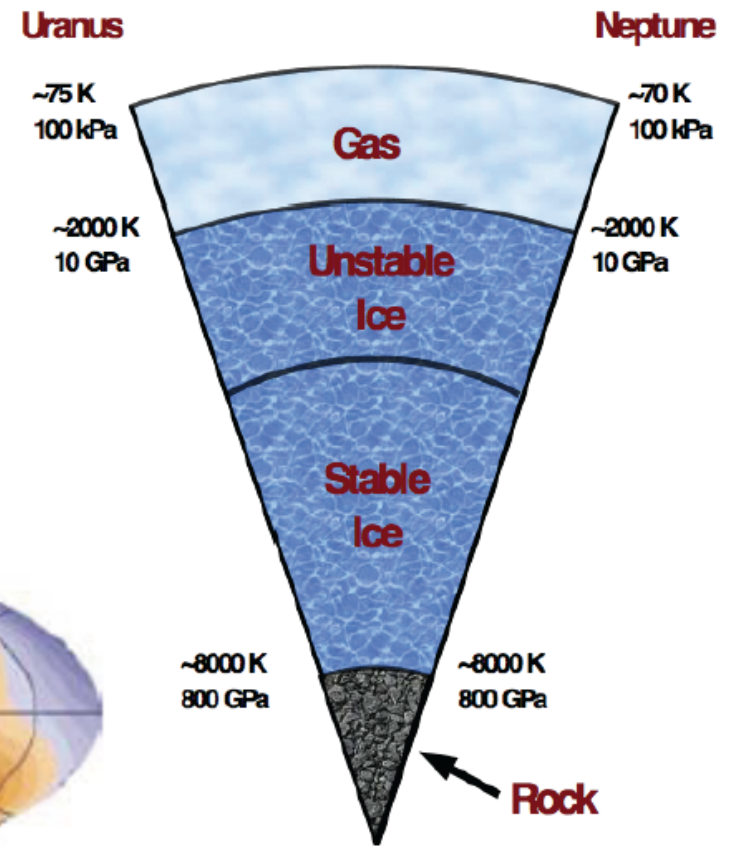
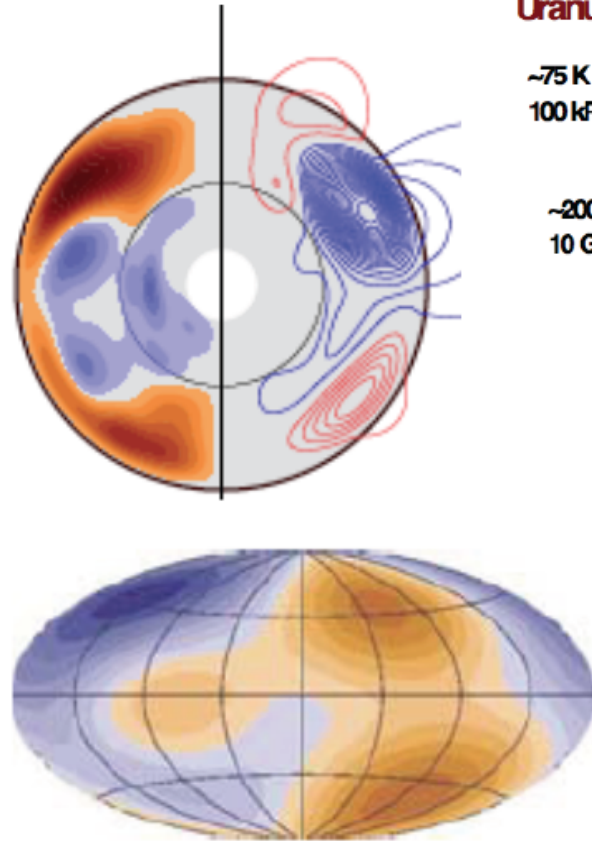
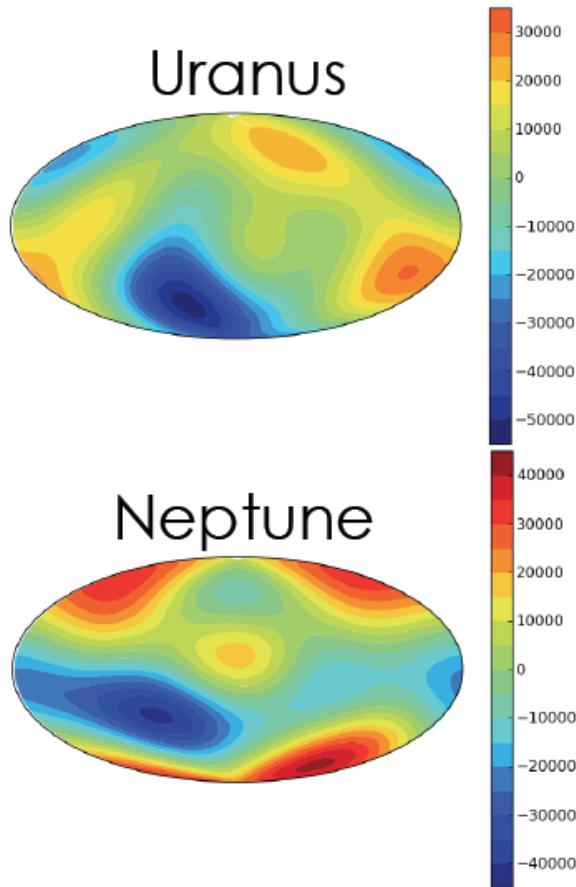
- large pressure range → radially variable properties can be important

# ICE GIANTS

Stanley

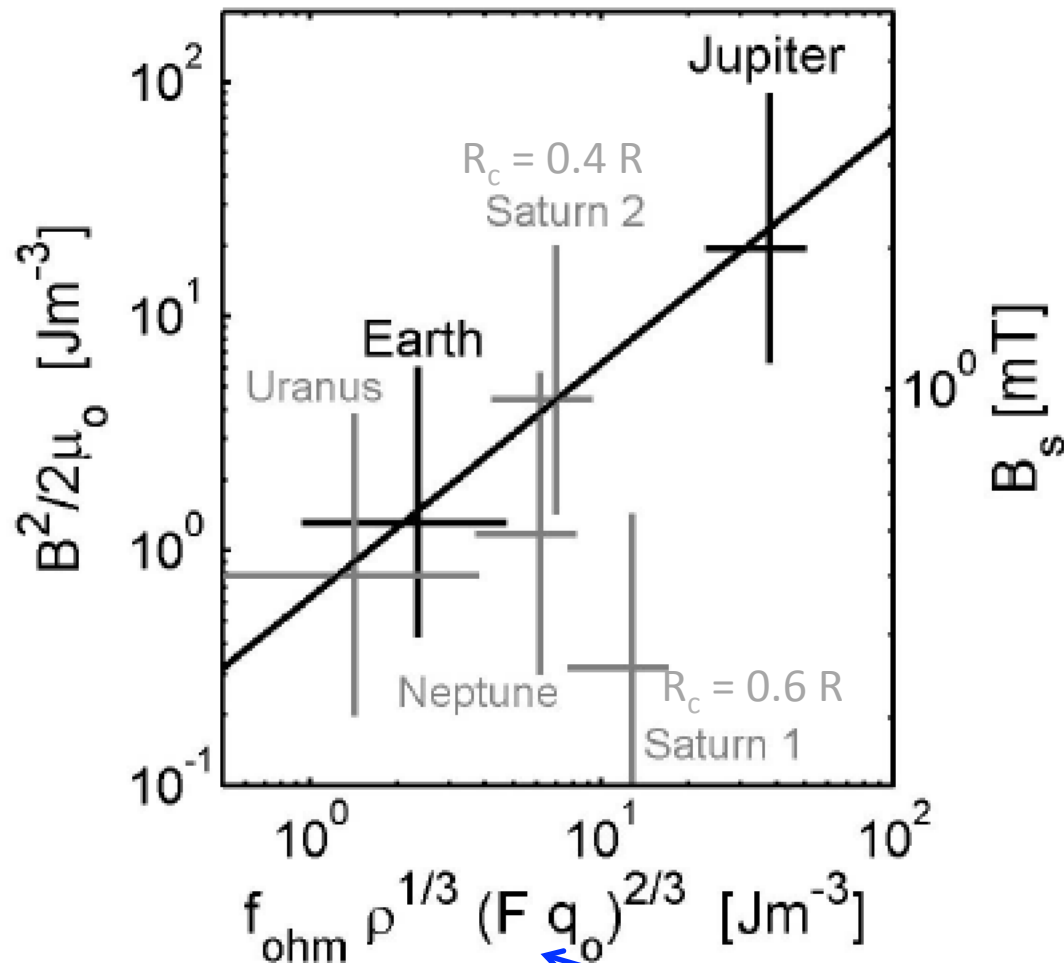
Stanley & Bloxham 2004, 2006

- work in a geometry suggested by low heat flow observations



# Level of saturation

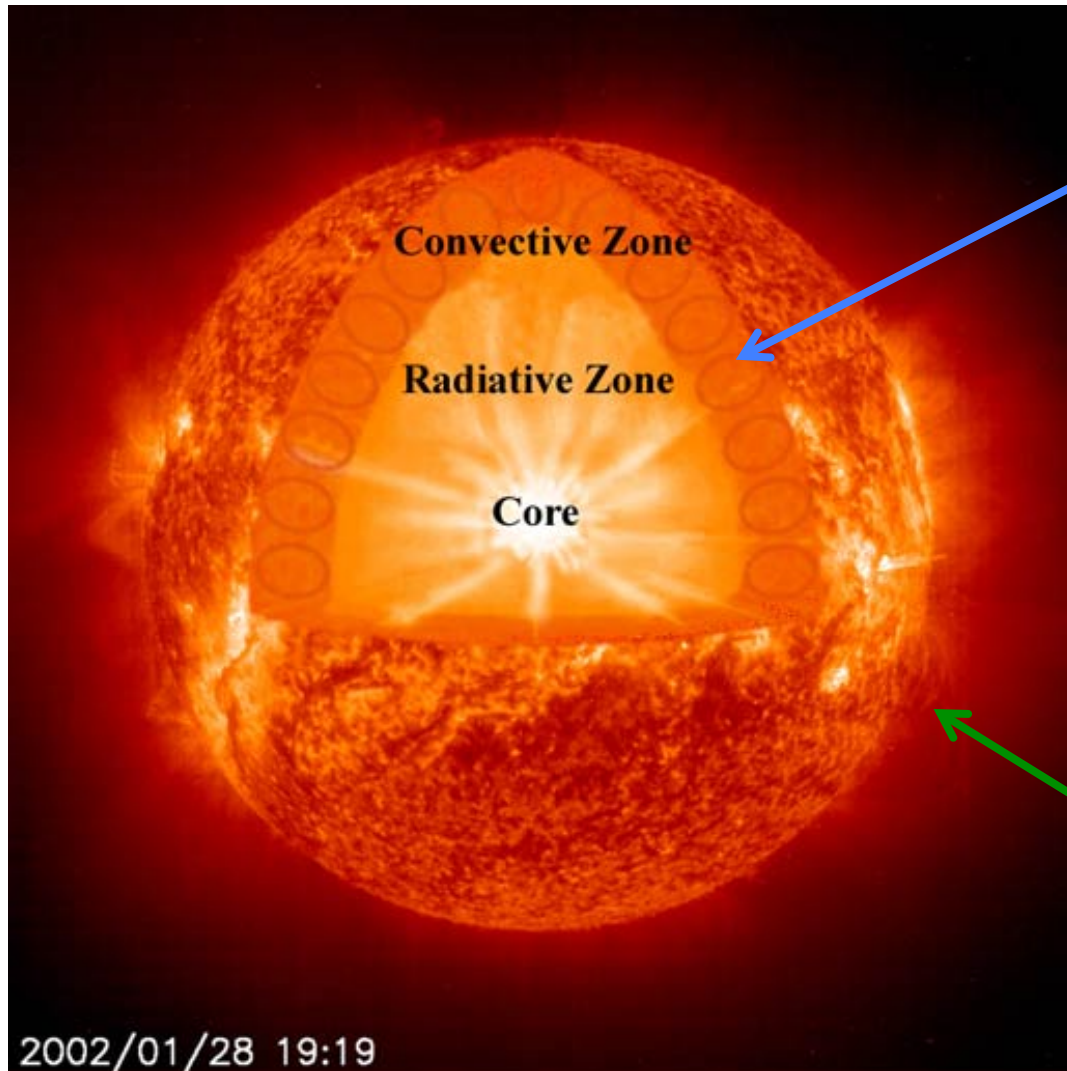
from Christensen



B saturates  
(exp growth ends)  
when driving  
power – thermal  
conduction  $q_0$  –  
balances Ohmic  
dissipation

