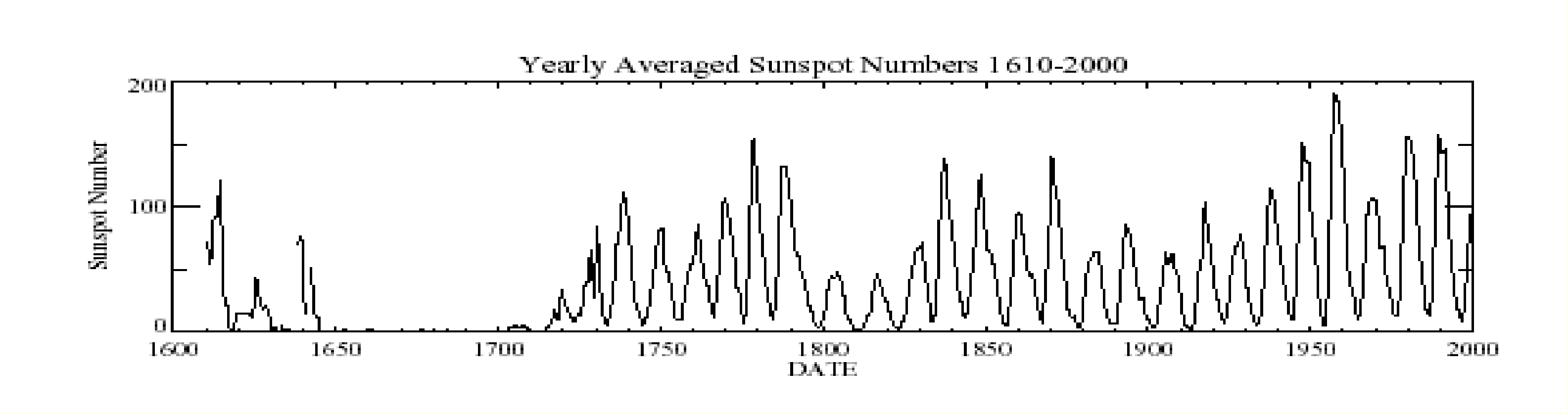
The Origin of the Solar Magnetic Cycle



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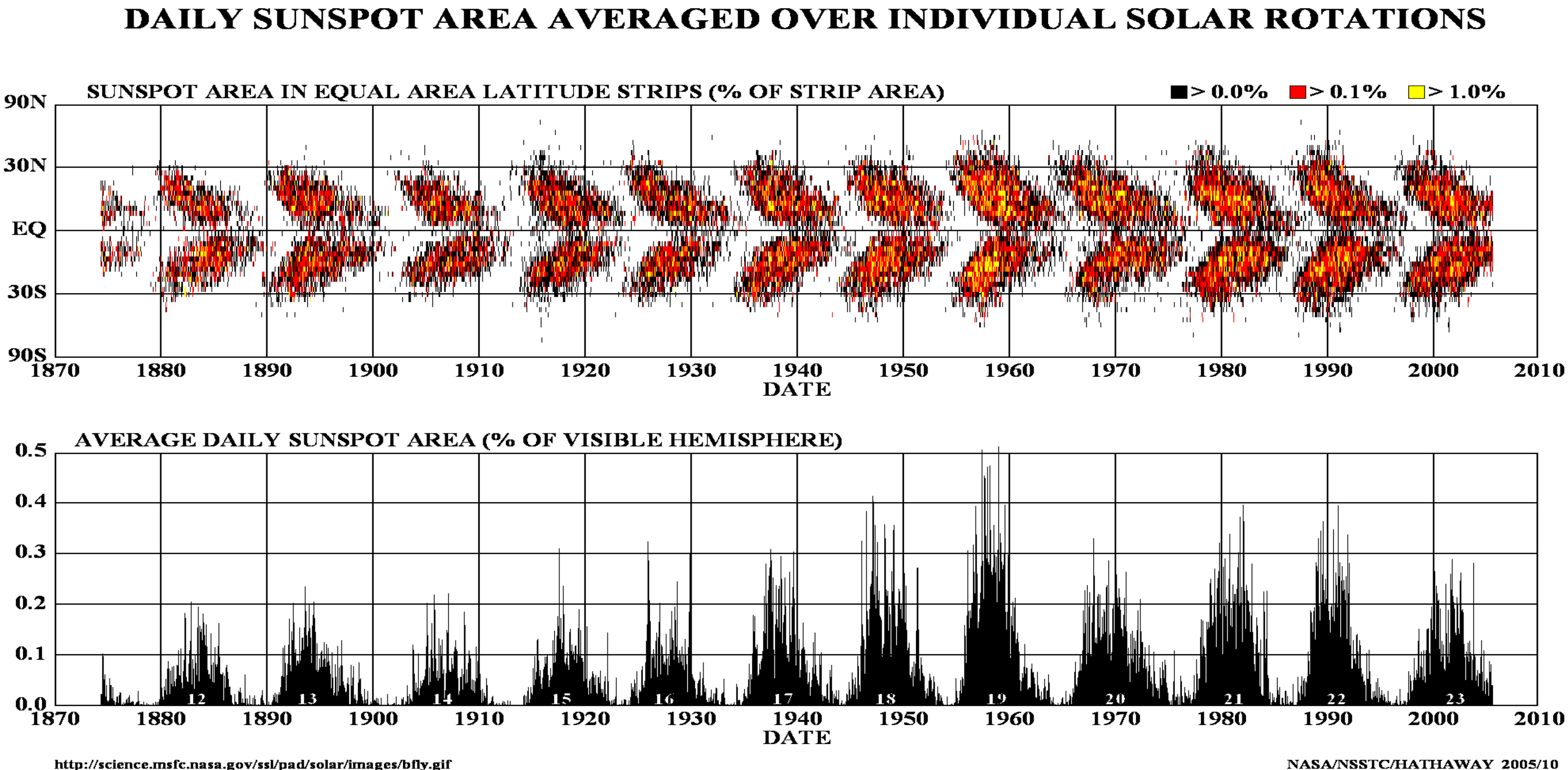
- **~ 150 years ago** – Schwabe discovered the 11-year cycle of sunspots (1844)
- **~ 100 years ago** – Hale discovered strong magnetic field in sunspots (B about 3000 G) (1908)
- **~ 50 years ago** – Parker formulated dynamo theory for the origin of astronomical magnetic fields (1955)
- **At present** – Time for another major breakthrough! Is it happening?

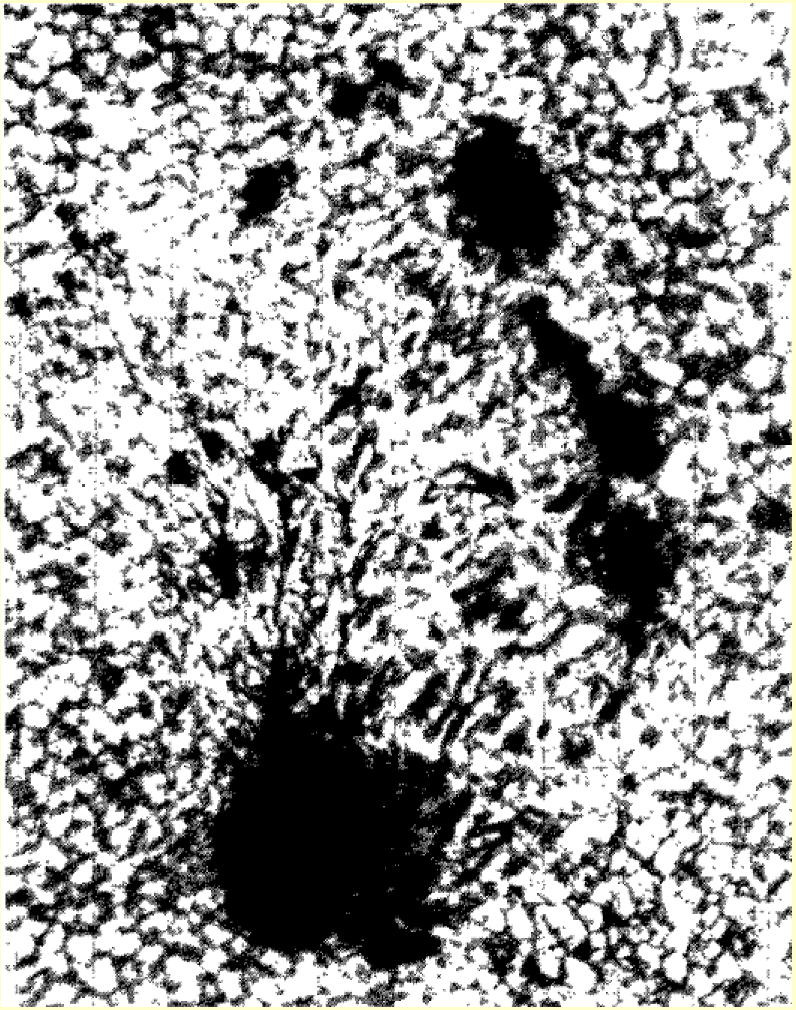
Plan of the Talk

- Summary of relevant observational data
- Theory of sunspot formation
- Periodic models of the cycle
- Cause of cycle irregularity & prediction

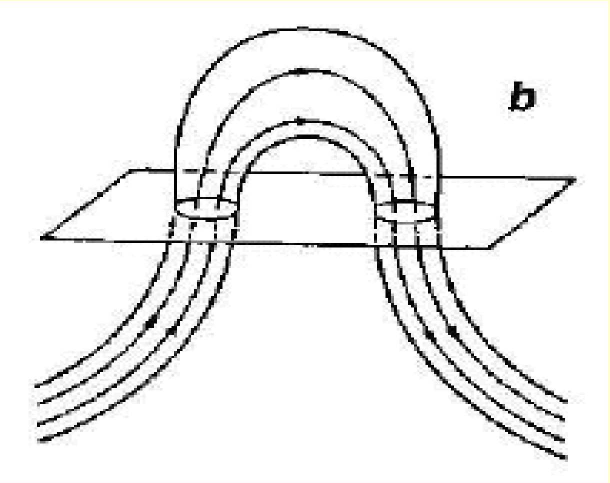
1844: Schwabe discovers solar cycle
1858: Carrington discovers latitudinal drift
1904: Maunder invents *butterfly diagram*



Hale et al. (1919) – Often two large sunspots are seen side by side with opposite polarities

