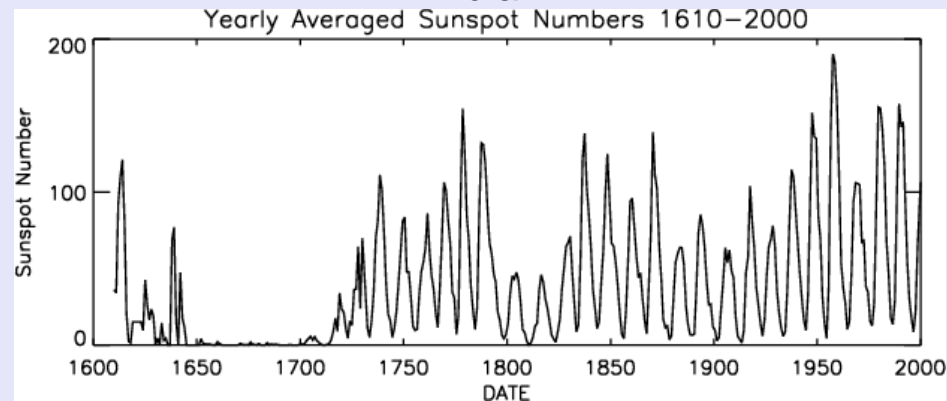


# *Can Solar Cycles be Predicted using Theoretical Models?*

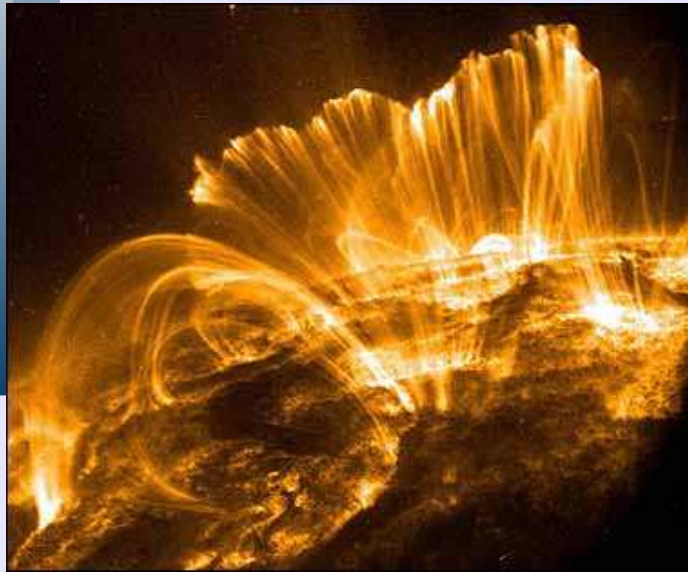
Piyali Chatterjee

([piyalic@tifr.res.in](mailto:piyalic@tifr.res.in))

Department of Astronomy and Astrophysics, Tata Institute of Fundamental Research, Mumbai, India.