dimensionless factors

# How it works in the Sun

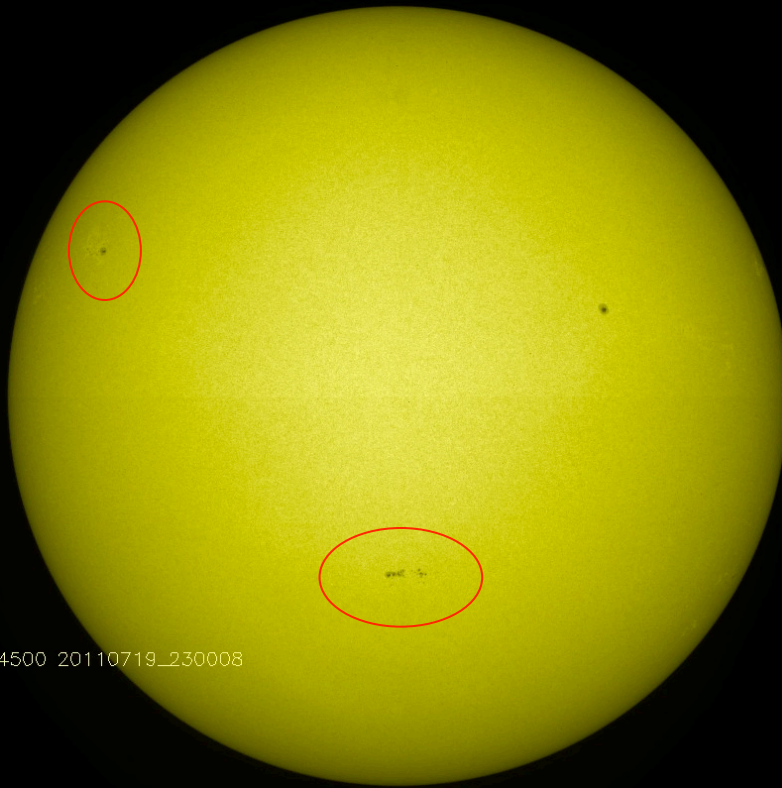


- Entire Star: H/He plasma
- Convection Zone (CZ)
  - Outer 200,000 km
  - Turbulence:  
 $Re = 10^{10}$
  - Thermally driven
  - Good conductor  
 $Rm = 10^8$
  - Rotation effective  
 $Ro = 10^{-2}$
- Corona – conductive but tenuous:
  - $J$  smaller ( $\sim 0$ ?)

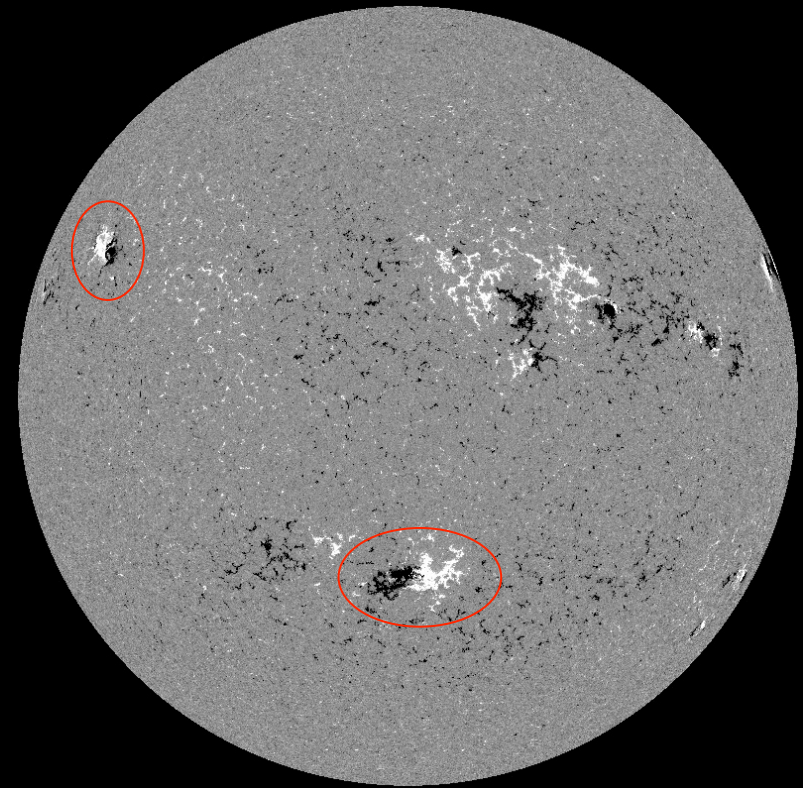


# Evidence of the dynamo

Magnetic field where there are sunspots



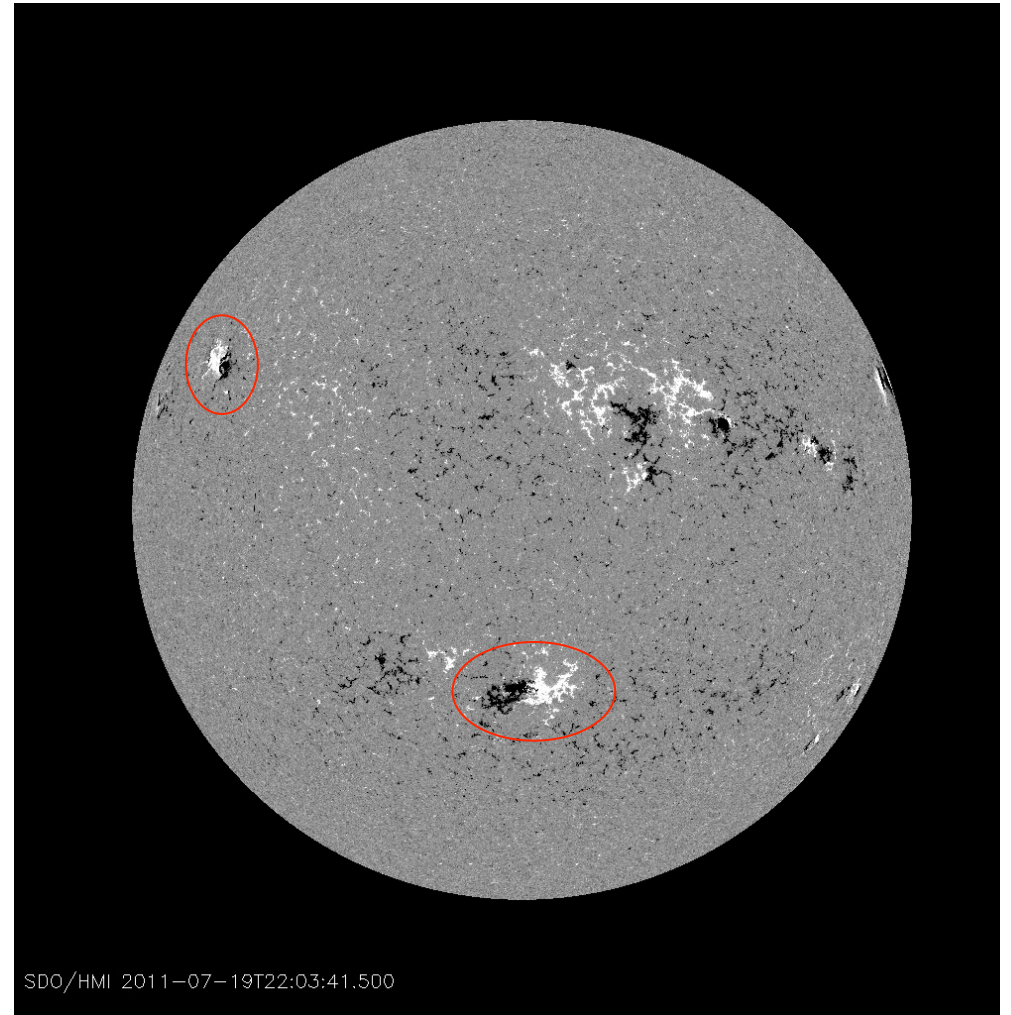
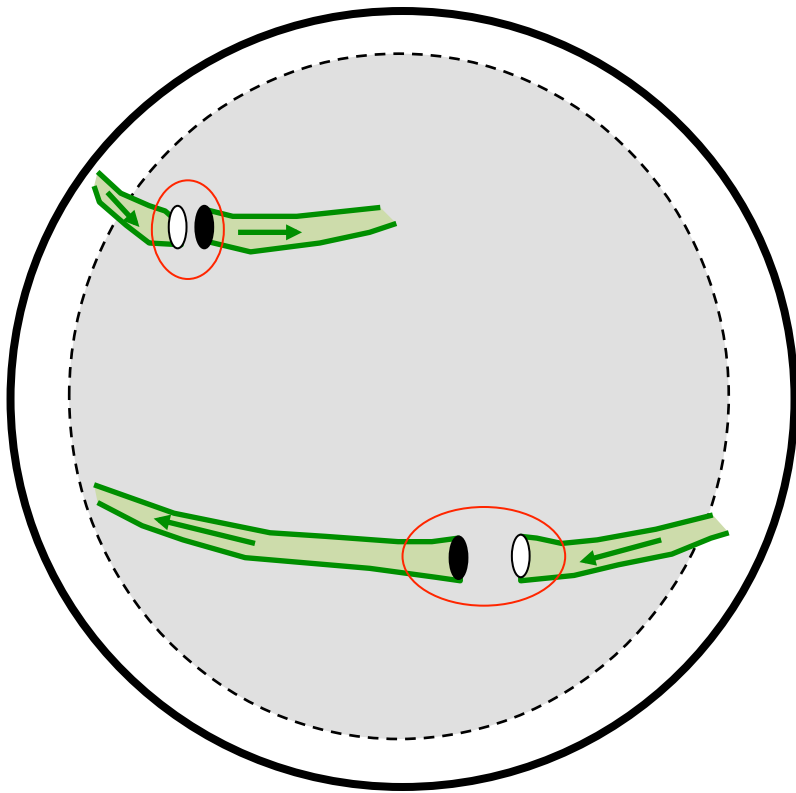
SDO/AIA-4500 20110719\_230008



Field outside sunspots and elsewhere too

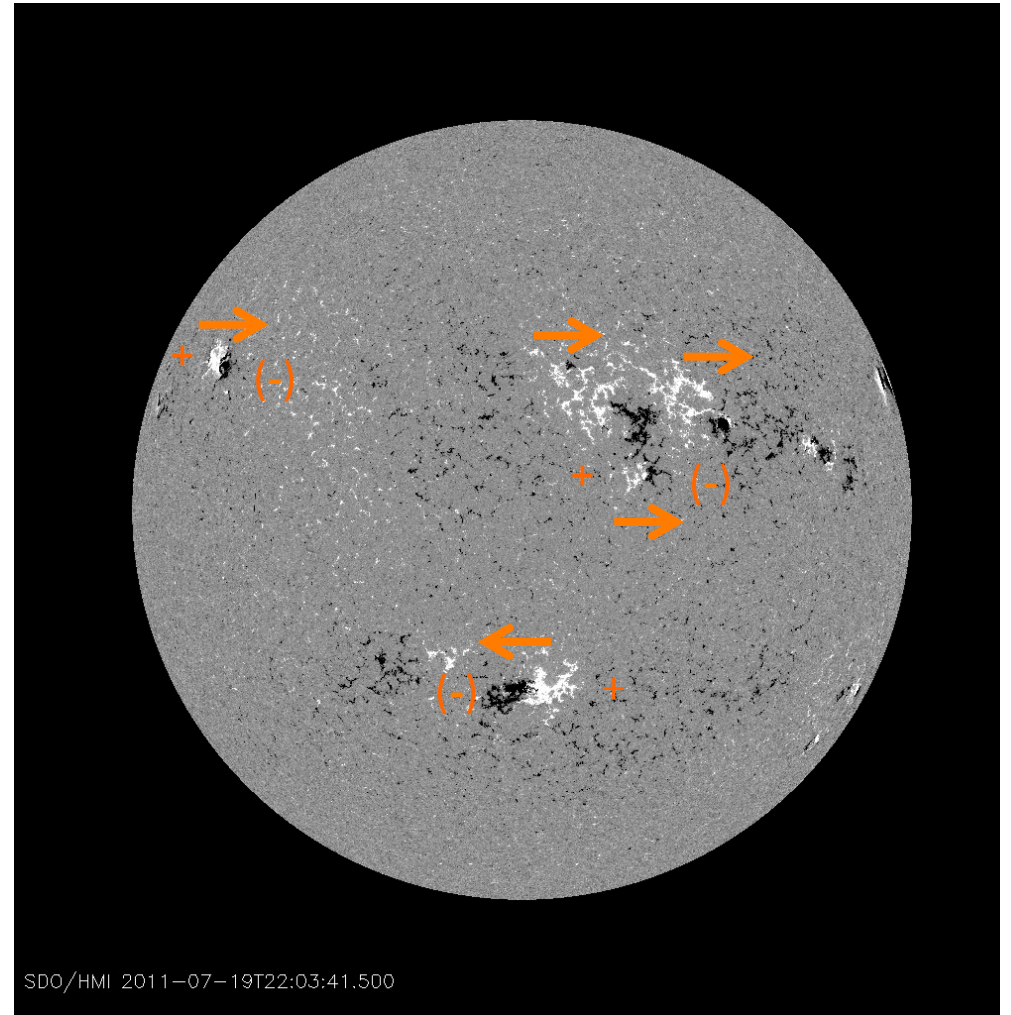
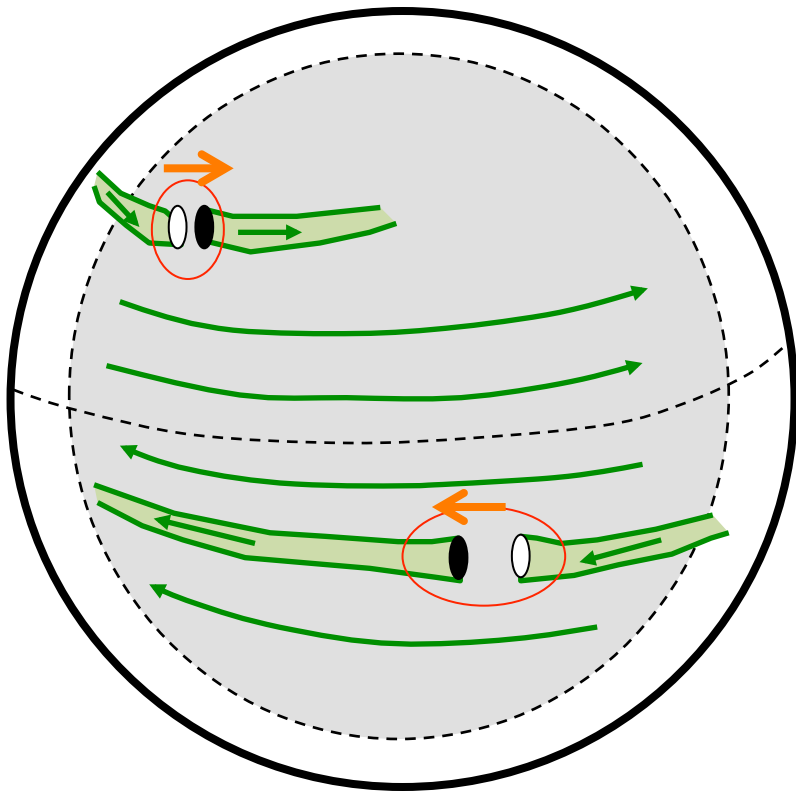
# Evidence of the dynamo