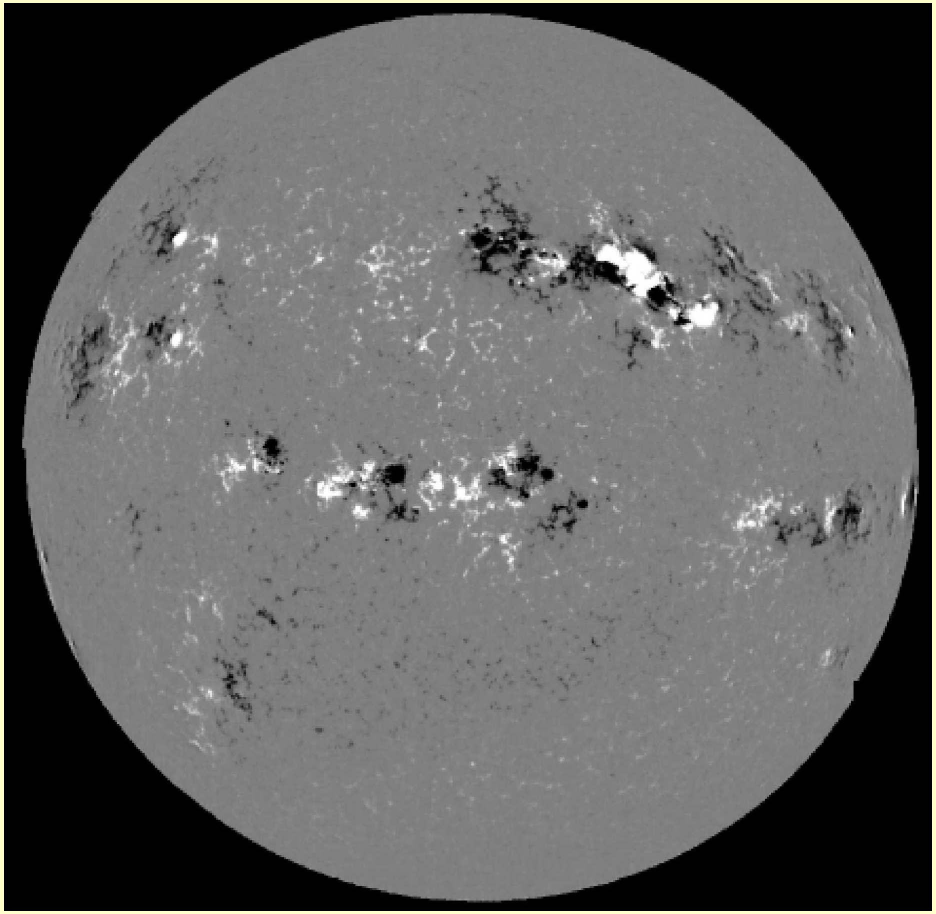


A strand of magnetic flux has come through the surface!



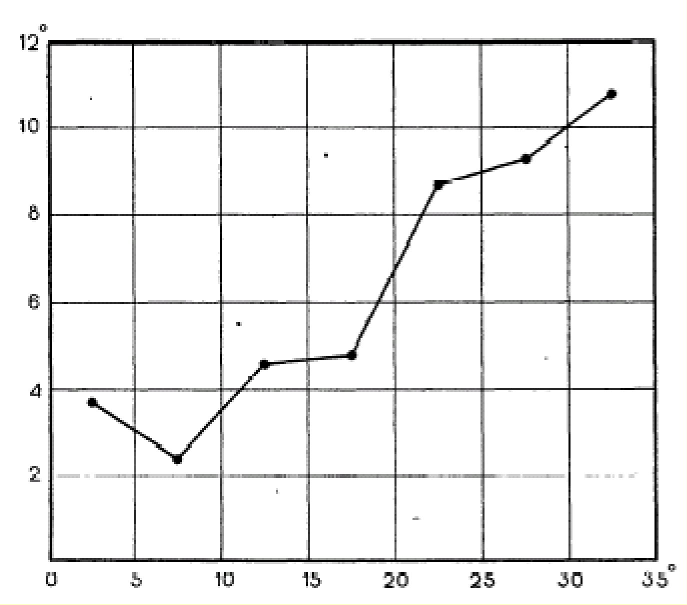
Magnetogram map (white +ve, black –ve)

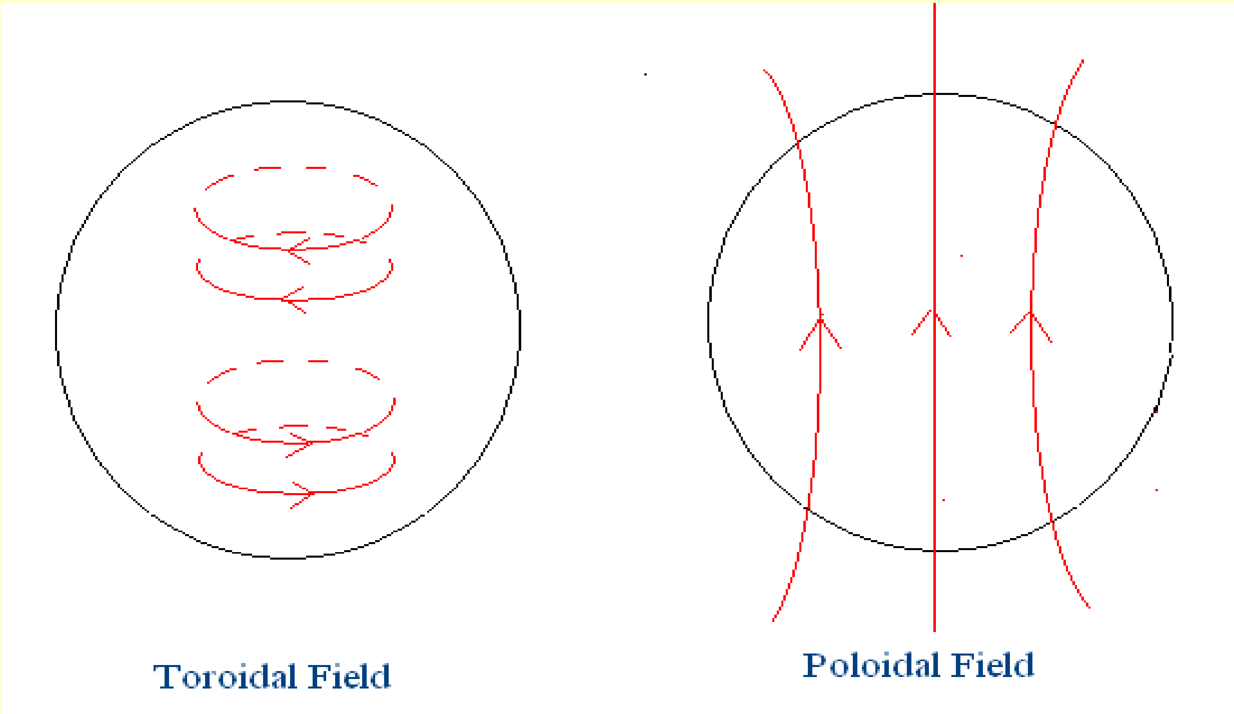
Polarity is opposite (i) between hemispheres; (ii) from one 11-yr cycle to next >> 22-yr period



Tilt of bipolar regions increases with latitude

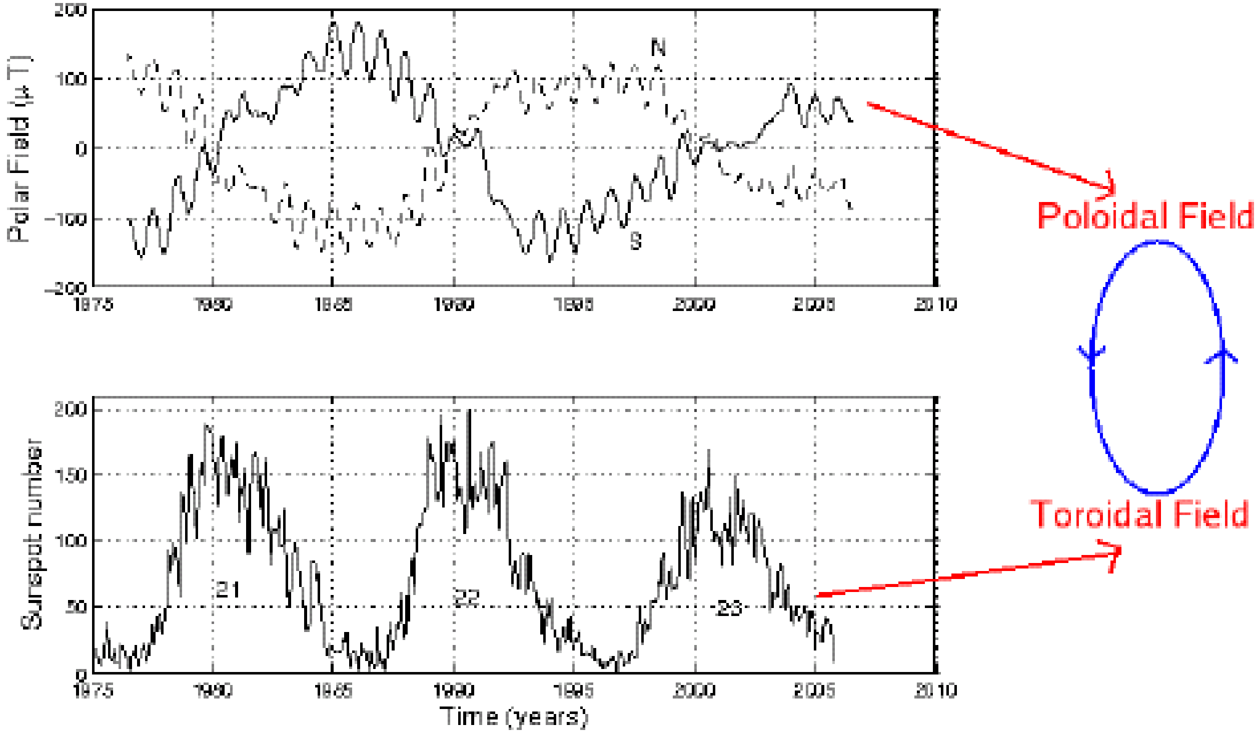
- Joy's law (Joy 1919)





Parker (1955) suggested oscillation between the toroidal and poloidal fields.