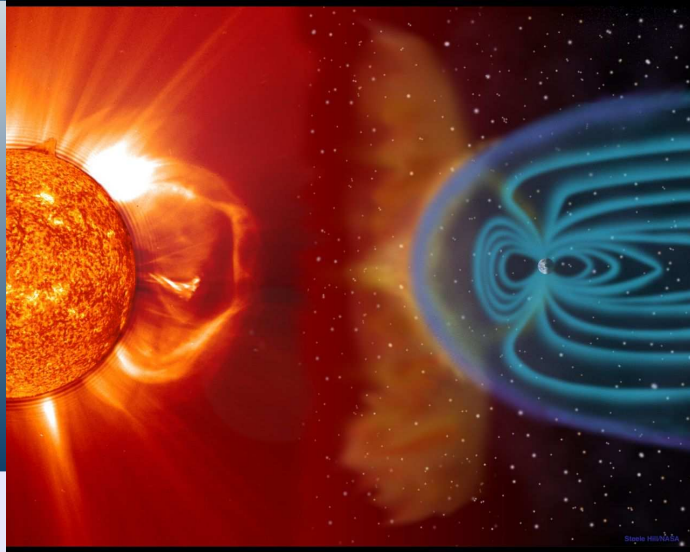


## Why Study Solar Magnetism? - I



- ☞ Solar Flares and Coronal Mass Ejections are biggest explosions in the solar system – eject magnetized plasma and charged particles.  
 Flare Energies  $\sim 10^{26}$  J: Hiroshima Atom Bomb  $\sim 10^{14}$  J  
**March 13, 1989:** About 1 million people in Quebec (Canada) were without electricity for 8 hours.  
**Cause** A major solar flare on March, 9
- ☞ Energetic charged particles from flares can reach Earth's geomagnetic poles to produce aurorae and cause various geomagnetic disturbances.

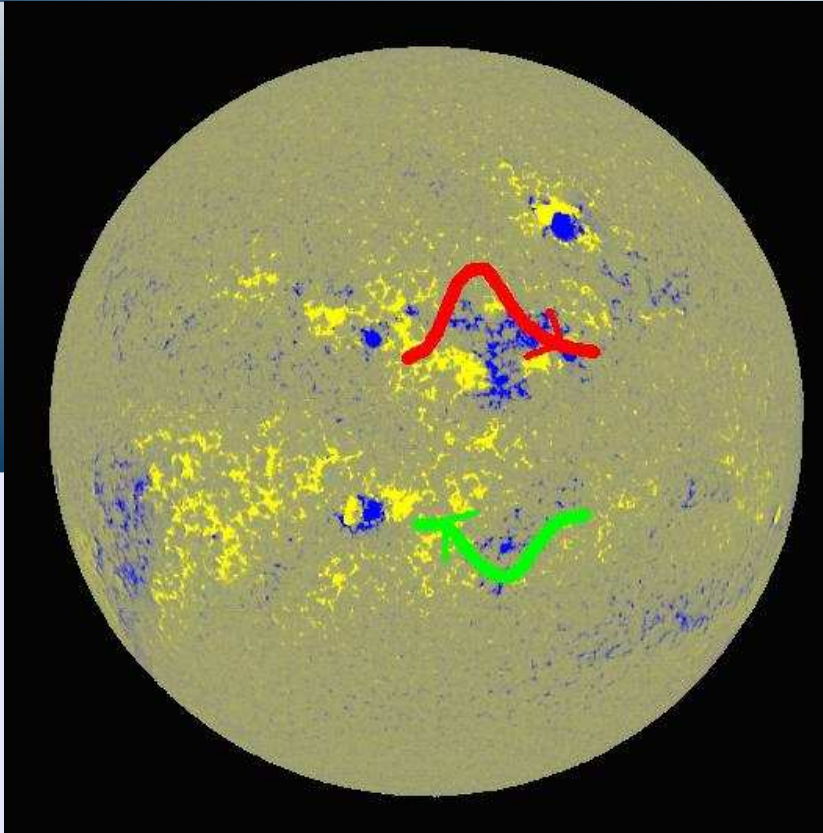
## Why Study Solar Magnetism? - II



### Solar magnetic storms can

- ☞ Disrupt radio communication by affecting the ionosphere.
- ☞ Damage electronic equipment in man-made satellites.
- ☞ Trip power grids. Nuclear plants also at risk
- ☞ Make polar airline routes dangerous. Northern oil pipelines also affected