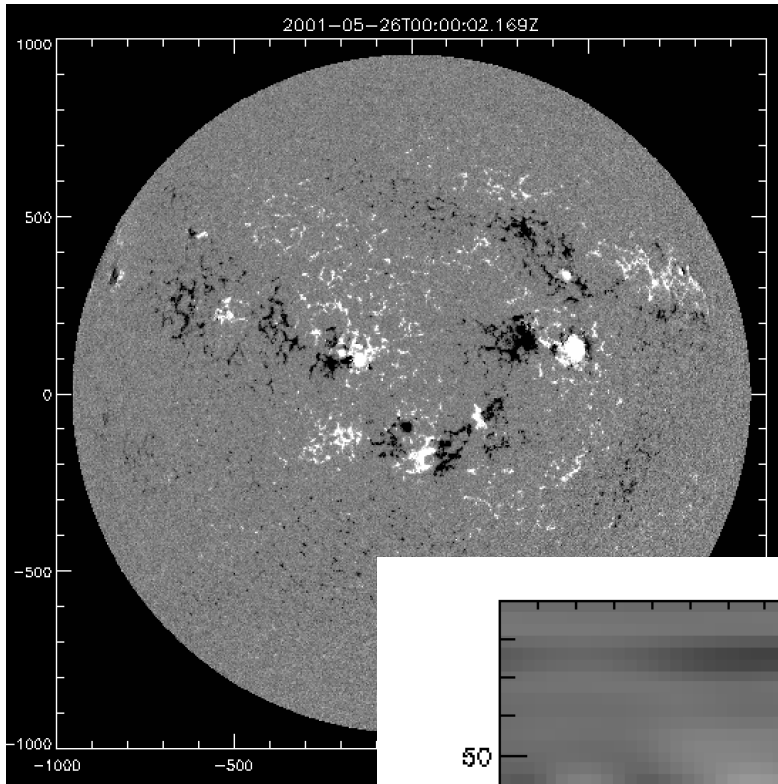
Field is **fibril**



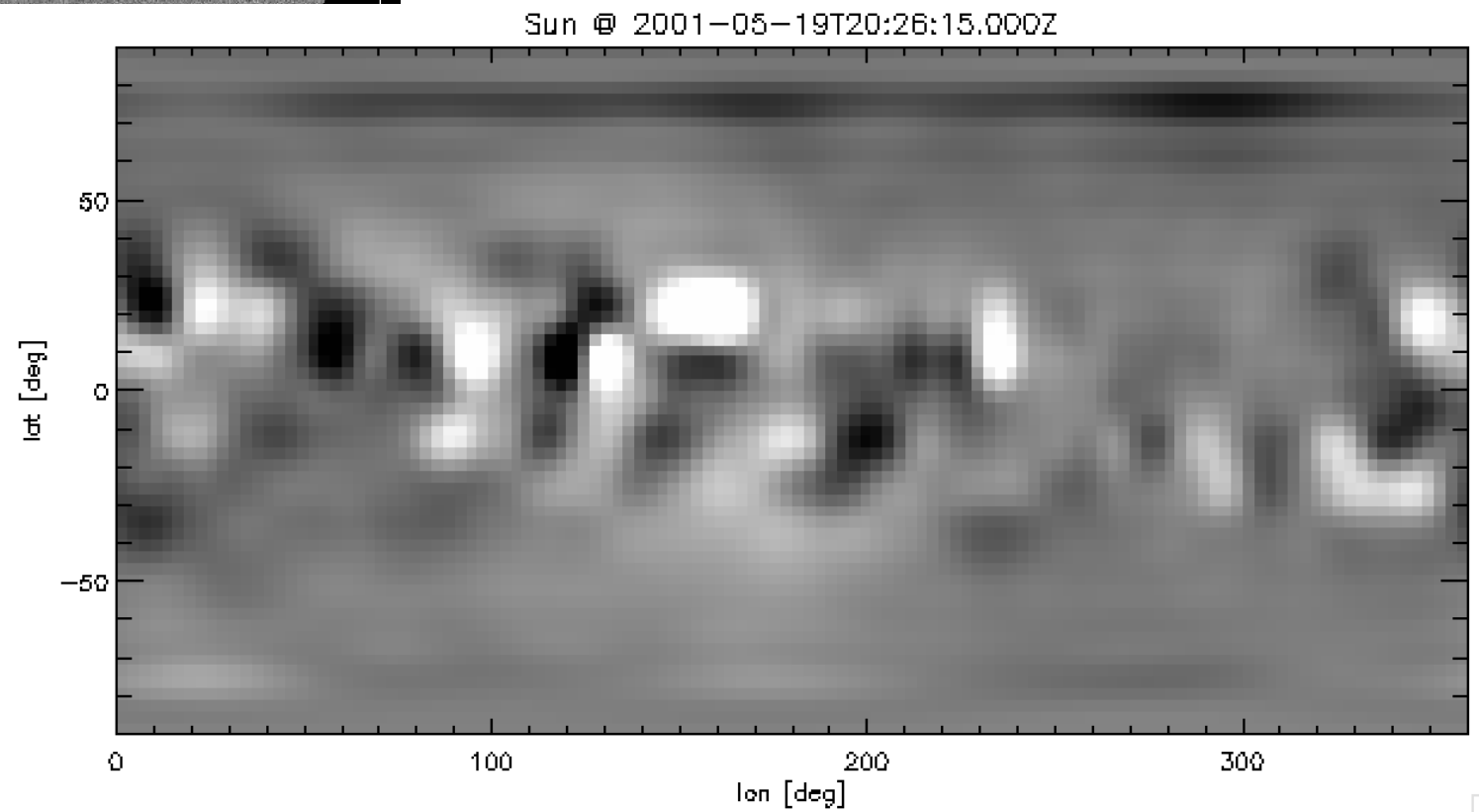
# Evidence of the dynamo

Field orientation: mostly toroidal

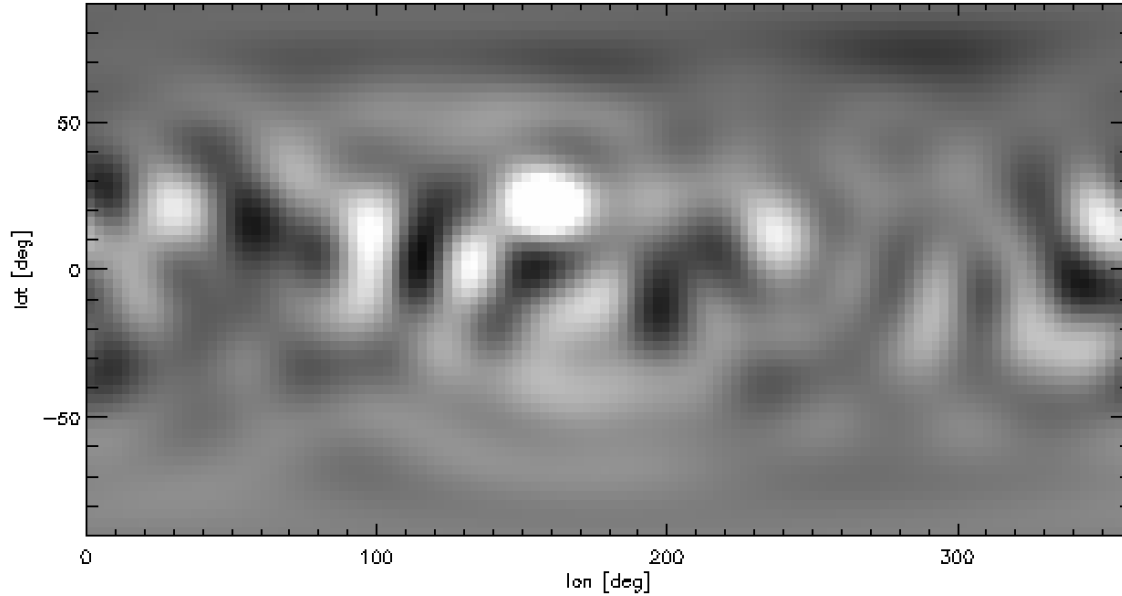




Synoptic plot: unwrapped  
view built up over time



$l < 14$  @ 2001-05-19T20:26:15.000Z

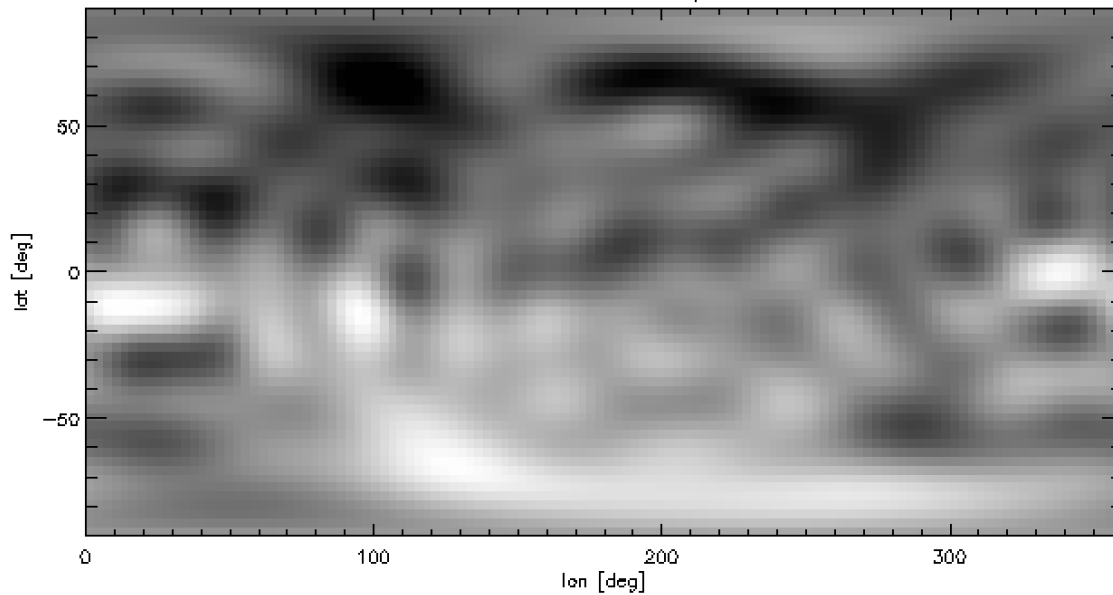


$$Rm = 10^8$$

$$Ro = 10^{-2}$$

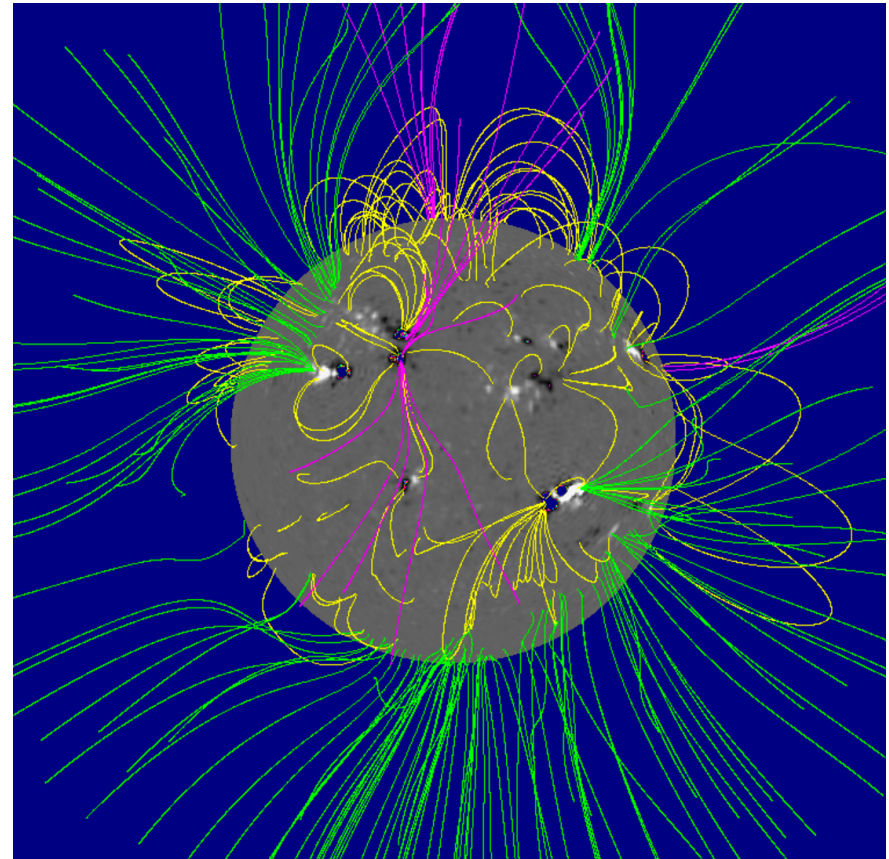
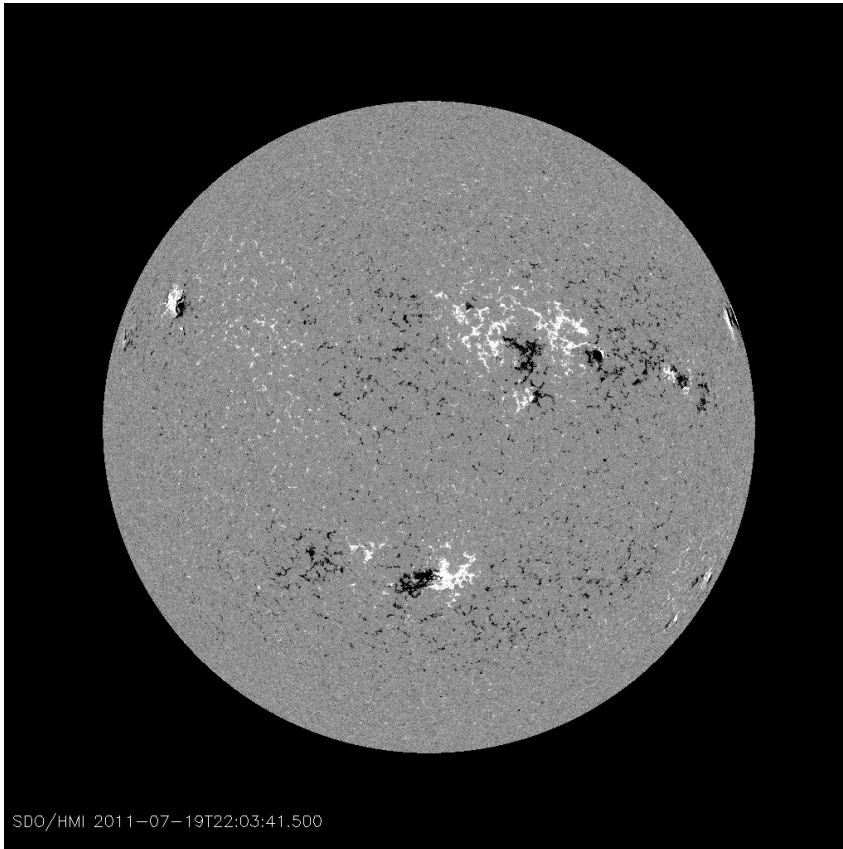
Dynamo  