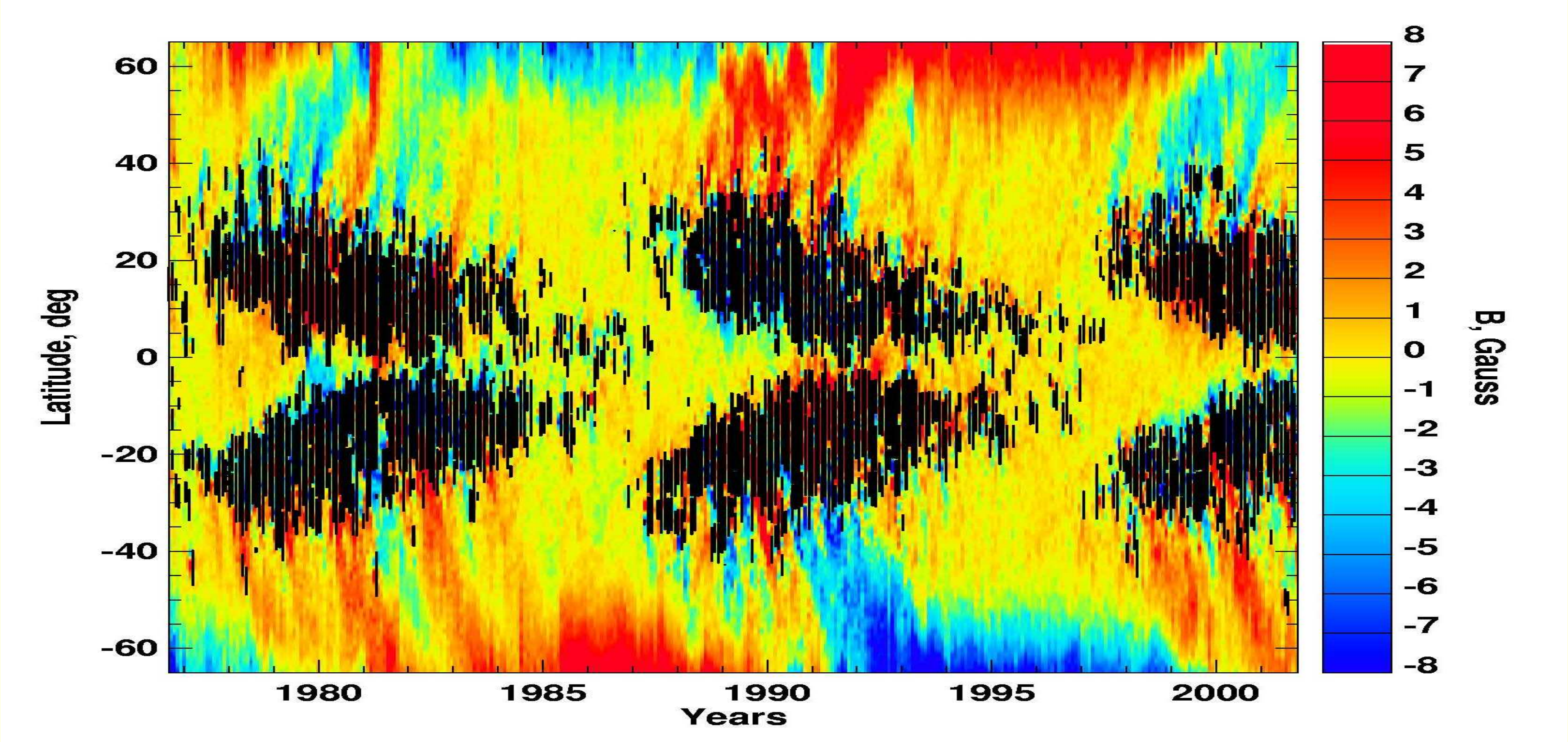
Babcock (1955) detected the weak poloidal field (~ 10 G)



The polar fields and the sunspot number as functions of time

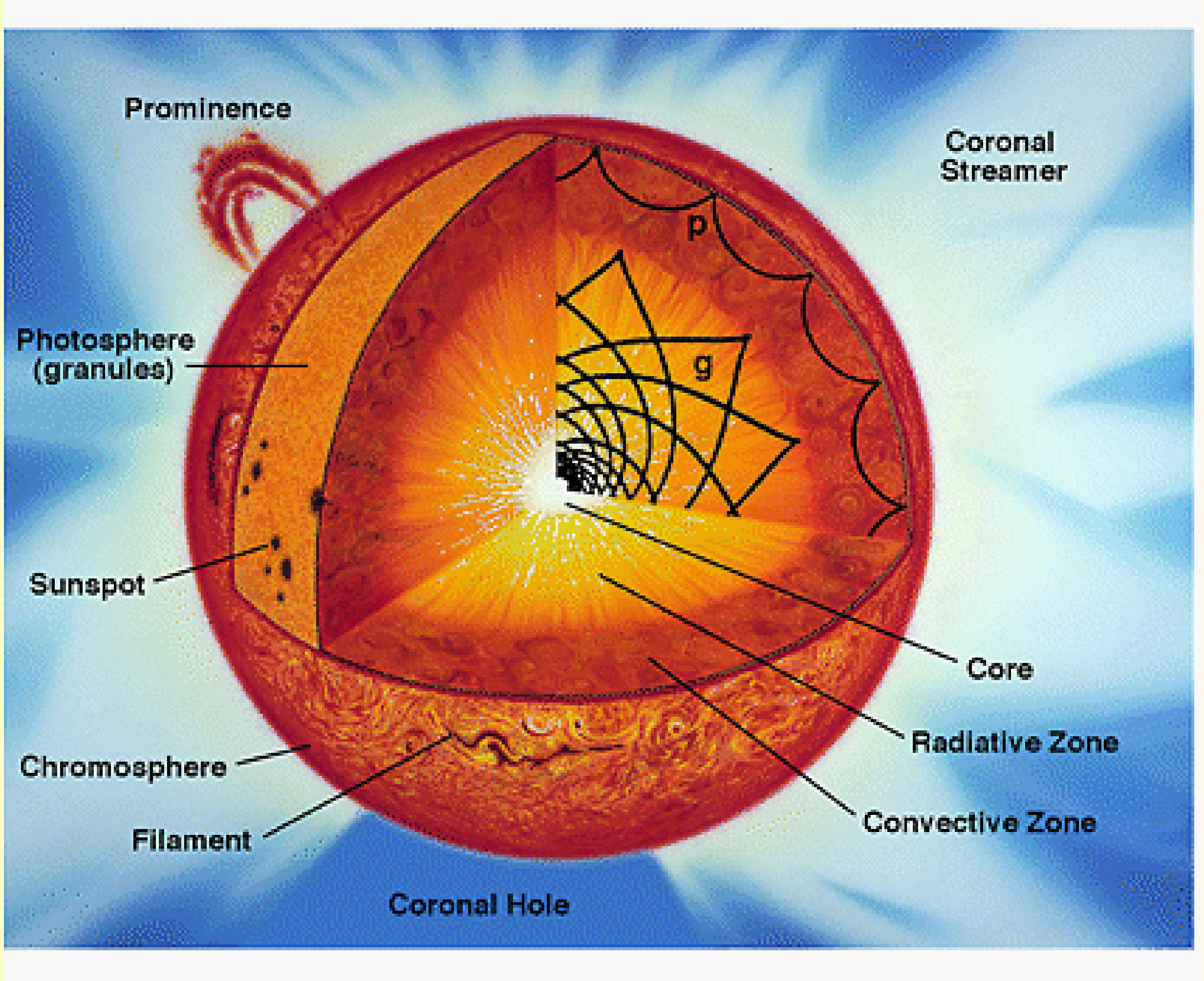
Babcock and Babcock (1955) – Weak fields outside sunspots (< 10 G)

Unipolar patches shift poleward with solar cycle (1965 – 1990) – Bumba & Howard, Howard & LaBonte, Makarov & Sivaraman, Wang et al.



Polar field reverses at the time of sunspot maximum.

Weak, diffuse fields must be another manifestation of solar cycle – ignored by early theorists!



Sunspots are magnetic field concentrations in turbulent plasma

Solar equator rotates faster than the solar pole.

Angular velocity distribution in the interior?

Helioseimology

Leighton, Noyes & Simon 1962 – discover solar oscillations

Deubner 1974 – recognizes them as normal modes

Eigen-functions

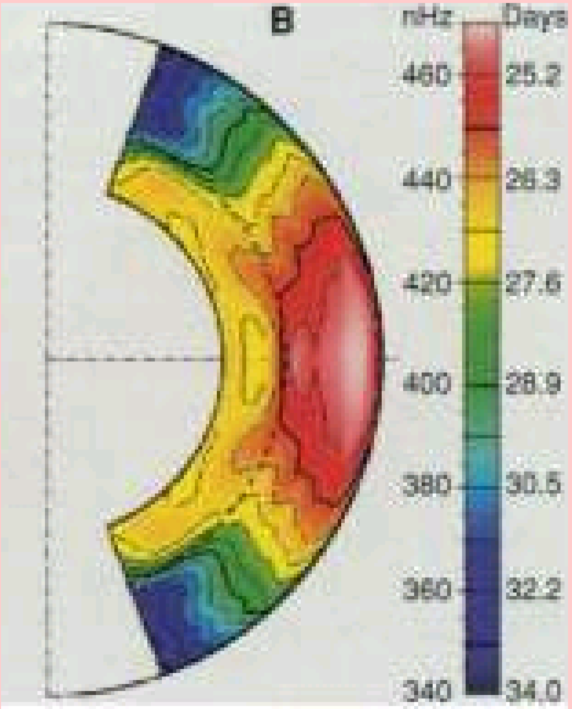
$$\xi_{nlm} = R_n(r) Y_{lm}(\theta, \phi) e^{i\omega_{nlm} t}$$

In the absence of rotation

$$\omega_{nl(+m)} = \omega_{nl(-m)}$$

Rotation causes splitting

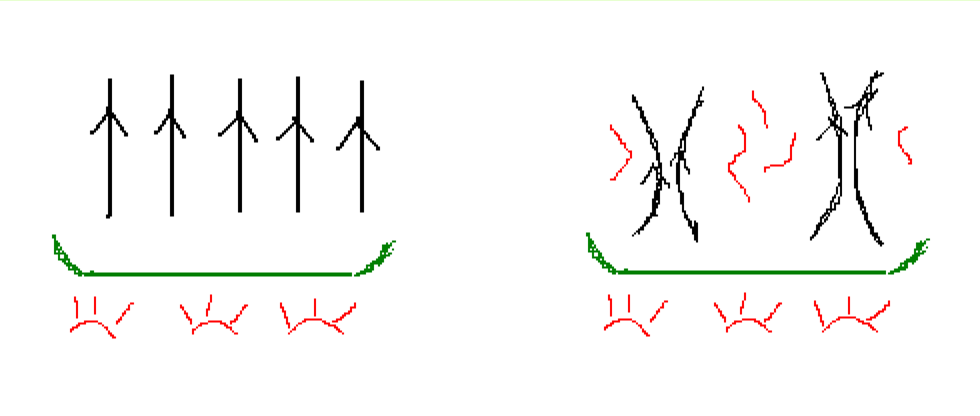
Tachocline at the bottom of convection zone

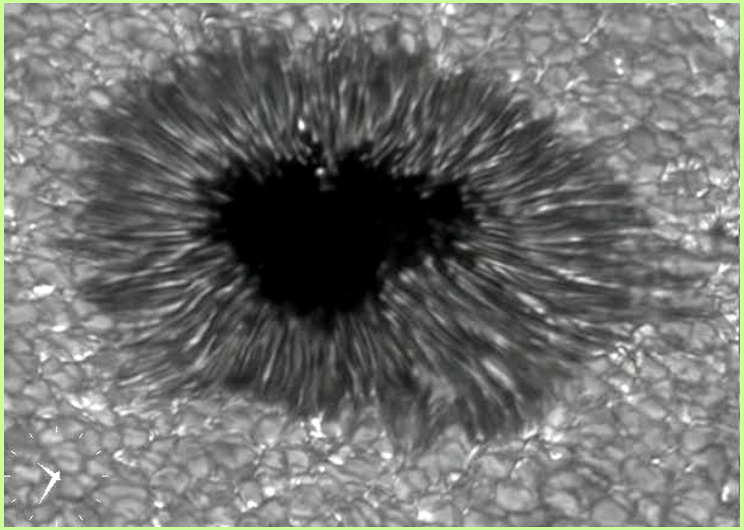


Magnetoconvection

Linear theory – Chandrasekhar 1952

Nonlinear evolution – Weiss 1981; . . .