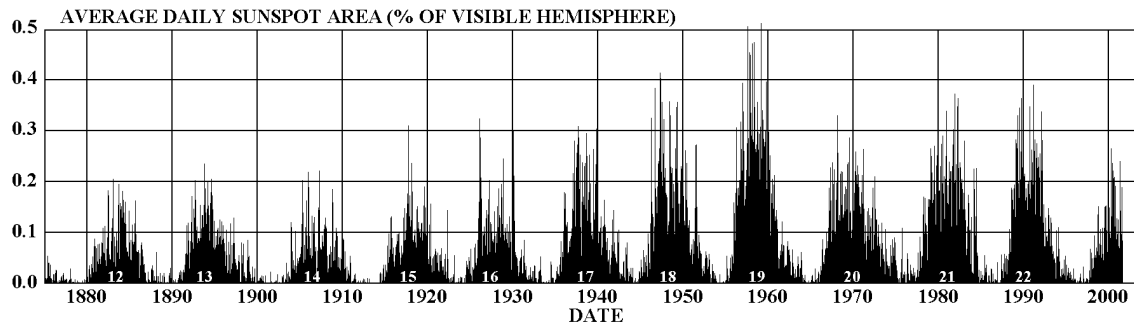
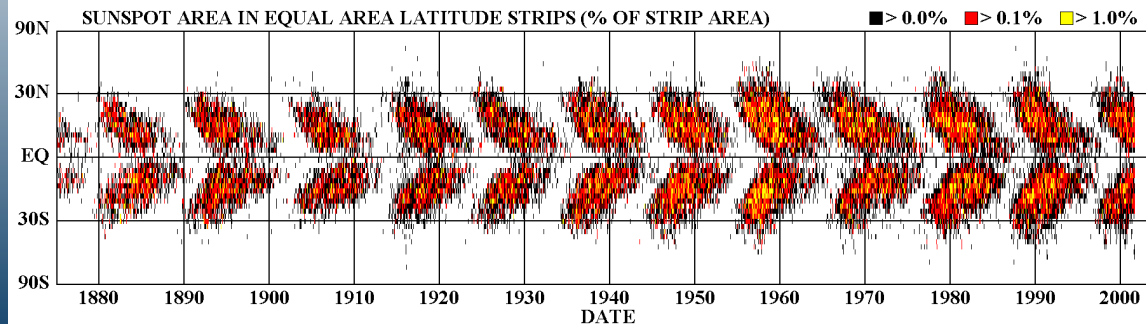
## Sunspots: Tracers of solar activity - I



- First telescopic observations by Galileo and Scheiner (1600s).
- Hale (1908) discovered strong magnetic fields ( $\sim 3000$  G) inside sunspots.
- Sunspots appear as bipolar pairs and have systematic tilts.
- The polarity of sunspot magnetic fields is opposite in two hemispheres.