comparison:  
Sun vs. Earth

Earth 2010 @  $r = 0.55$ ;  $l < 14$



$$Rm = 10^2$$

$$Ro = 10^{-6}$$



Assume corona has small  
(negligible) current:

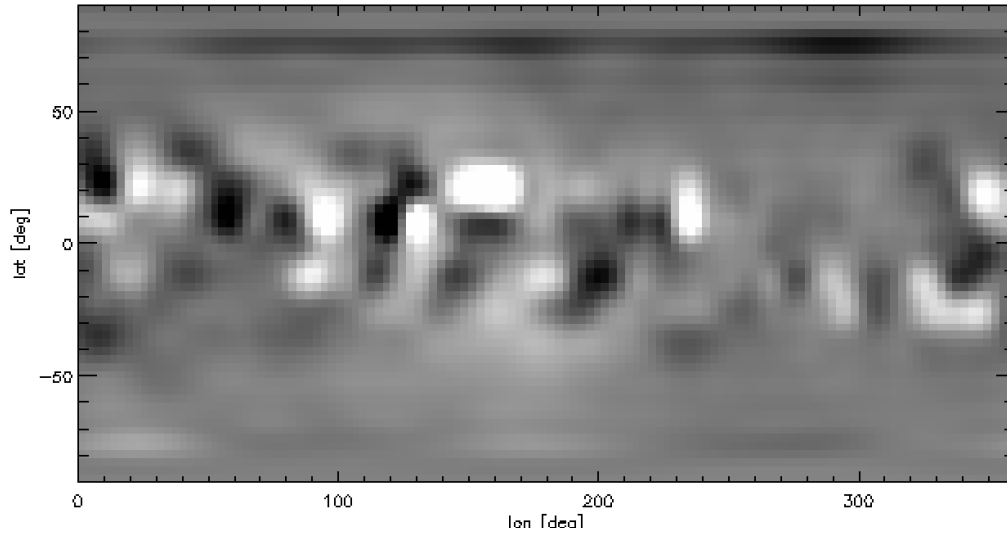
$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} = 0$$

$$\mathbf{B} = -\nabla \chi$$

$$\nabla \cdot \mathbf{B} = -\nabla^2 \chi = 0$$

$$\chi(r, \theta, \phi) = \sum_{\ell, m} \tilde{g}_{\ell, m} Y_{\ell}^m(\theta, \phi) \left( \frac{R_{\oplus}}{r} \right)^{\ell+1}$$