Sunspots are magnetic field concentrations with suppressed convection

Magnetic field probably exists as flux tubes within the solar convection zone

Axisymmetric magnetic field

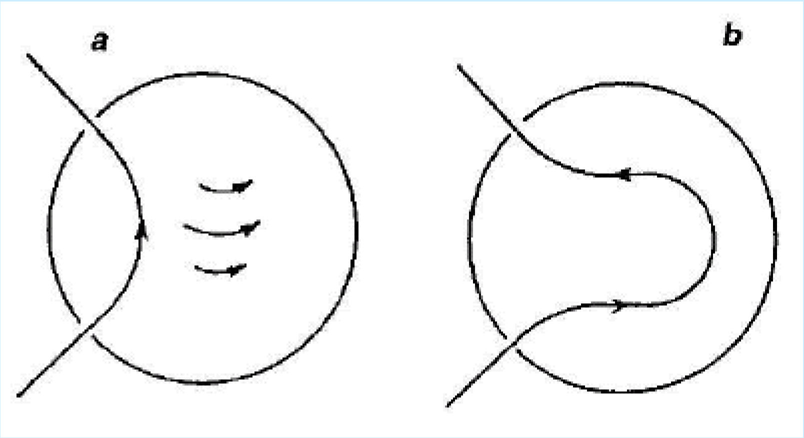
$$\mathrm{B} = B_r \mathrm{e}_r + B_\theta \mathrm{e}_\theta + B_\phi \mathrm{e}_\phi$$

Poloidal Component

Responsible for weak fields

Toroidal Component

Gives rise to sunspots



Differential rotation – produces toroidal field from poloidal field

Tachocline – strong differential rotation, generation of toroidal magnetic field

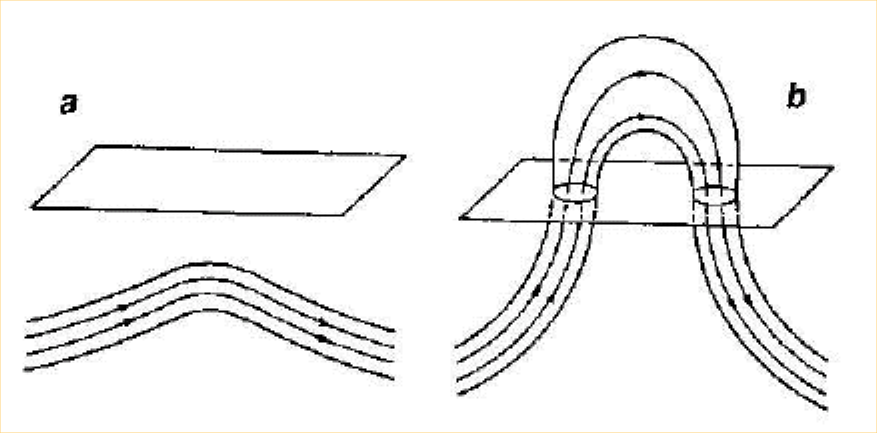
Flux Tube

$$p_{\mathrm{out}} = p_{\mathrm{in}} + \frac{B^2}{2\mu} \longrightarrow p_{\mathrm{in}} \leq p_{\mathrm{out}}$$

Usually the inside is under-dense

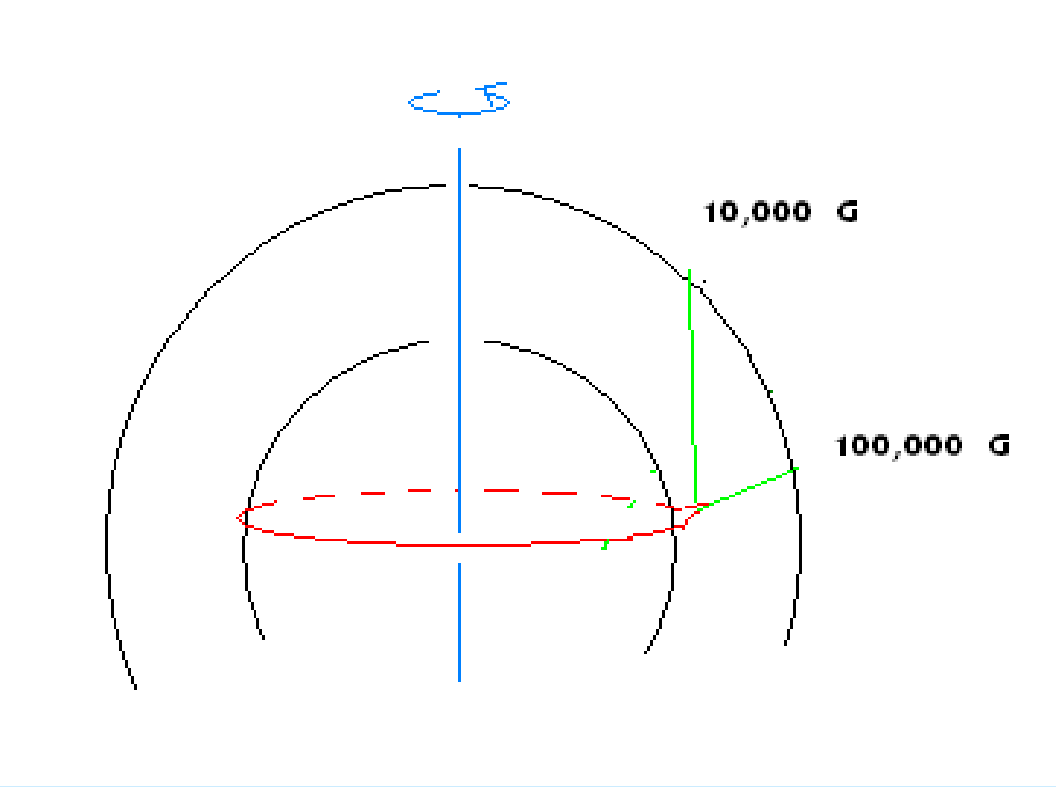
Magnetic buoyancy (Parker 1955)

Very destabilizing within the convection zone, but much suppressed below its bottom



3D dynamics of flux tubes in solar convection zone

(Choudhuri & Gilman 1987; Choudhuri 1989; D'Silva & Choudhuri 1993; Fan et al. 1993; Caligari et al. 1995)



Early dynamo models suggested B at bottom to be 10,000 G, but such fields are diverted by Coriolis force (Choudhuri & Gilman 1987)

Only 100,000 G fields can emerge at sunspot latitudes

Joy's Law (1919) – Tilts of bipolar sunspots increase with latitude

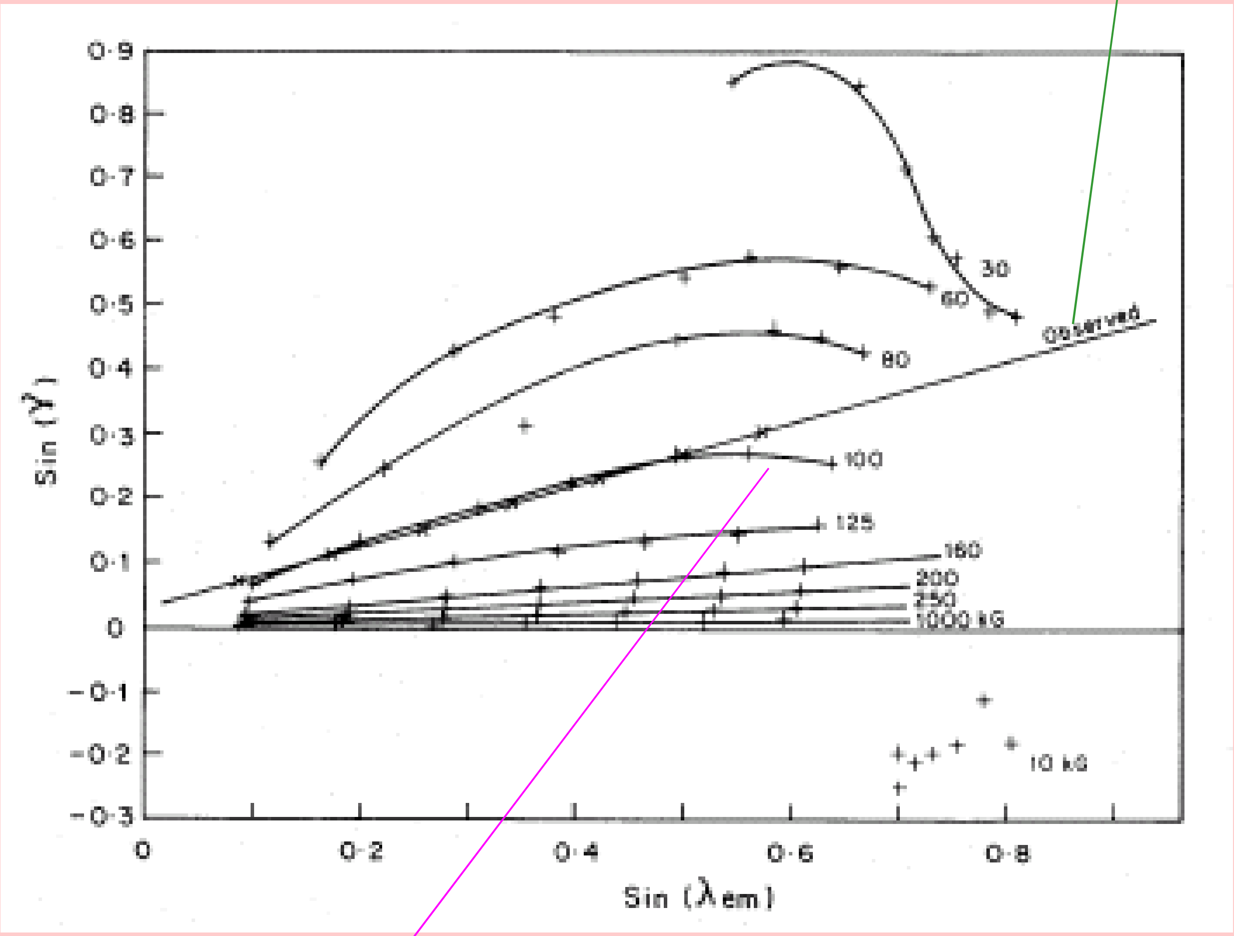
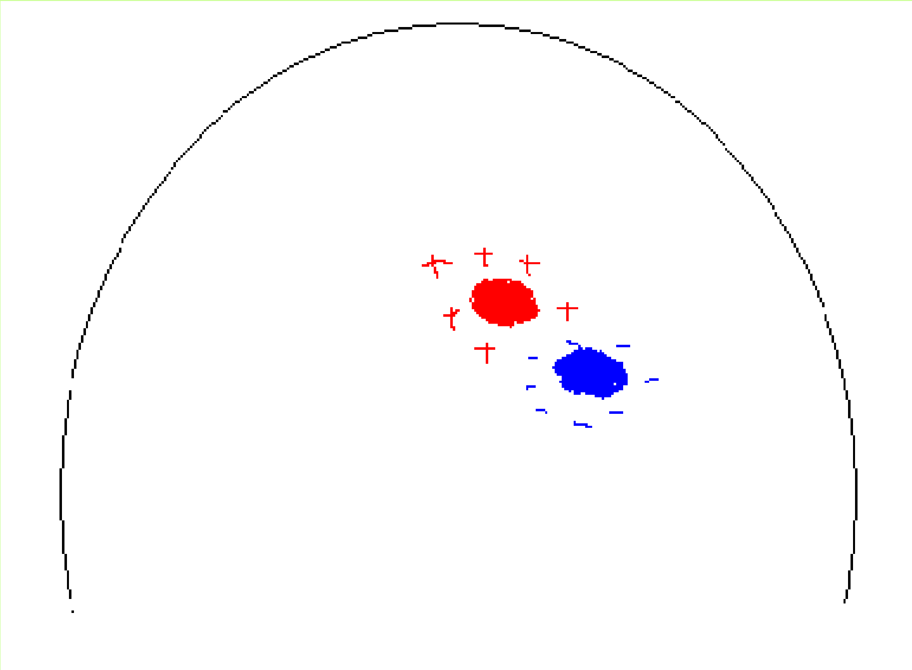