# Sunspots: Tracers of solar activity - II

## DAILY SUNSPOT AREA AVERAGED OVER INDIVIDUAL SOLAR ROTATIONS



<http://science.msfc.nasa.gov/ssl/pad/solar/images/bfly.gif>

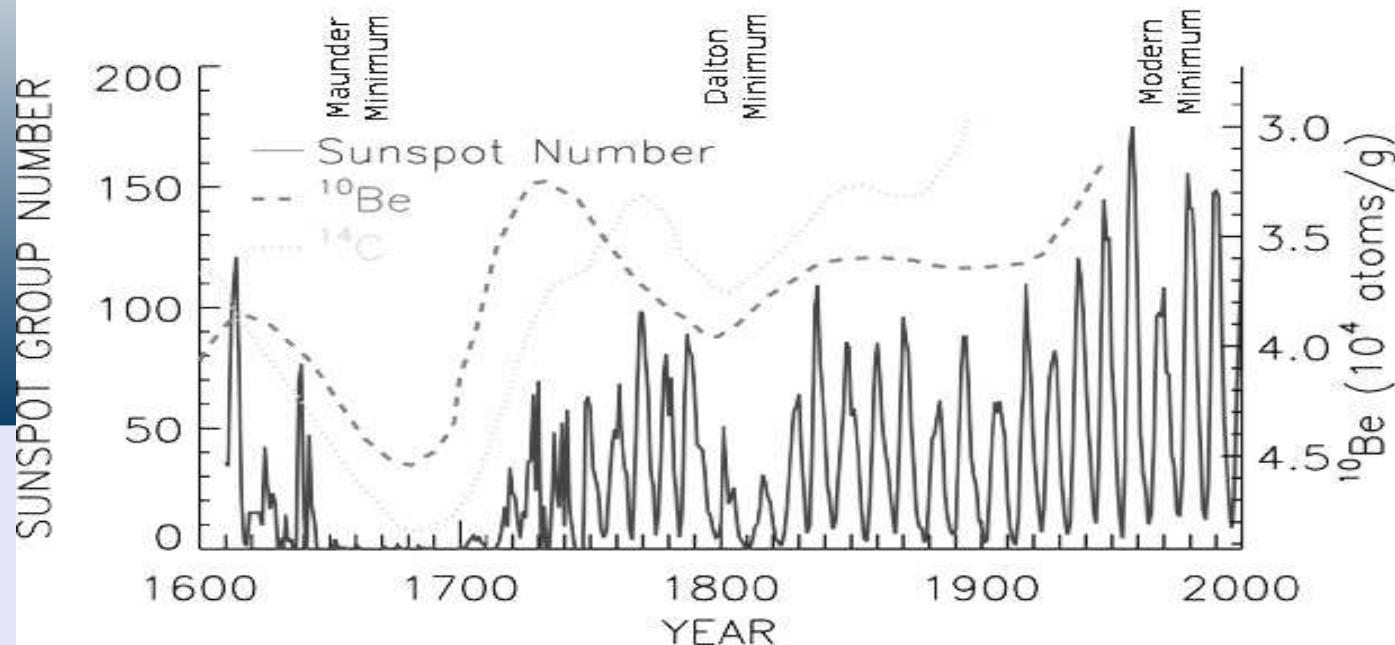
NASA/MSFC/HATHAWAY 08/2001

**1844:** Schwabe discovers solar cycle.

**1858:** Carrington discovers equatorward latitudinal drift with solar cycle.

**1904:** Maunder invents *butterfly diagram*.

## Sunspots: Tracers of solar activity - III

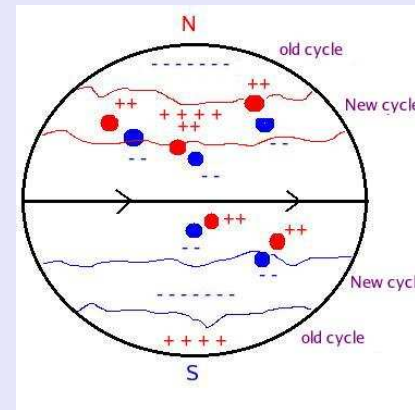


- ★ Number of sunspots observed on the Sun vary with time.
- ★ Time variation is predominantly cyclic, mean period is 11 years.
- ★ However, there are large amplitude fluctuations.

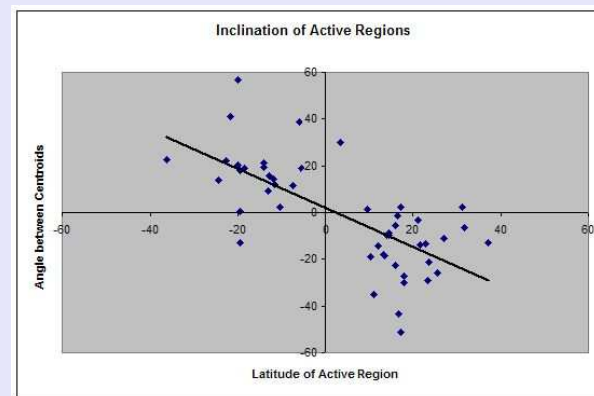
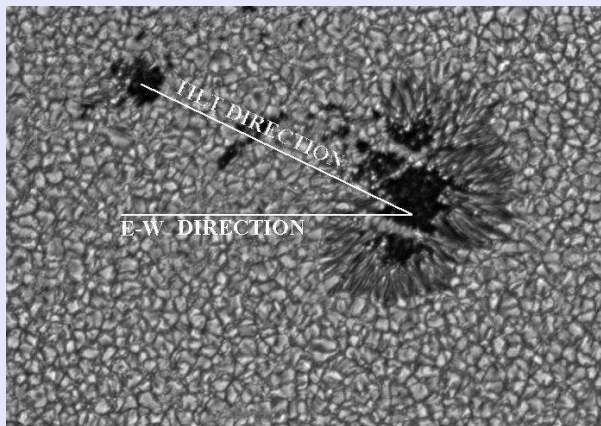
# Sunspots: Tracers of solar activity - IV

## Polarity of active regions: Hale's polarity rule (1919)

- ★ Leading spots of the bipolar active regions have same polarity in a given cycle.
- ★ Polarity changes with transition to a new cycle.
- ★ Polarity of leading spots is opposite in northern and southern hemispheres.