Sun @ 2001-05-19T20:26:15.000Z

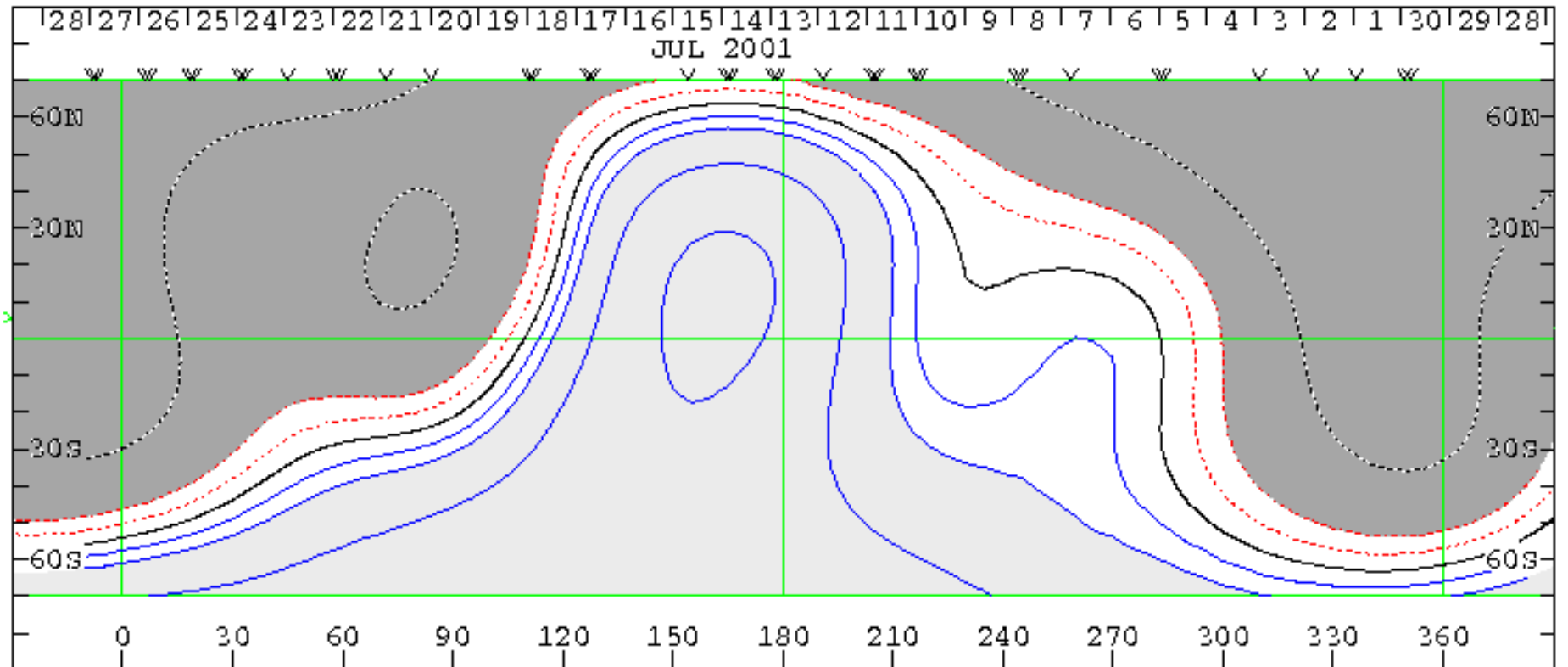


$r = R_{\odot}$

$r = 2.5 R_{\odot}$

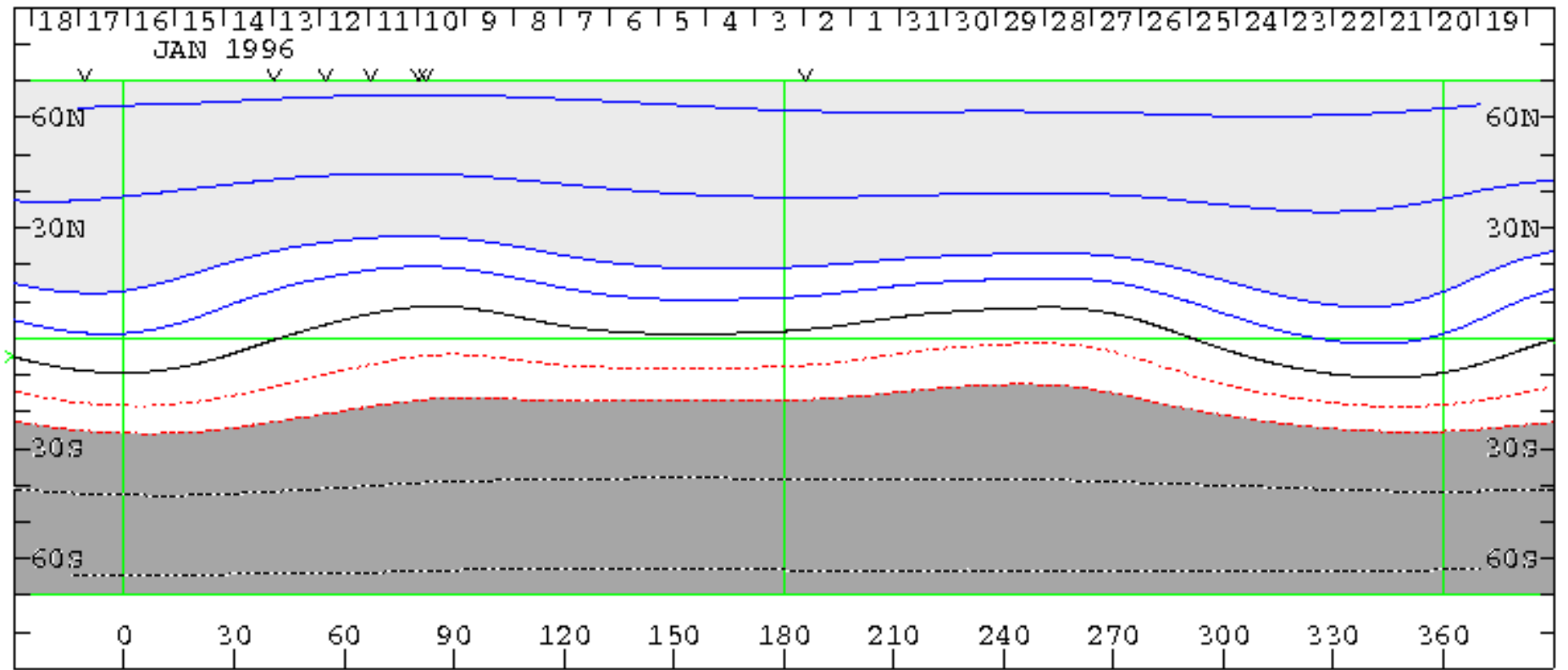
WSO - Source Surface Field

0, ±1, 2, 5, 10, 20 MicroTesla



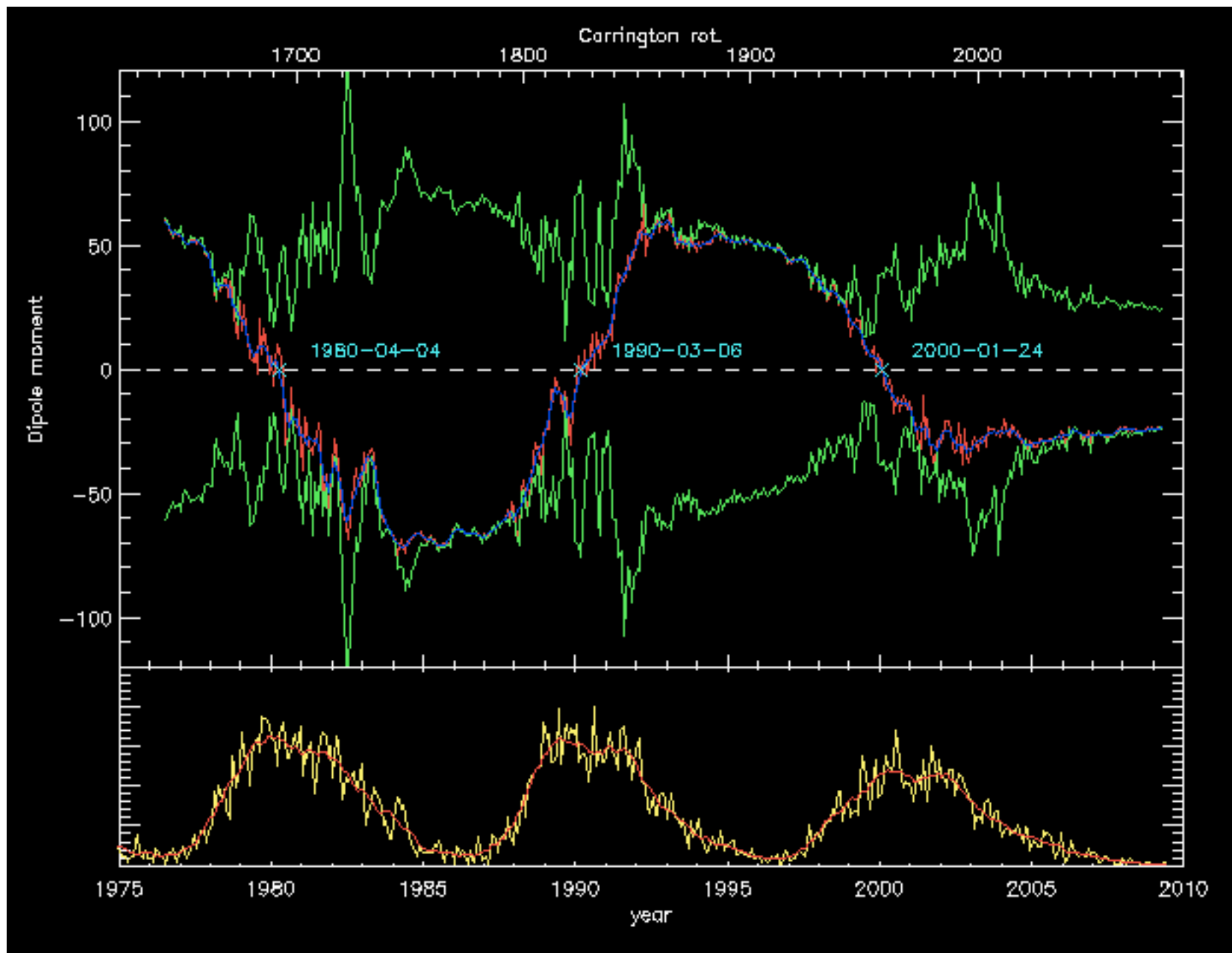
WSO - Source Surface Field

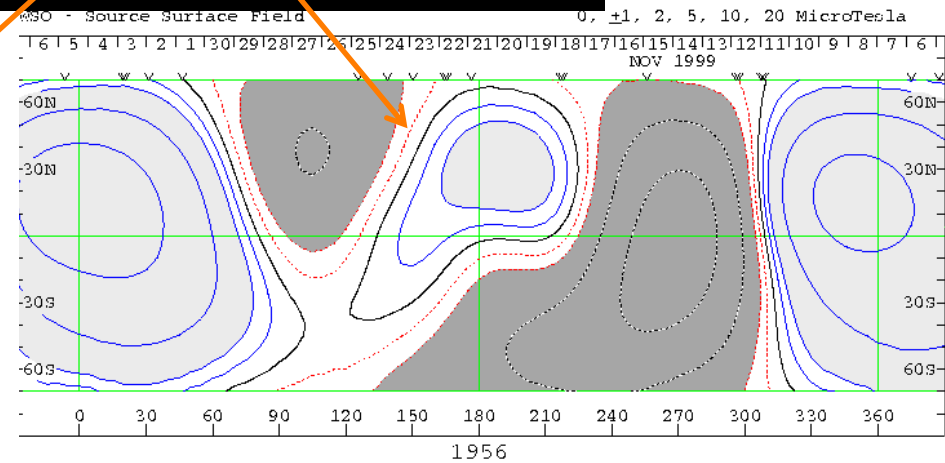
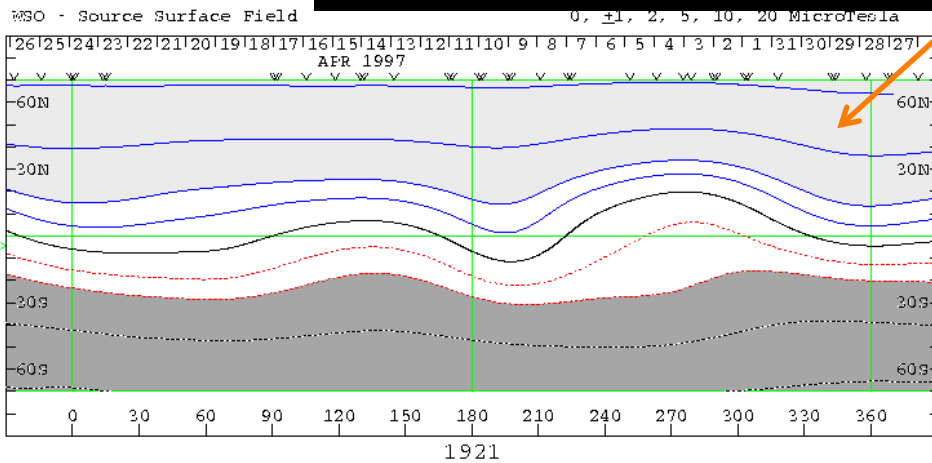
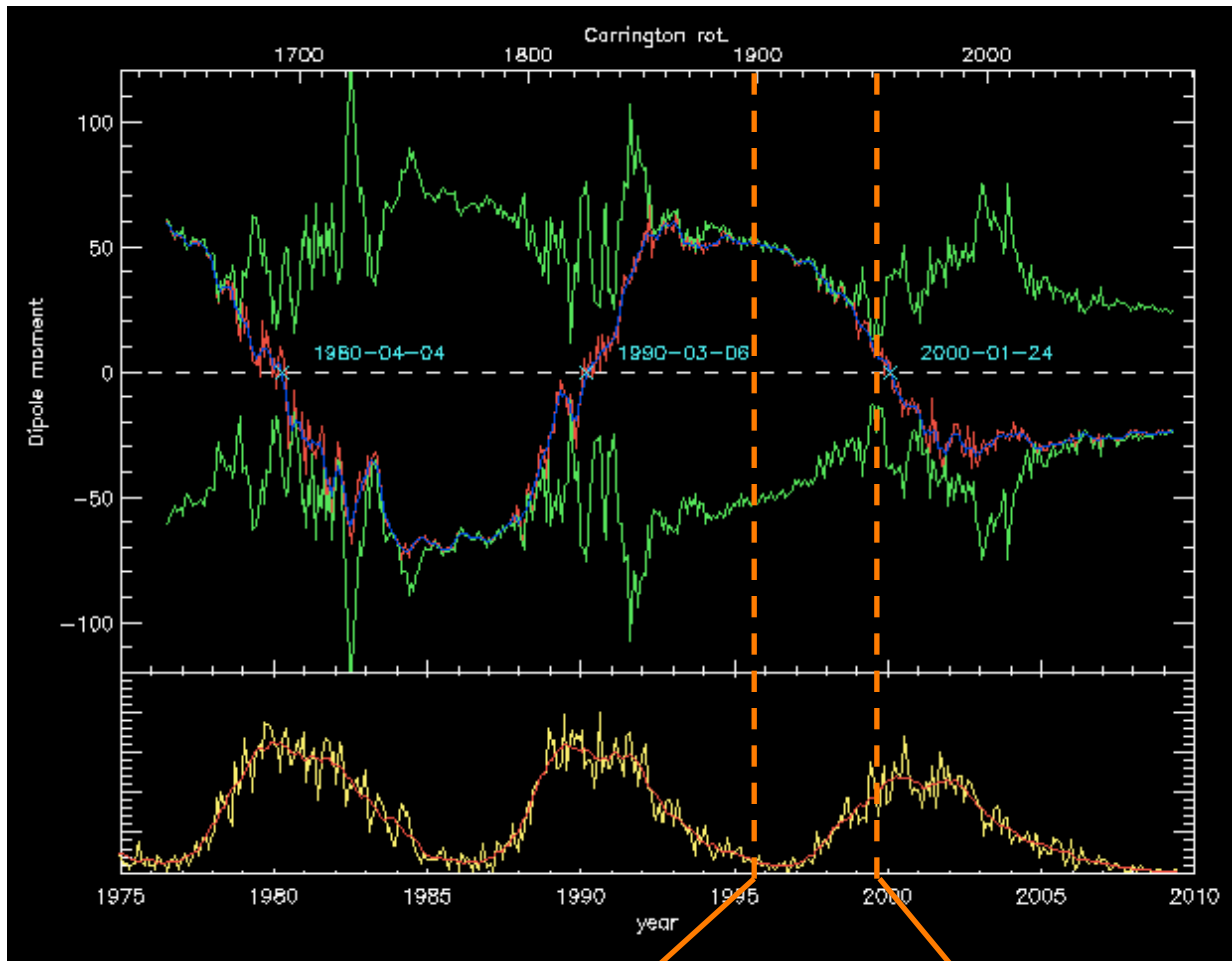
0,  $\pm 1$ , 2, 5, 10, 20 MicroTesla