Figure from D'Silva & Choudhuri (1993) – First quantitative explanation!

Only 100 kG = 100,000 G fields match observations!

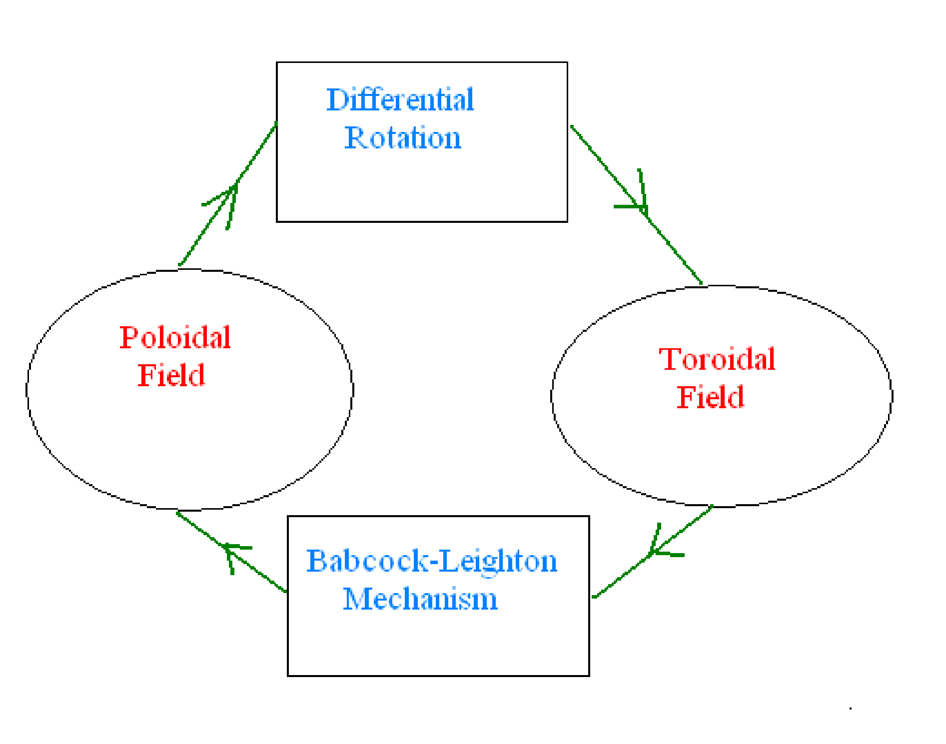
Mechanism for poloidal field generation (Babcock 1961; Leighton 1969)

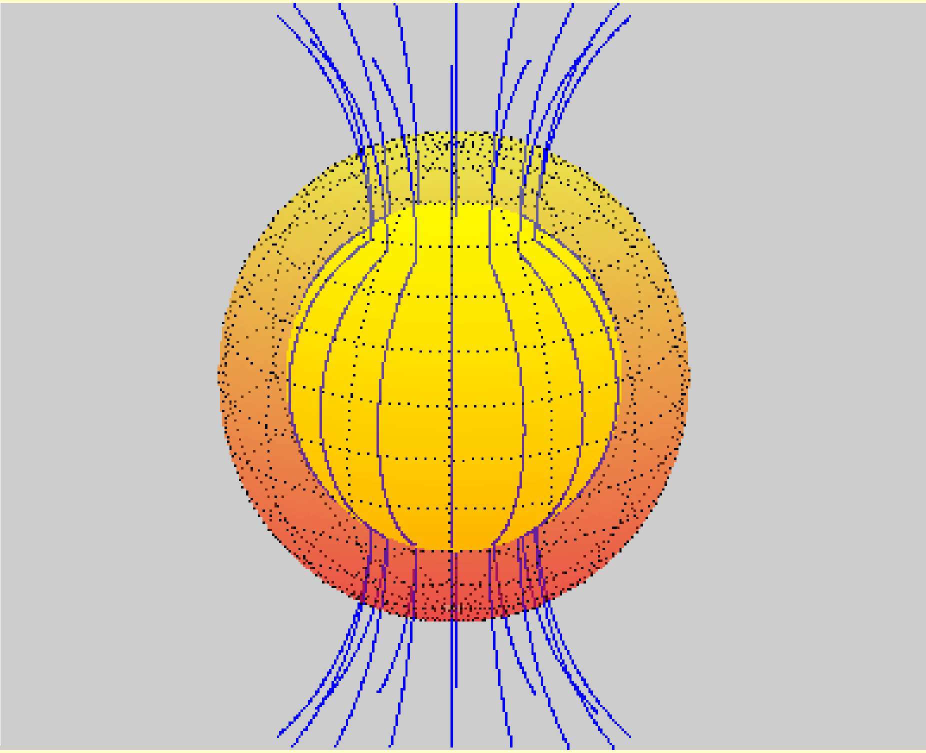


Decay of tilted bipolar sunspots

Toroidal field > bipolar sunspots > poloidal field

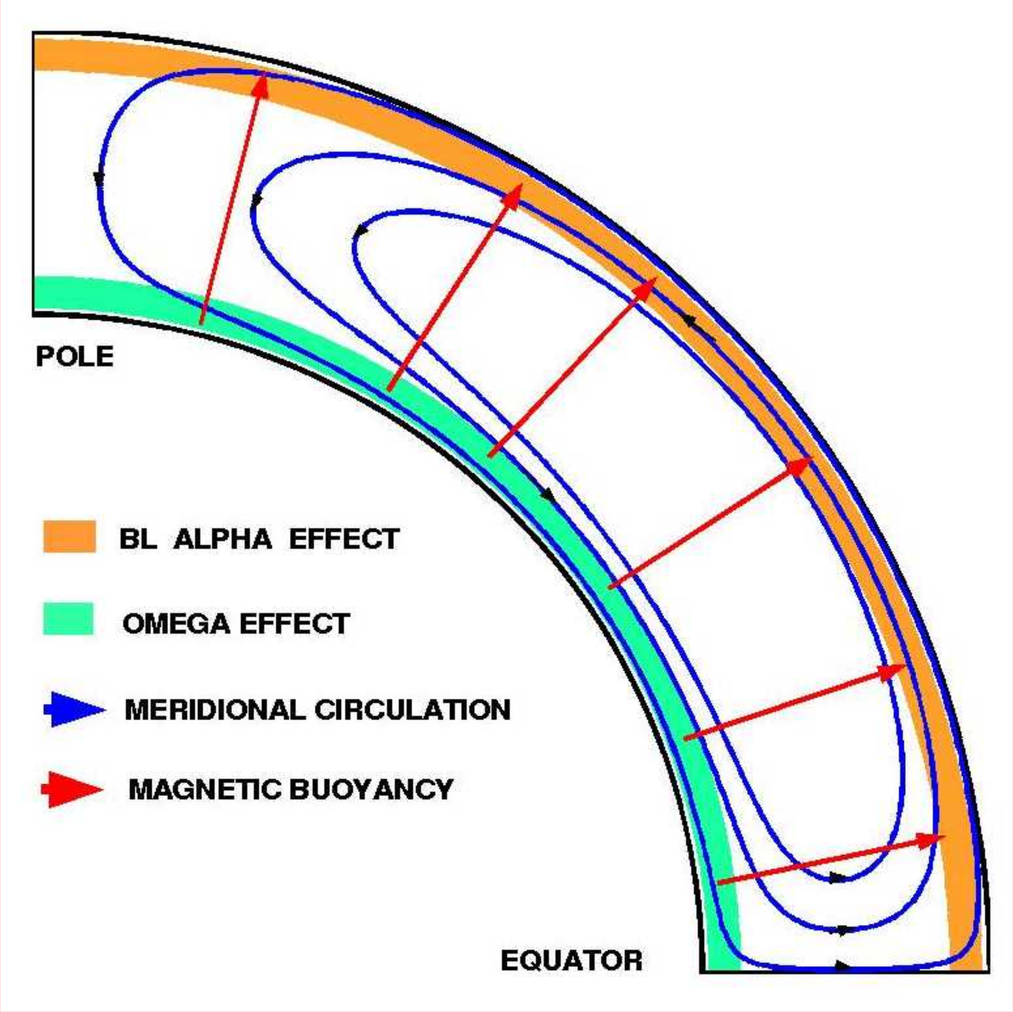
The original idea of Parker (1955) and Steenbeck, Krause & Radler (1966) involved twisting of toroidal field by helical turbulence – not possible if toroidal field is 100,000 G.