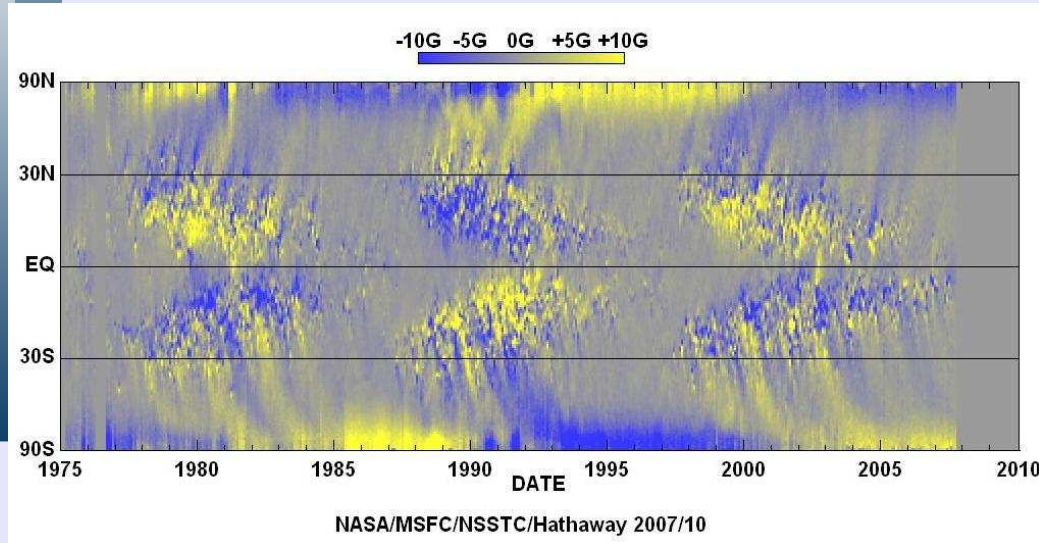
## Tilt of active regions increase with latitude: Joy's Law (1919)



**Together they imply:** During an odd cycle the leading spot in NH (SH) has 'N' ('S') polarity and lies nearer the equator than the following spot.

**Regularity of polarity reversals imply:** Global nature of solar magnetic field generation

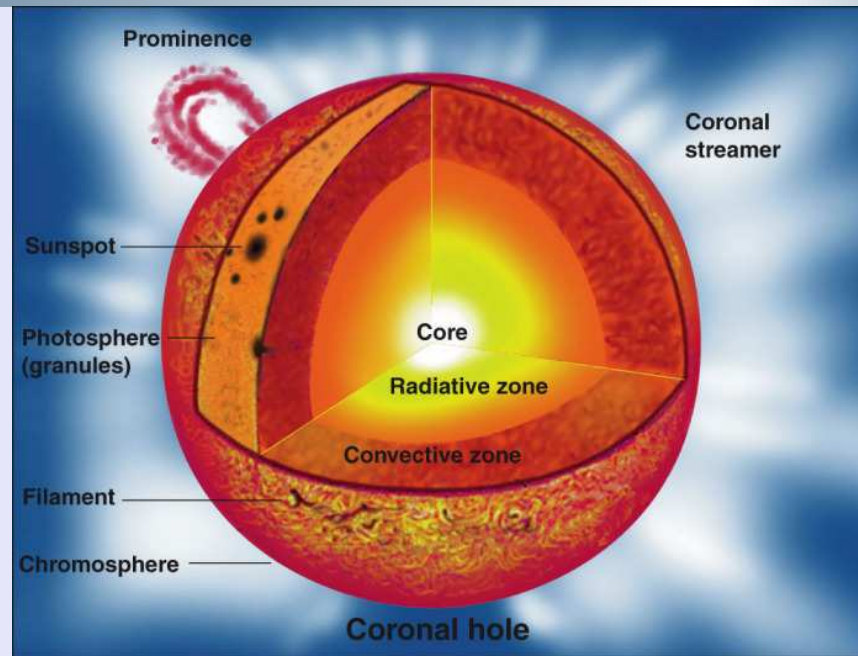
# Polar Fields: Tracers of solar activity - I