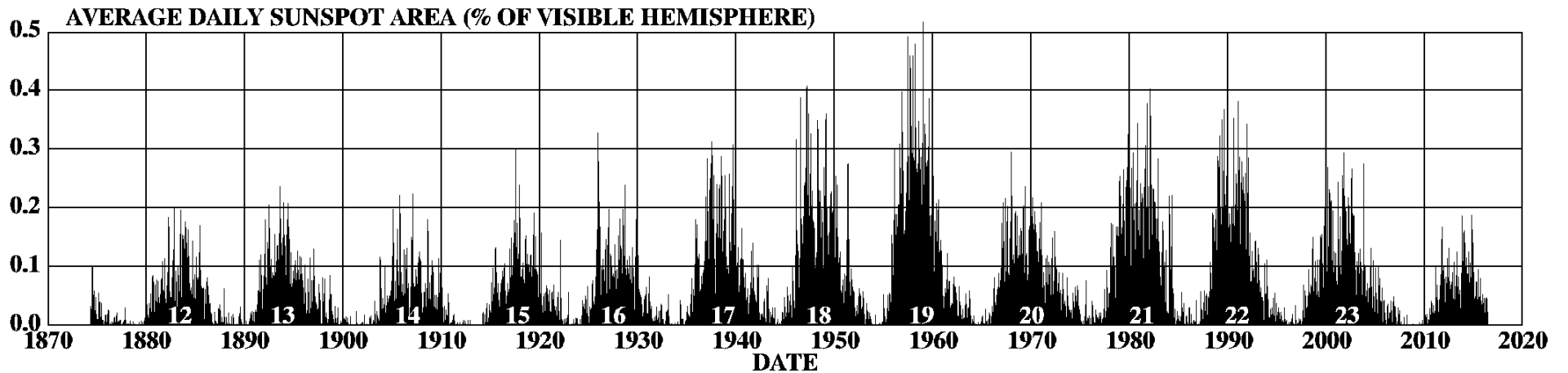
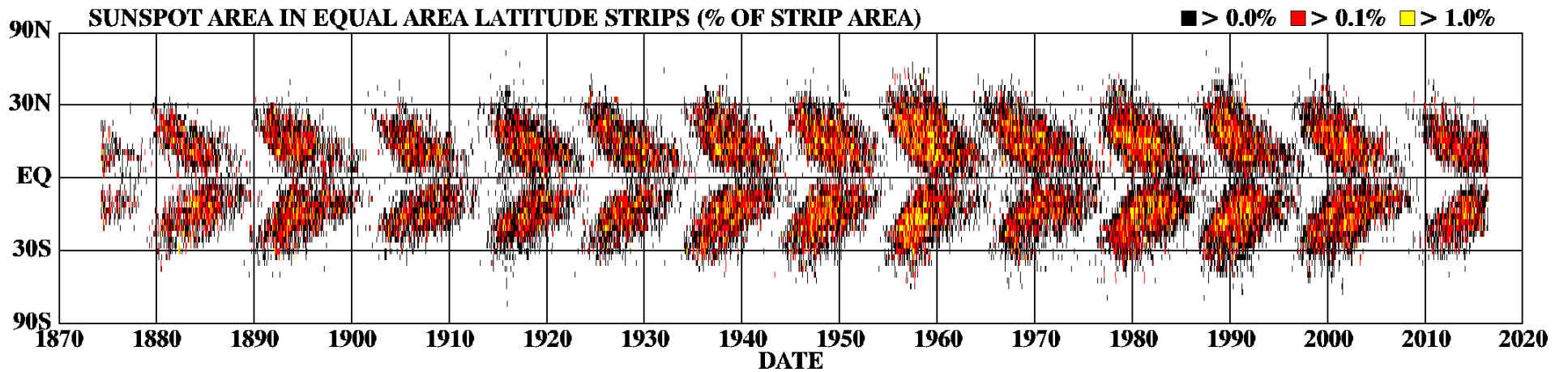
1904







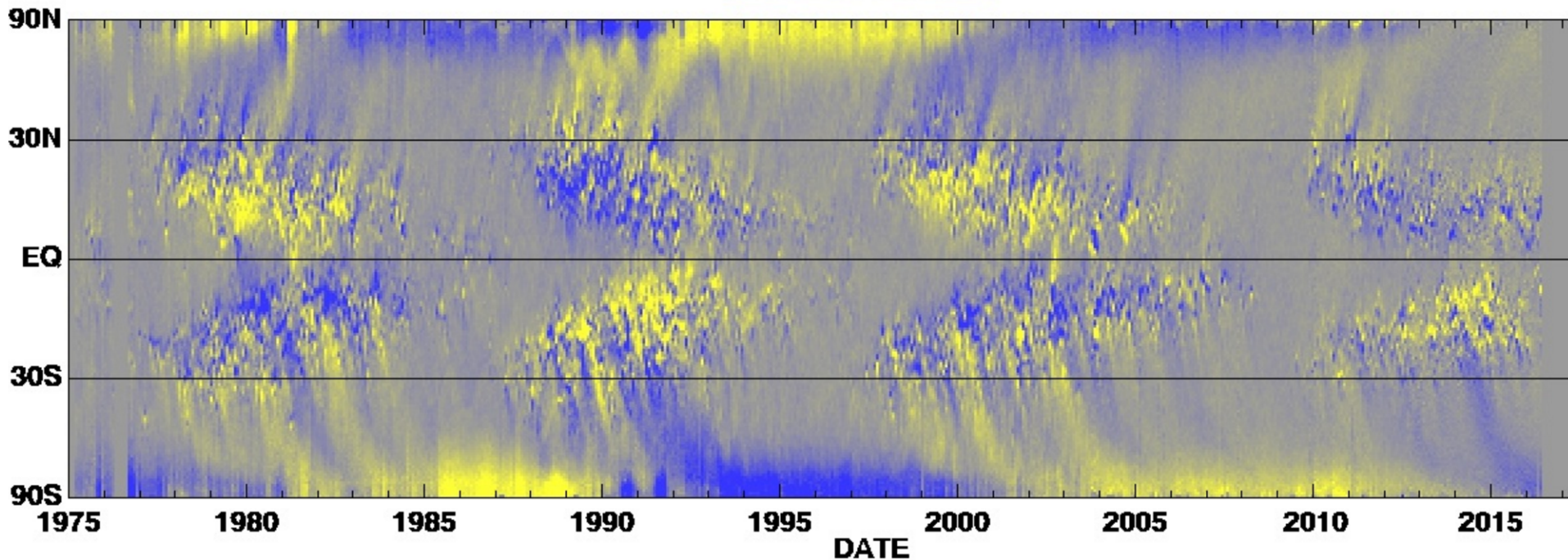
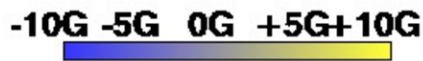
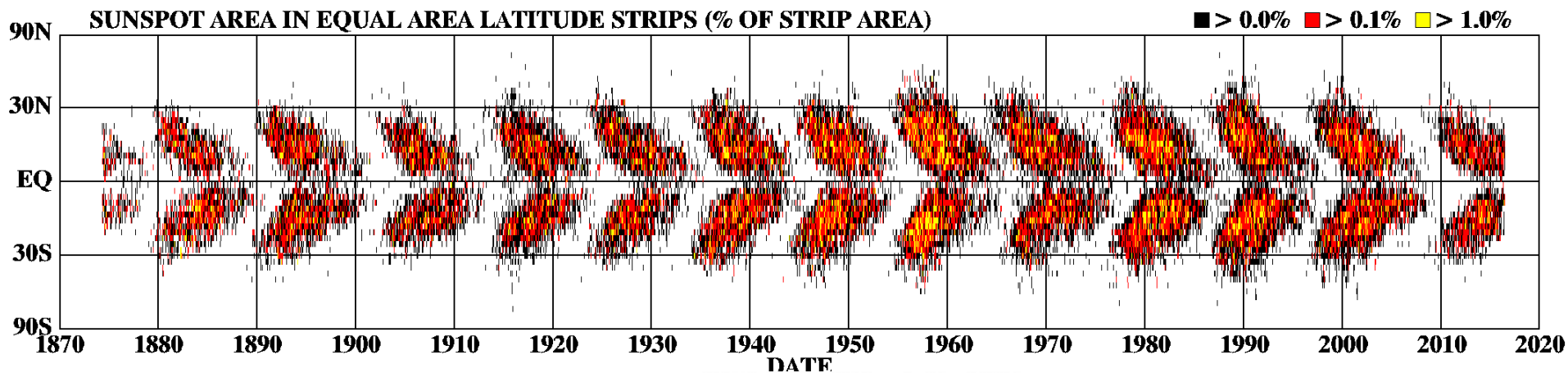
# DAILY SUNSPOT AREA AVERAGED OVER INDIVIDUAL SOLAR ROTATIONS



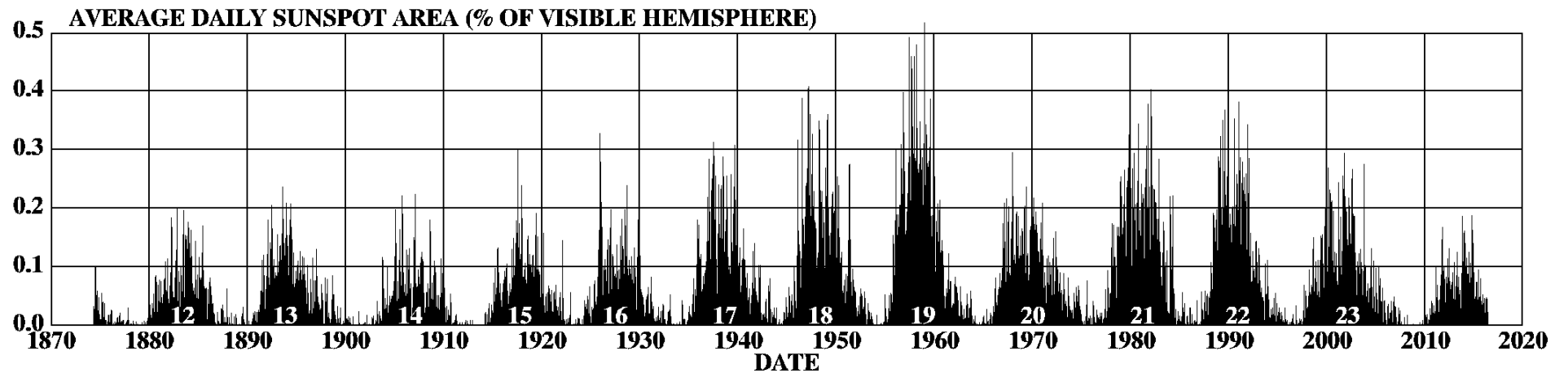
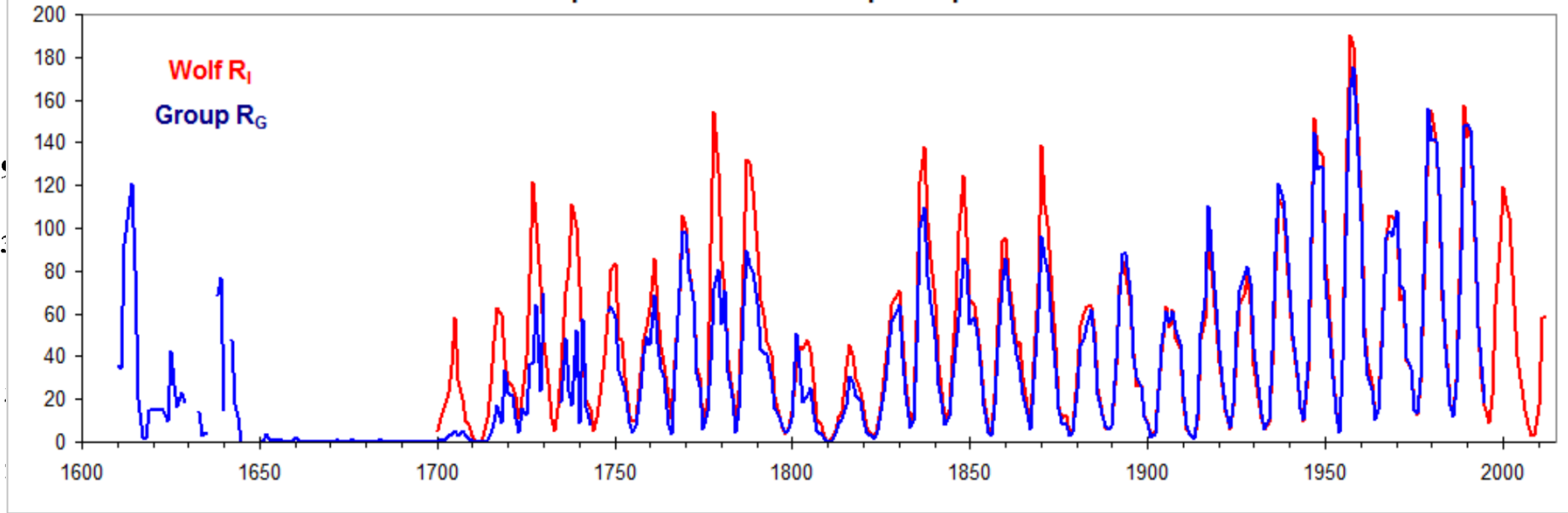
<http://solarscience.msfc.nasa.gov/>