The dynamo cycle - A modified version of the original idea due to Parker (1955)

Flux transport dynamo in the Sun (Choudhuri, Schussler & Dikpati 1995; Durney 1995)



Differential rotation > toroidal field generation

Babcock-Leighton process > poloidal field generation

Meridional circulation carries toroidal field equatorward & poloidal field poleward

Basic idea was given by Wang, Sheeley & Nash (1991)

Basic Equations

Magnetic field

$$\boldsymbol{B} = B(r,\theta)\boldsymbol{e}_\phi + \nabla \times [A(r,\theta)\boldsymbol{e}_\phi],$$

Velocity field

$$\Omega(r,\theta)\, r \sin\theta\, \mathbf{e}_\phi + \mathbf{v}$$

$$\frac{\partial A}{\partial t} + \frac{1}{s}(\boldsymbol{v}.\nabla)(sA) = \eta_\mathrm{p}\left(\nabla^2 - \frac{1}{s^2}\right)A + \alpha B,$$

$$\frac{\partial B}{\partial t} + \frac{1}{r}\left[\frac{\partial}{\partial r}(rv_r B) + \frac{\partial}{\partial \theta}(v_\theta B)\right] = \eta_\mathrm{t}\left(\nabla^2 - \frac{1}{s^2}\right)B$$
$$+ s(\boldsymbol{B}_\mathrm{p}.\nabla)\Omega + \frac{1}{r}\frac{\mathrm{d}\eta_\mathrm{t}}{\mathrm{d}r}\frac{\partial}{\partial r}(rB)$$

The code *Surya* solves these equations

For a range of parameters, the code relaxes to periodic solutions (Nandy & Choudhuri 2002)

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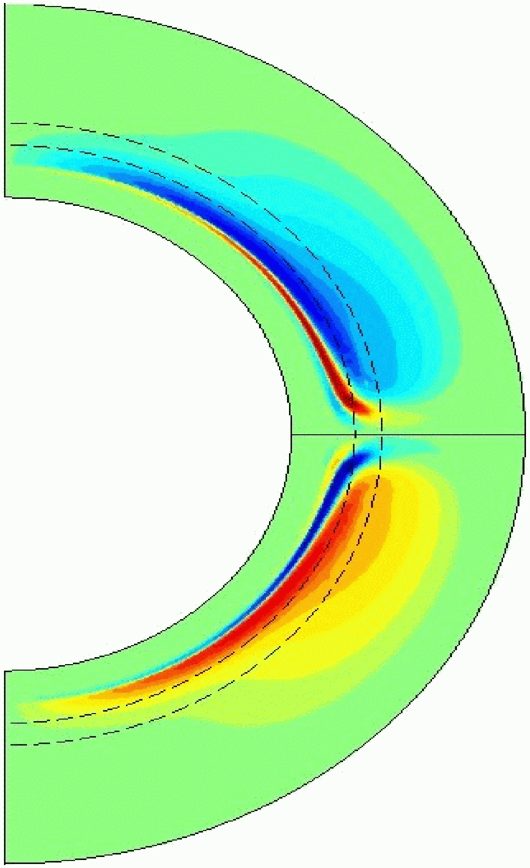
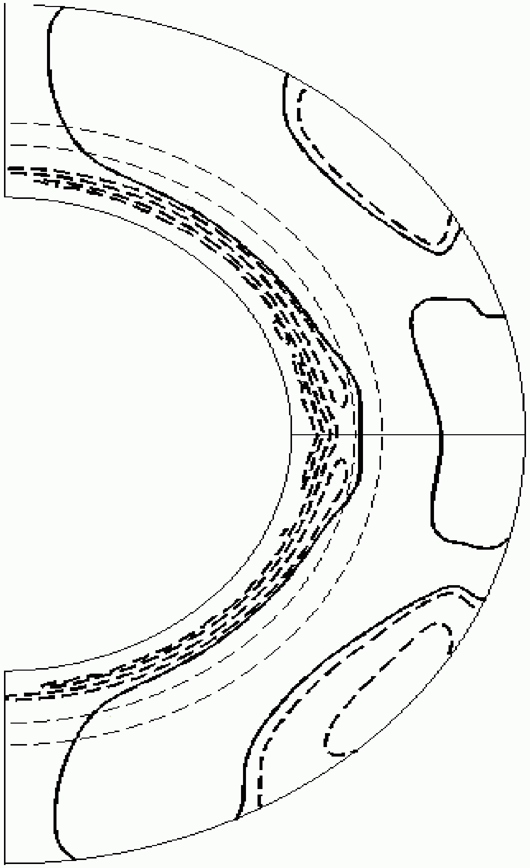
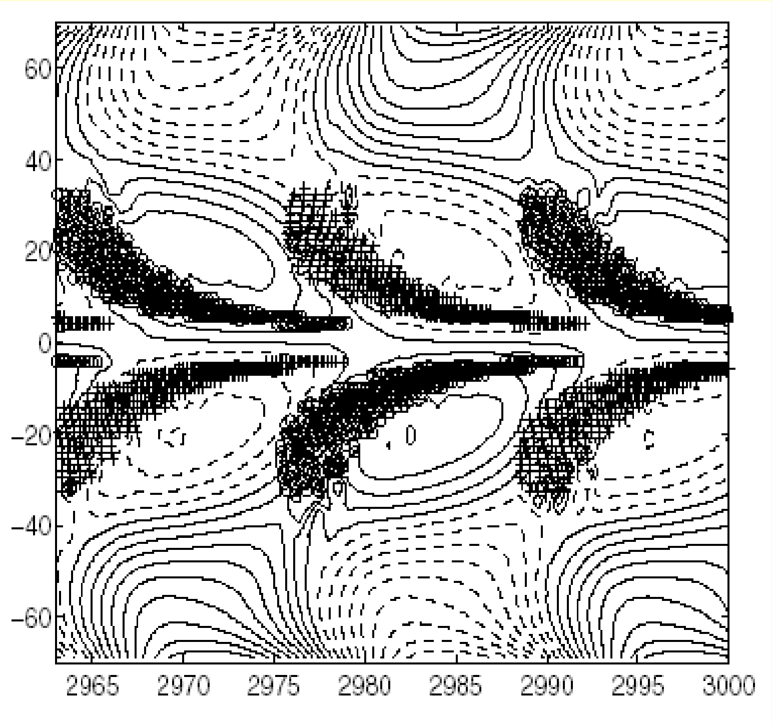


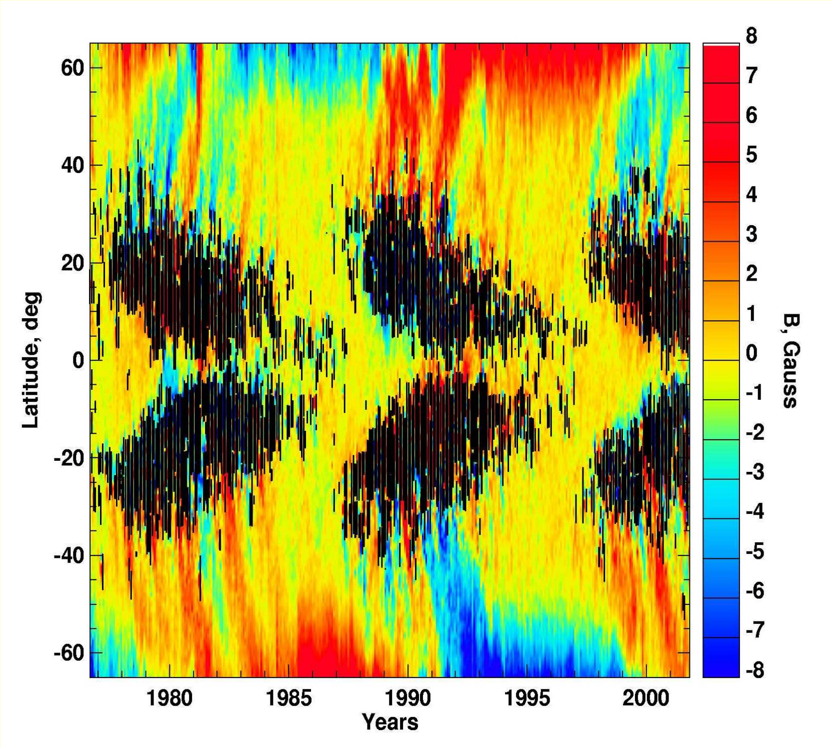
Time = 10.9874 yrs



Results from detailed model of Chatterjee, Nandy & Choudhuri (2004)

Butterfly diagrams with both sunspot eruptions and weak field at the surface > Reasonable fit between theory & observation





Flux Transport dynamo

(Choudhuri, Schussler & Dikpati 1995)

High diffusivity model

(diffusion time ~ 5 yrs)

IISc group

(Choudhuri, Nandy,

Chatterjee, Jiang, Karak)

Low diffusivity model

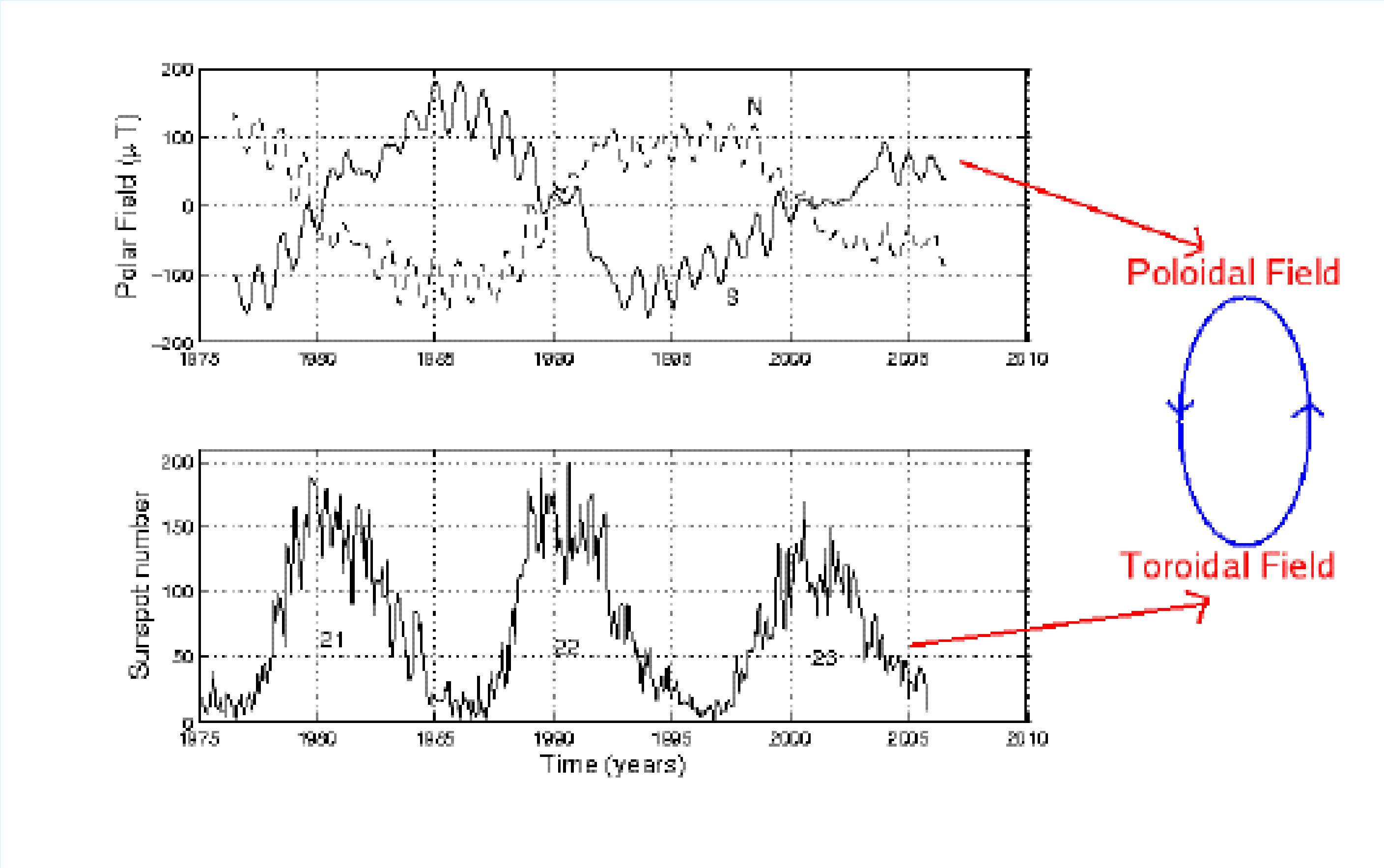
(diffusion time ~ 200 yrs)