- ★ Babcock & Babcock developed the solar magnetograph in 1948.
- ★ They report presence of weak diffuse magnetic fields on the Sun restricted to latitudes  $> 55^\circ$ .
- ★ These unipolar regions ( $\sim 10G$ ) appear to migrate poleward in contrast to sunspots which migrate equatorward.
- ★ Polar fields reverse polarity every 11 years during the sunspot maximum.
- ★ Polar fields have opposite polarities in Northern and Southern hemispheres.



## Structure of the Sun



Courtesy of Encyclopaedia Britannica, Inc., illustration by Anne Hoyer Becker, from "A New Understanding of Our Sun," by Jay M. Pasachoff, 1989 Britannica Yearbook of Science and the Future

- ☞ Inside the Sun matter exists in form of *Plasma*.
- ☞ All the interesting magnetic phenomena takes place in the convection zone, comprising outer 30% of the Sun. The convection zone has both small scale turbulent motions and large scale structured motions.

Deal with the Dynamics of Magnetized Plasmas — **MHD**

# *MHD: Governing Equations.*

## ↪ The Induction Equation

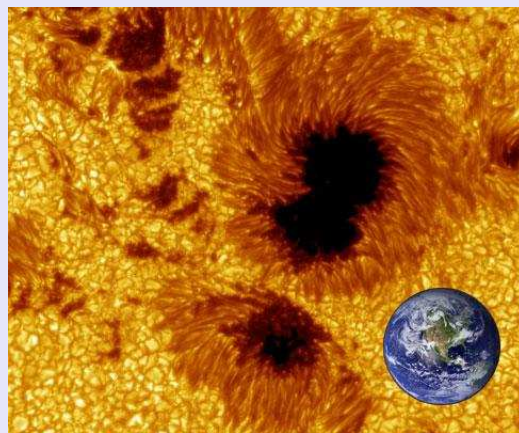
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

↪ Magnetic Reynolds Number  $\mathfrak{R}_M = VL/\eta \gg 1$  in astrophysical systems.

↪ Magnetic Field moves with the plasma – Alfven's Theorem of **Flux Freezing** (1942).

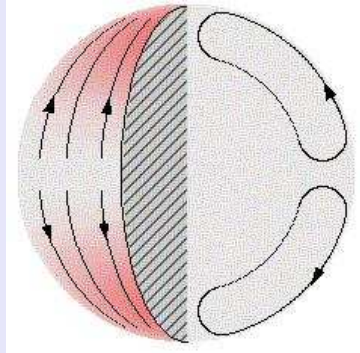
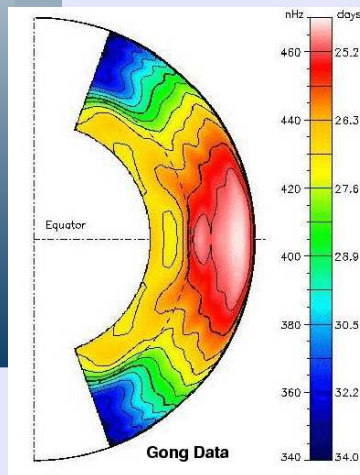
# Magnetoconvection

- ☞ **Magnetoconvection** – *Theory of interaction between magnetic field and thermal convection* (Chandrasekar 1952; Weiss 1981).
- ☞ Partitioning of space between magnetic field and convection – Magnetic fields excluded from regions of vigorous convection.
- ☞ Magnetic fields probably exist as **fluxtubes** rather than pervading entire convection zone.
- ☞ Sunspots are magnetic field concentrations with suppressed convection.