HATHAWAY NASA/ARC 2016/07

# DAILY SUNSPOT AREA AVERAGED OVER INDIVIDUAL SOLAR ROTATIONS

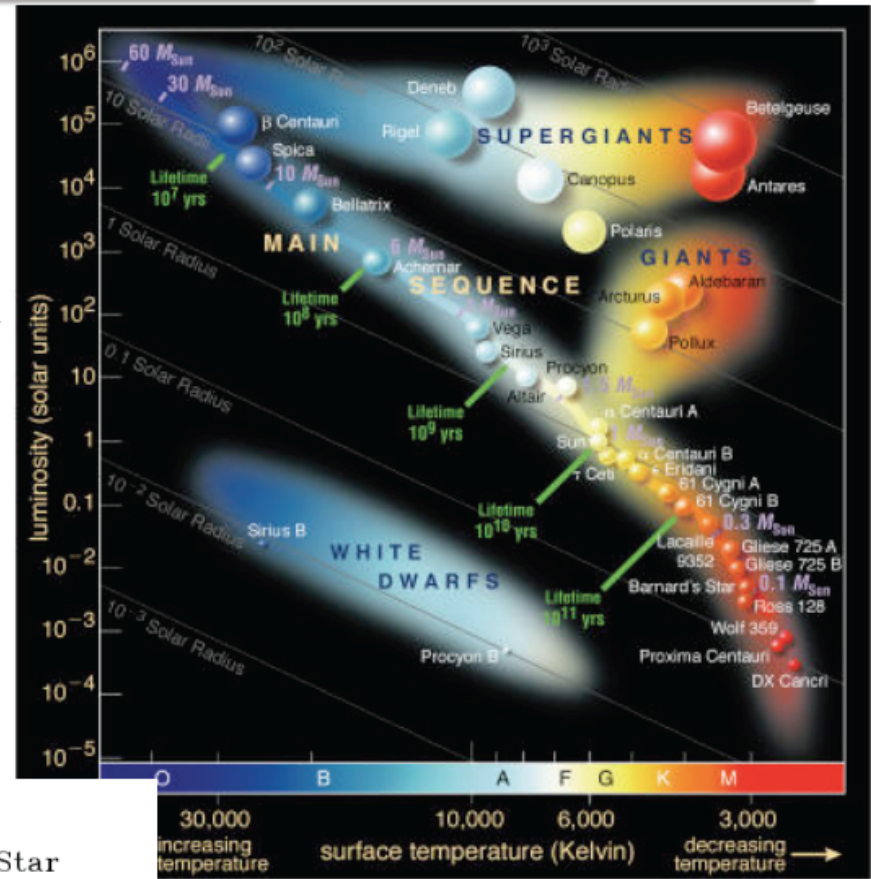


Comparison of Wolf and Group Sunspot Number Series

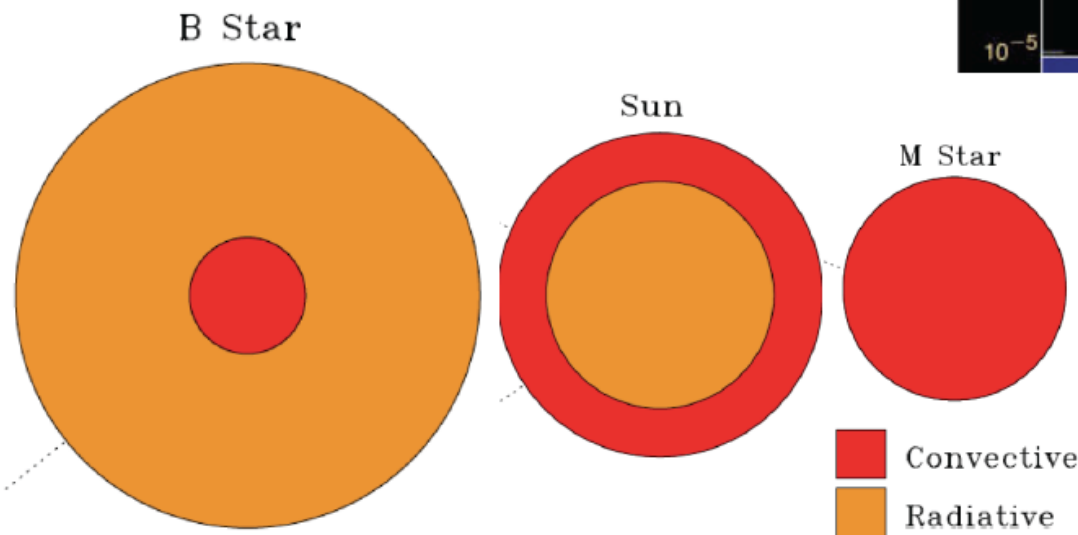


# STELLAR MAGNETIC FIELDS

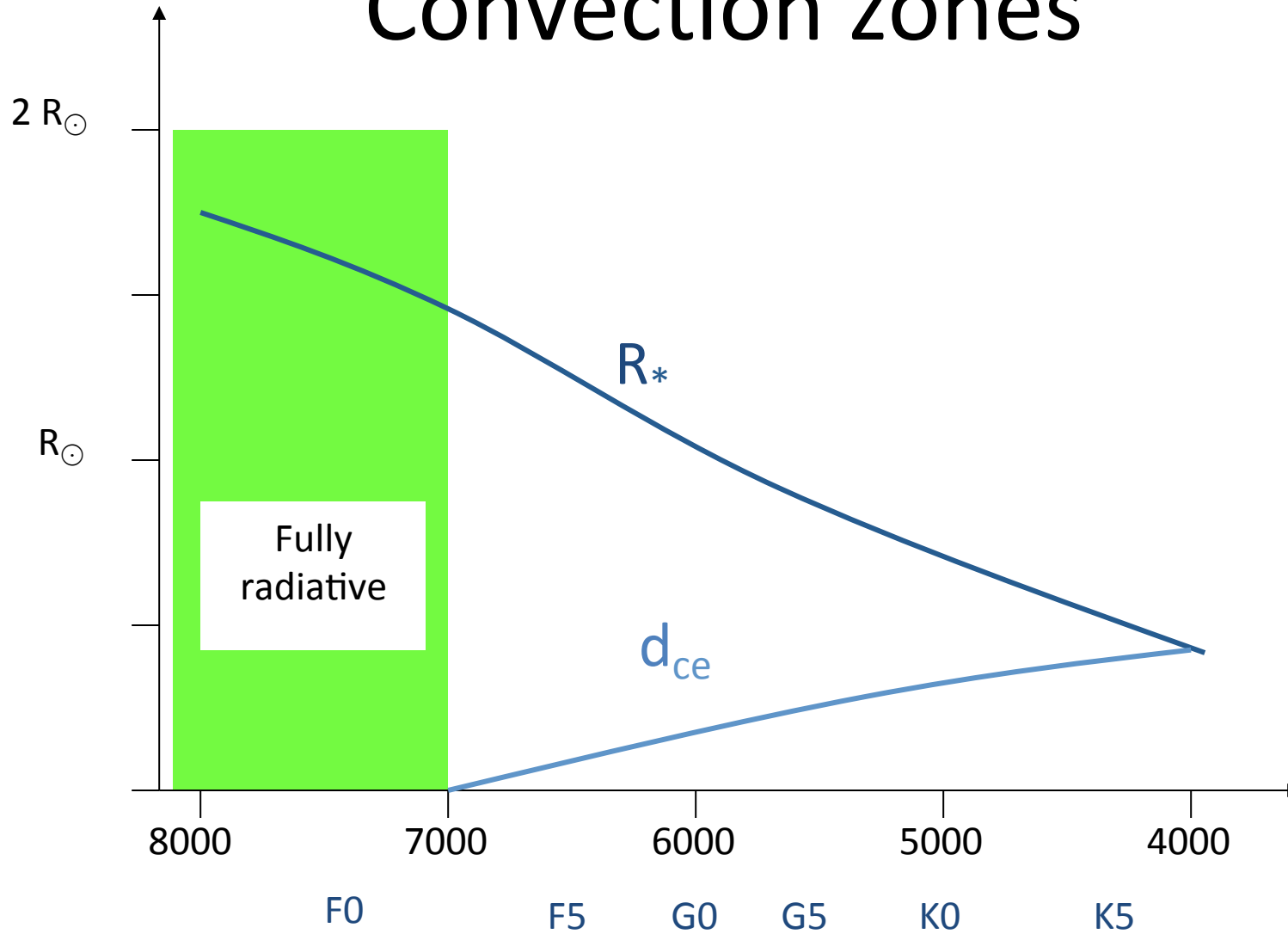
- correlations between stellar types and magnetic field properties, probably due to geometry of convection zones
- stars with outer convection zones (late-type stars) have observed magnetic fields whose strength tends to increase with their angular velocity
- Cyclic variations are known to exist only for spectral types between G0 and K7).