HAO group

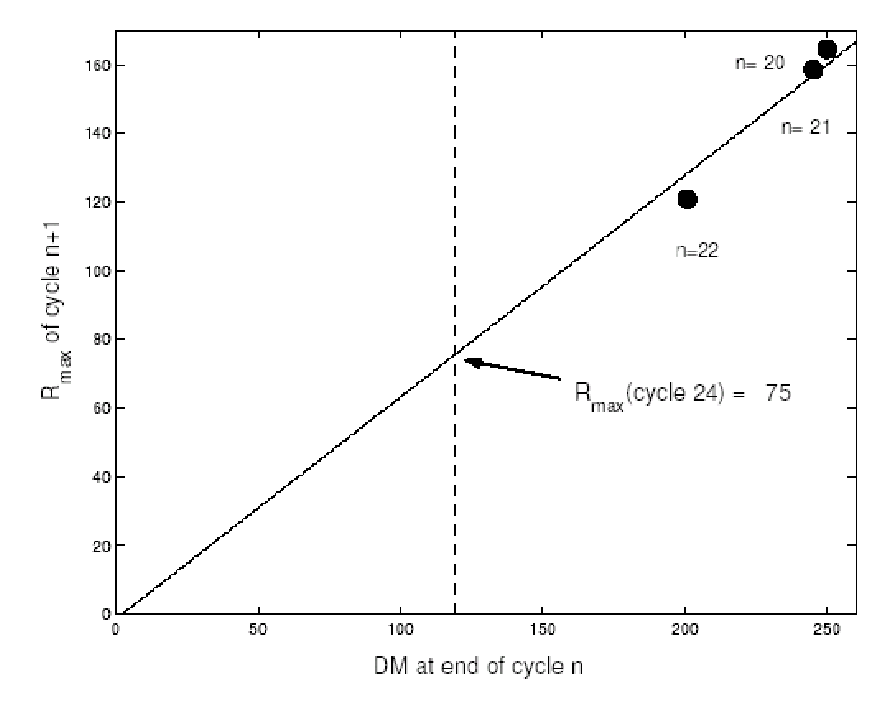
(Dikpati, Charbonneau,

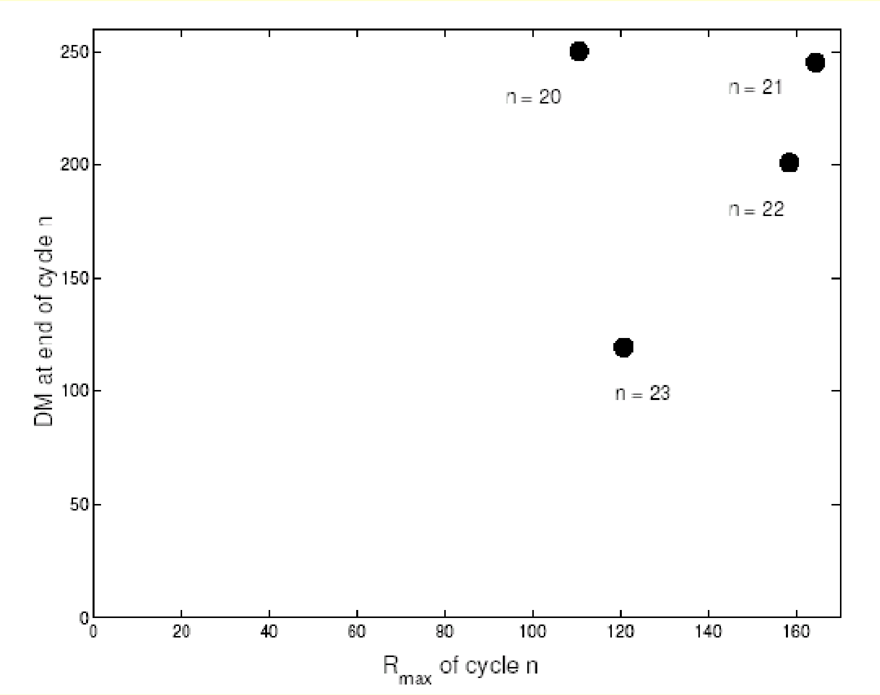
Gilman, de Toma)

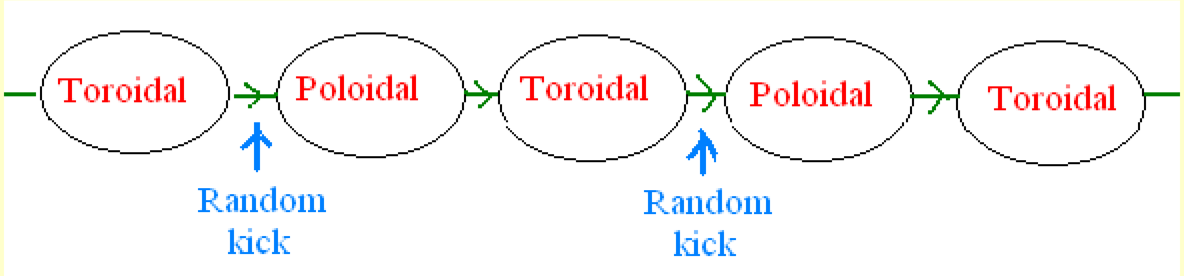
Differences between these models were systematically studied by Jiang, Chatterjee & Choudhuri (2007) and Yeates, Nandy & Mckay (2008)



The polar fields and the sunspot number as functions of time







Choudhuri, Chatterjee & Jiang (2007)

Polar field at the minimum gives an indication of the strength of the next solar maximum (Schatten, Scherrer, Svalgaard & Wilcox 1978)

Weak polar field at the present time suggests a very weak cycle 24 (Svalgaard, Cliver & Kamide 2005; Schatten 2005)

What can we say from theoretical solar dynamo models?

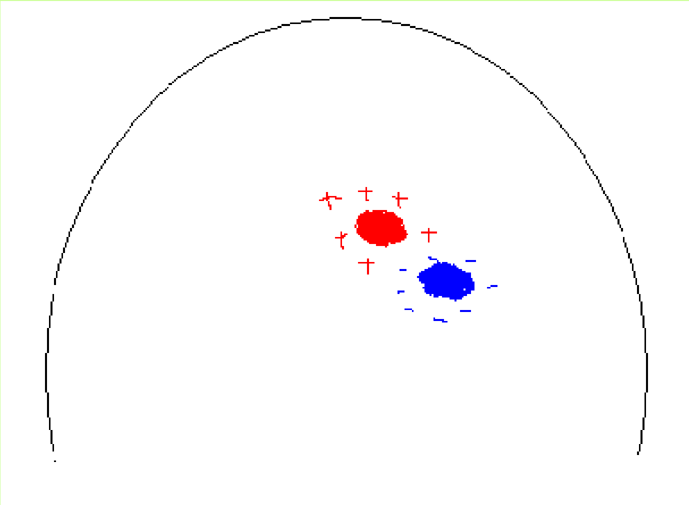
Dikpati & Gilman (2006) predict a strong cycle 24!

They took Toroidal -> Poloidal as determinstic

Tobias, Hughes & Weiss (2006) comment:

"Any predictions made with such models should be treated with extreme caution (or perhaps disregarded), as they lack solid physical underpinnings."

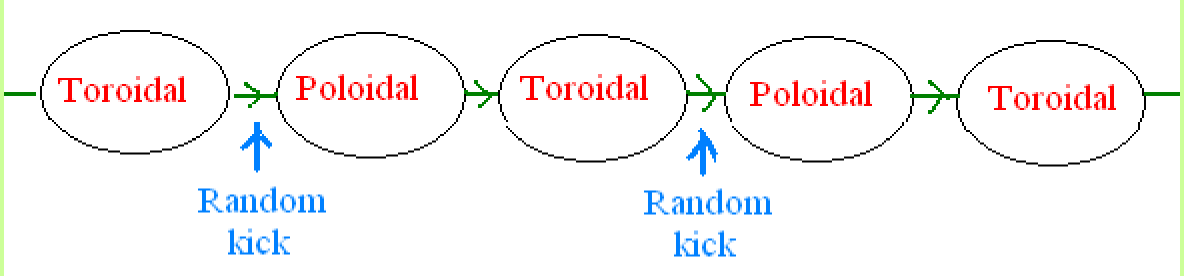
What is the source of irregularity in the solar cycle?



Joy's law: Bipolar sunspots have tilts increasing with latitude (D'Silva & Choudhuri 1993)

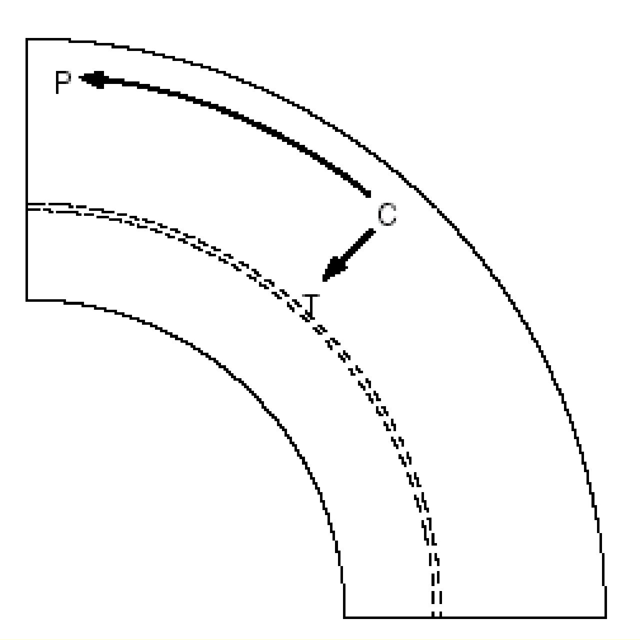
Their decay produces poloidal field (Babcock 1961; Leighton 1969)

Randomness due to large scatter in tilt angles (caused by convective turbulence – Longcope & Choudhuri 2002)



Fluctuations in meridional circulation another source!