Stanley



# Convection zones

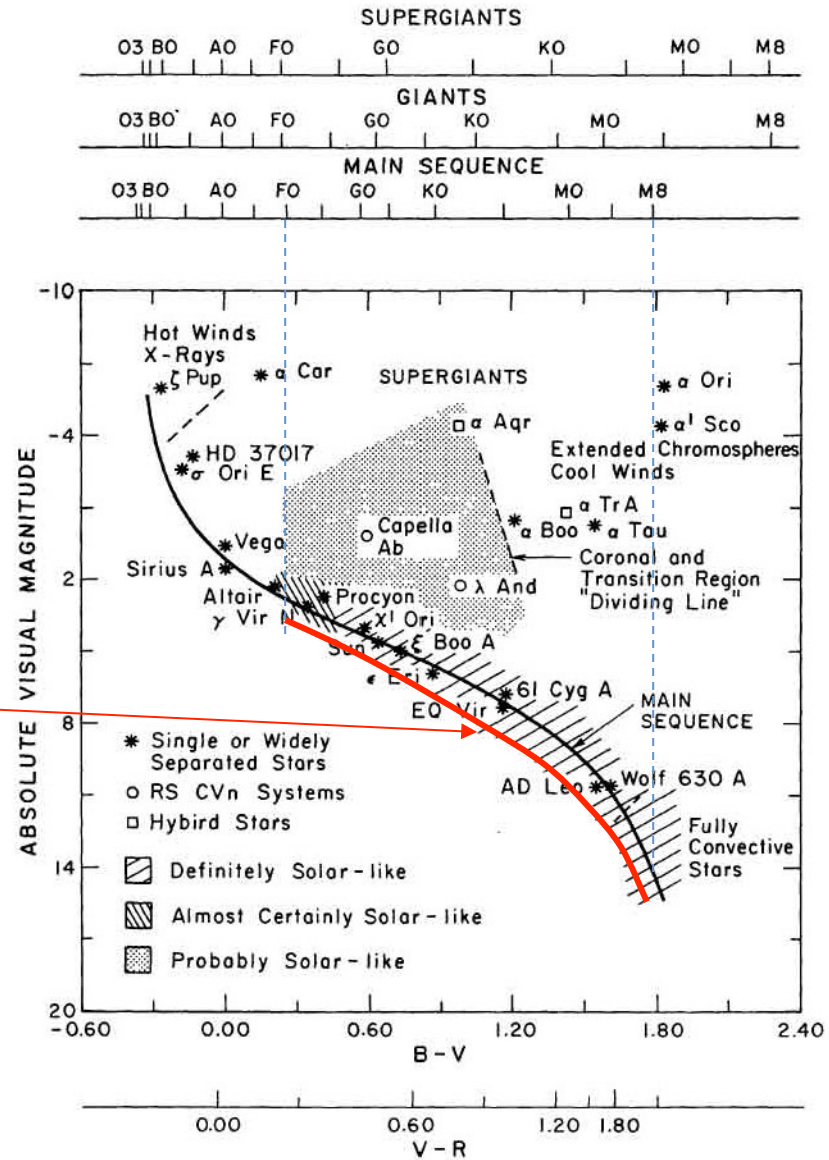


# Other stars

Evidence of magnetic activity

Activity on main sequence:  
types **F** → **M**

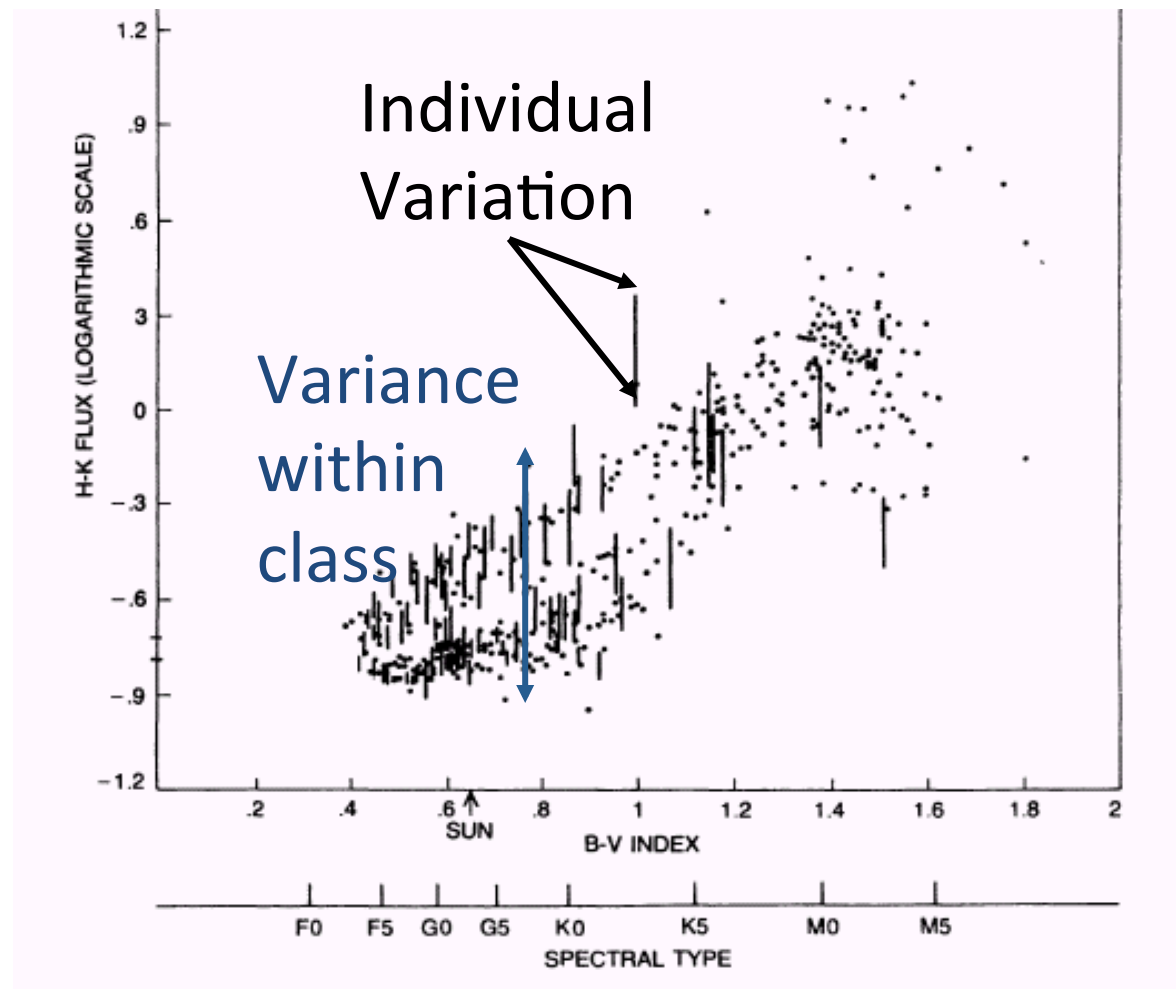
$$B-V > 0.4$$



(From Linsky 1985)



# Explaining Activity Levels



# The Dynamo Number

Parker's  
Dynamo #

$$N_D = \frac{\alpha_{\text{dyn}} \Omega' d^4}{\eta^2}$$

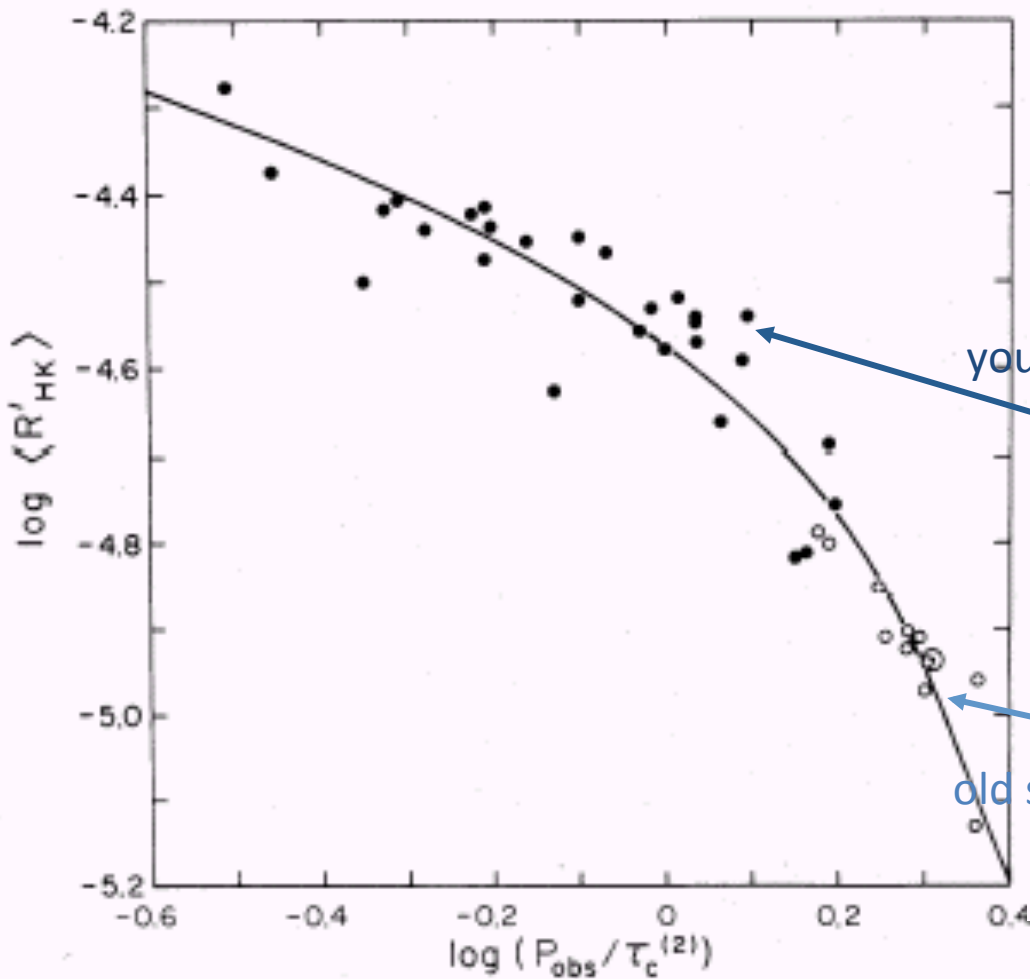
Dynamo is linear instability for  $N_D > N_{\text{crit}}$

Dynamo  $\alpha$ -effect:  $\alpha_{\text{dyn}} \equiv \tau \langle \mathbf{v} \cdot (\nabla \times \mathbf{v}) \rangle \sim \Omega d$

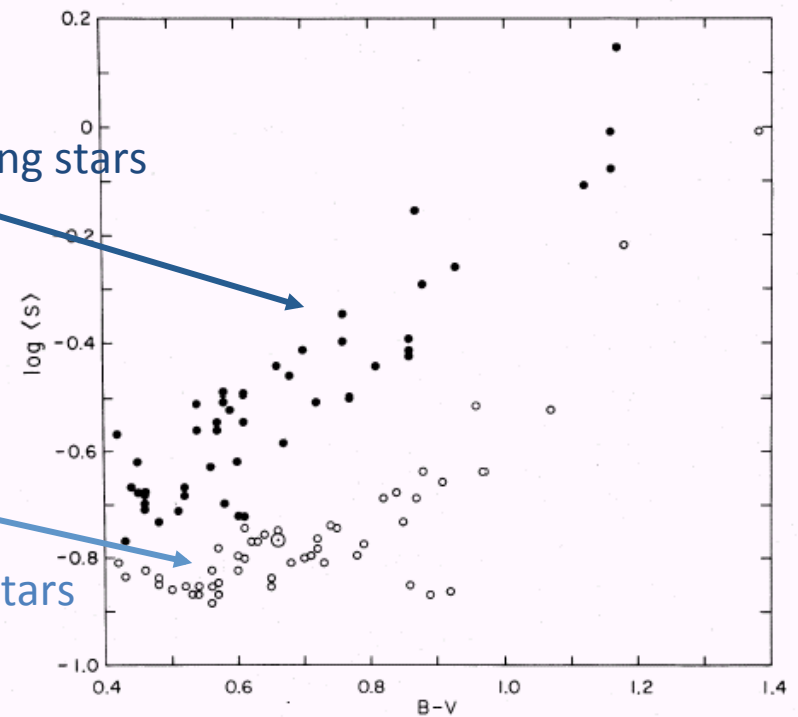
$$\eta = \eta_{\text{turb}} \sim \frac{d^2}{\tau_c} \quad \Omega' = \frac{d\Omega}{dr} \sim \frac{\Omega}{d}$$

$$N_D \sim (\Omega \tau_c)^2 \sim (P_{\text{obs}} / \tau_c)^{-2} = Ro^{-2}$$

# Activity vs. Rossby Number

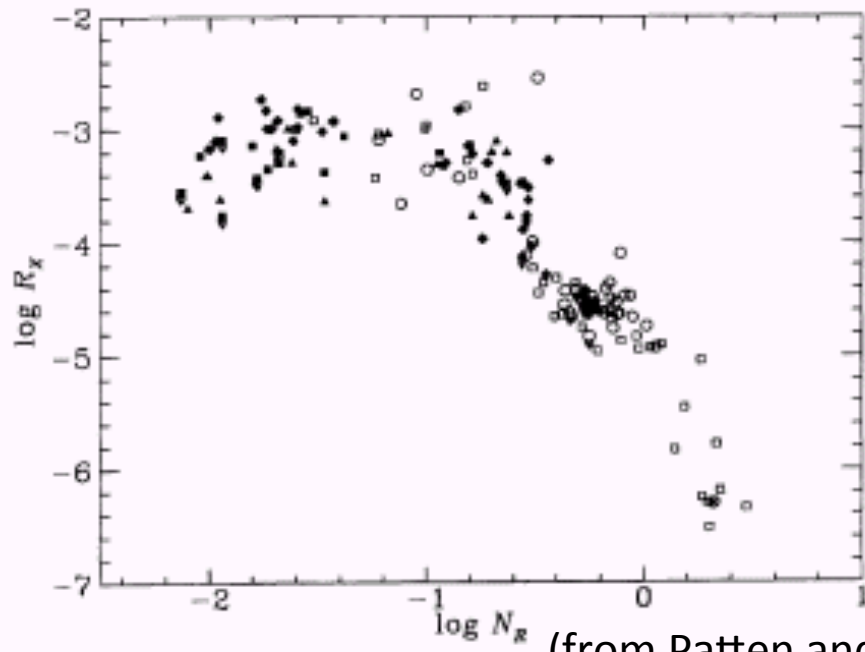


41 Local stars  
 $P_{obs}$  from  $S(t)$

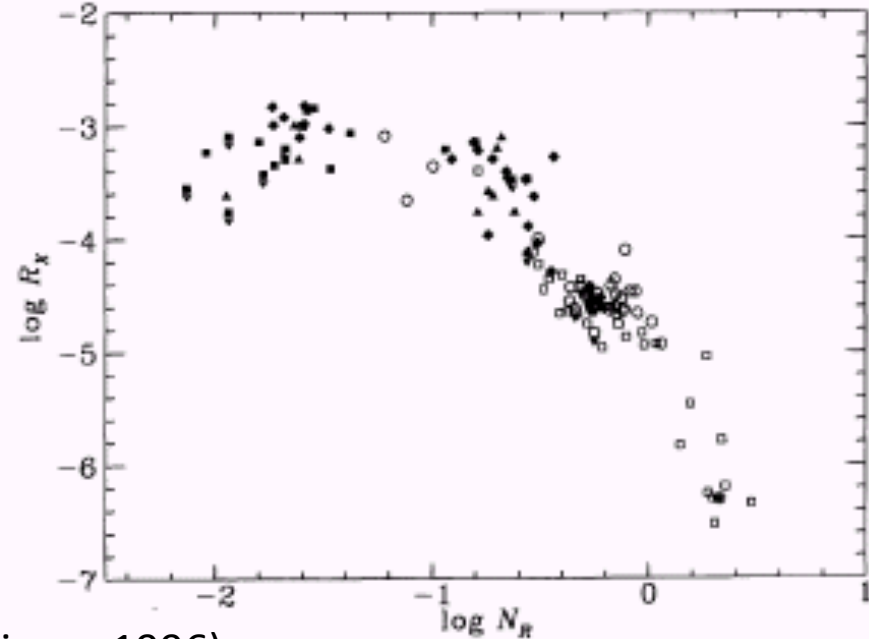


(from Noyes et al. 1984)

# Activity vs. Rossby Number



(from Patten and Simon 1996)



- Stars in open cluster 2391 (30My old)
- $R_X$  from ROSAT observations
- Rotation periods  $P_{\text{obs}}$  from optical photometry
- $N_R = Ro = P_{\text{obs}}/t_c$

# Summary

- Magnetic fields – all from dynamos
  - Conducting fluid
  - Complex motions w/ enough *umph*
- Create complex fields
- Fields evolve in time – reverse occasionally
- Differences from different parameters:

$R_m$ ,  $Re$ ,  $Ro$