Cause of correlation between the polar field at the minimum and the next cycle (Jiang, Chatterjee & Choudhuri 2007)



C – Poloidal field produced here by Babcock-Leighton mechanism

P – Field advected to the pole by meridional circulation

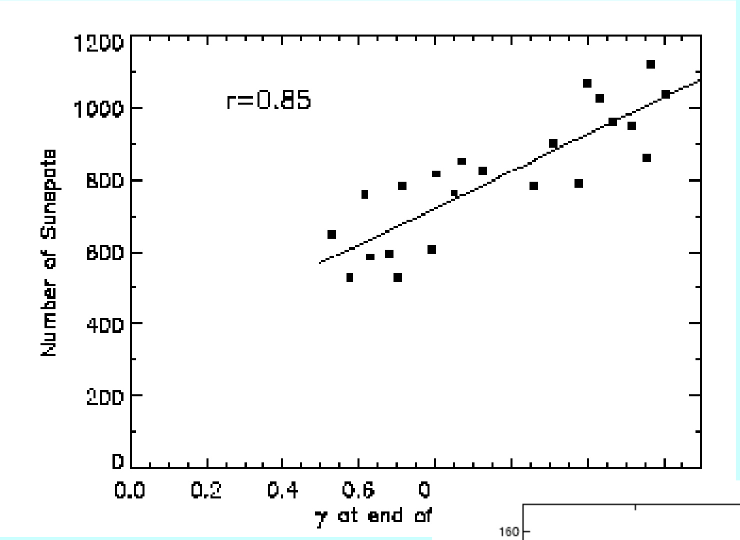
T – Poloidal field diffuses to tachocline to produce next cycle

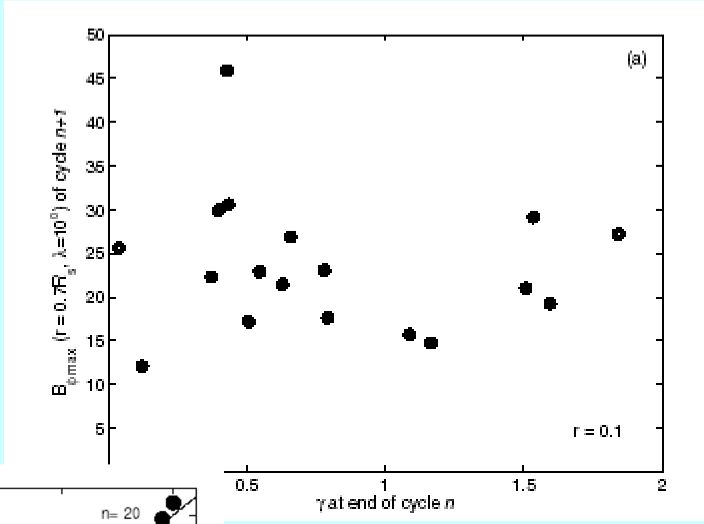
Correlation arises if C -> T diffusion takes 5-10 years

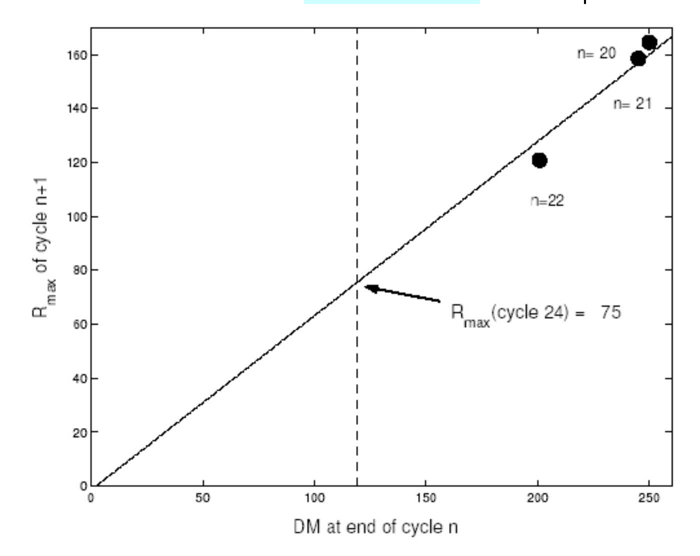
It is 5 years in our model and 250 years in Dikpati-Gilman model

Our diffusion coefficient is of order ~ (1/3)vl

Correlations seen in numerical simulations with random kicks at the sunspot minima (from Jiang, Chatterjee & Choudhuri 2007)





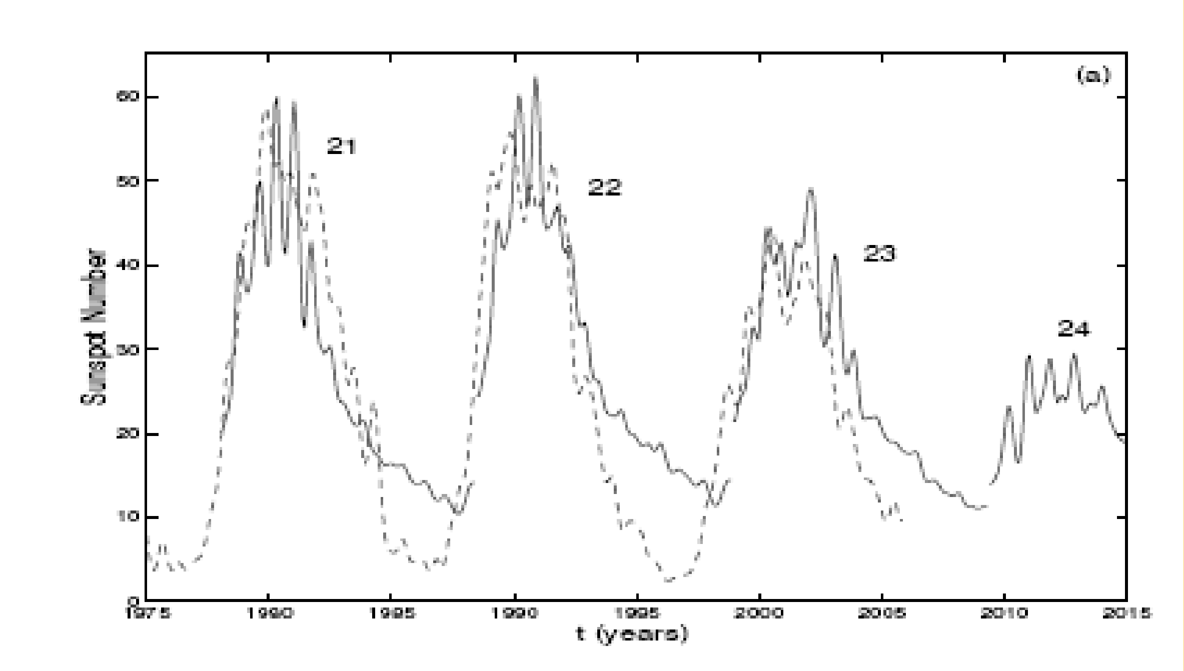


High diffusivi liffusivity

(our model) ati-Gilman)

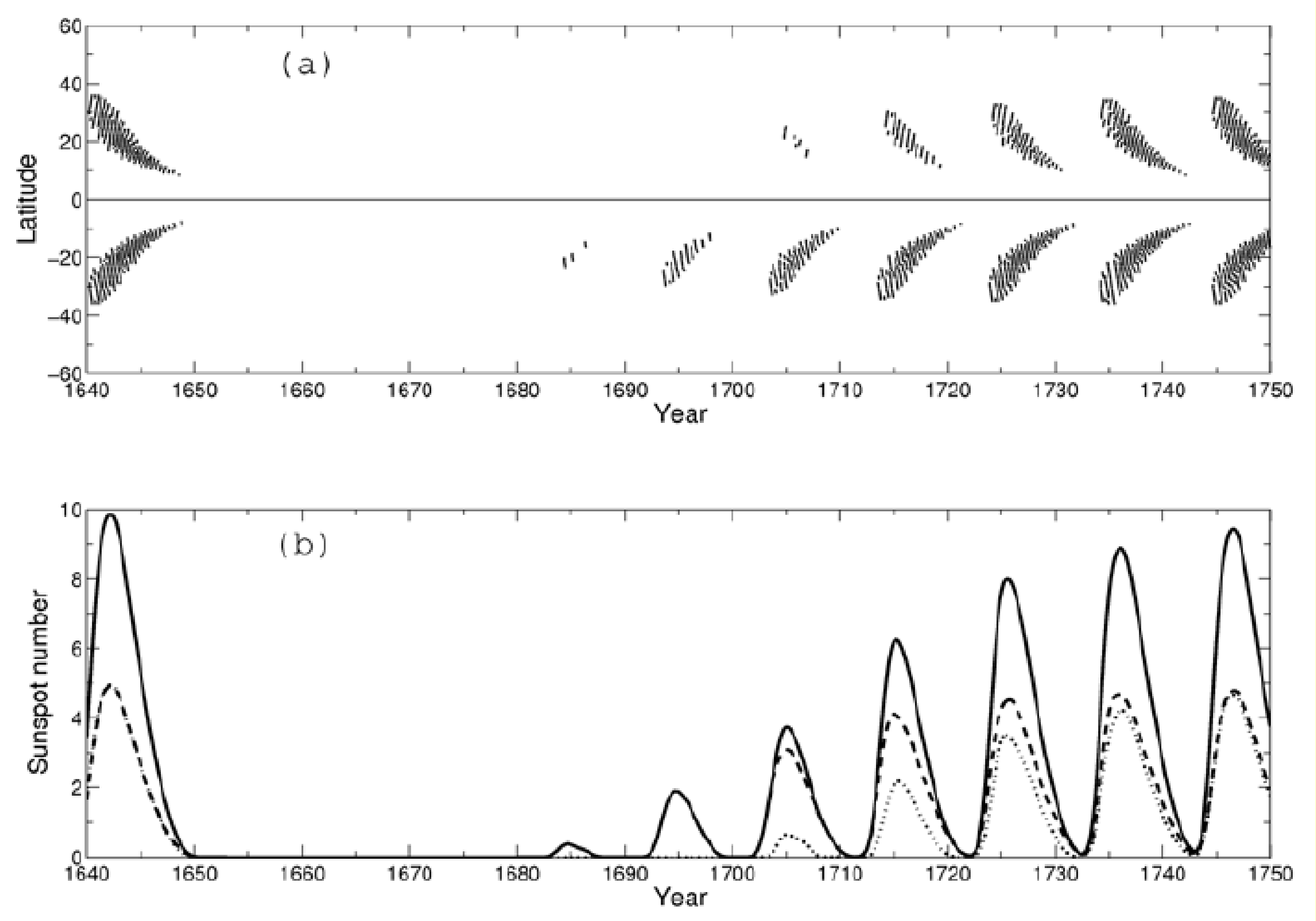
Modelling of actual solar cycles (Choudhuri, Chatterjee & Jiang 2007)

Use observational data of polar fields to model the random kicks



We predict that upcoming cycle 24 will be a very weak cycle!

Modelling of Maunder minimum with flux transport dynamo



From Choudhuri & Karak (2009)

Conclusion

Solar cycles are produced by produced by a flux transport dynamo involving the following processes:

- Toroidal field generation in tachocline by differential rotation
- Poloidal field generation at surface by Babcock-Leighton mechanism
- Advection by meridional circulation

Irregularities in cycles are primarily caused by fluctuations in the Babcock-Leighton process