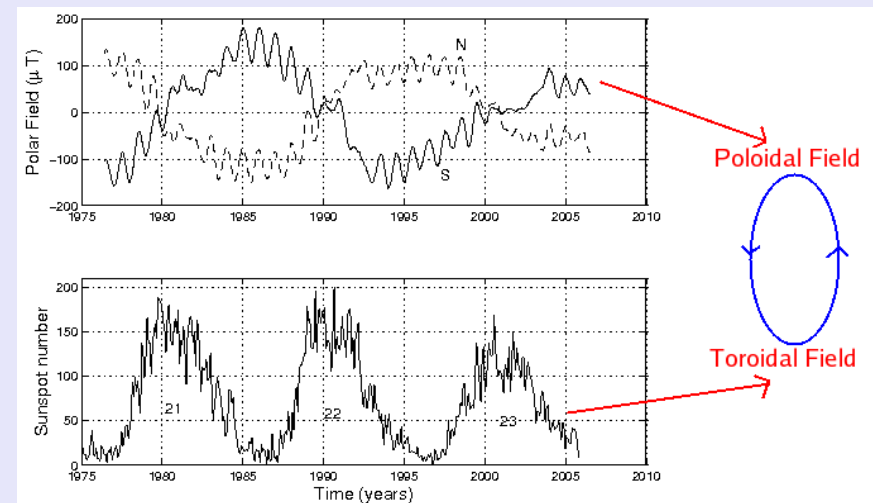
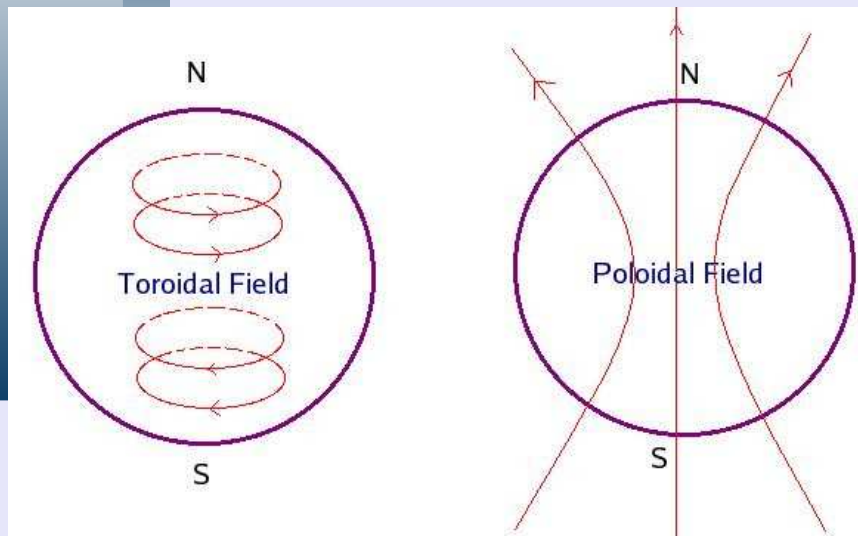
*Picture courtesy Swedish Solar Telescope*

## Angular Velocity Distribution and meridional flow



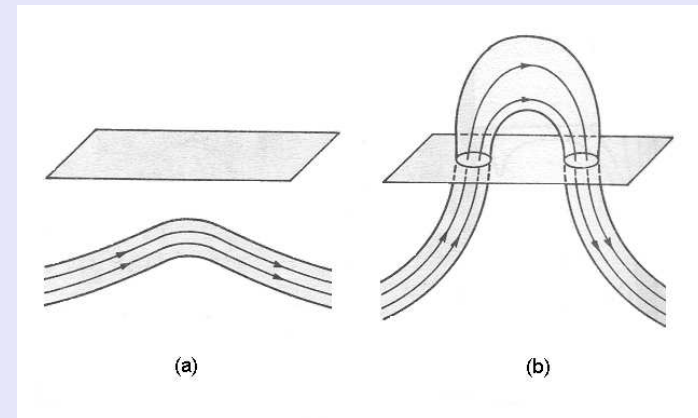
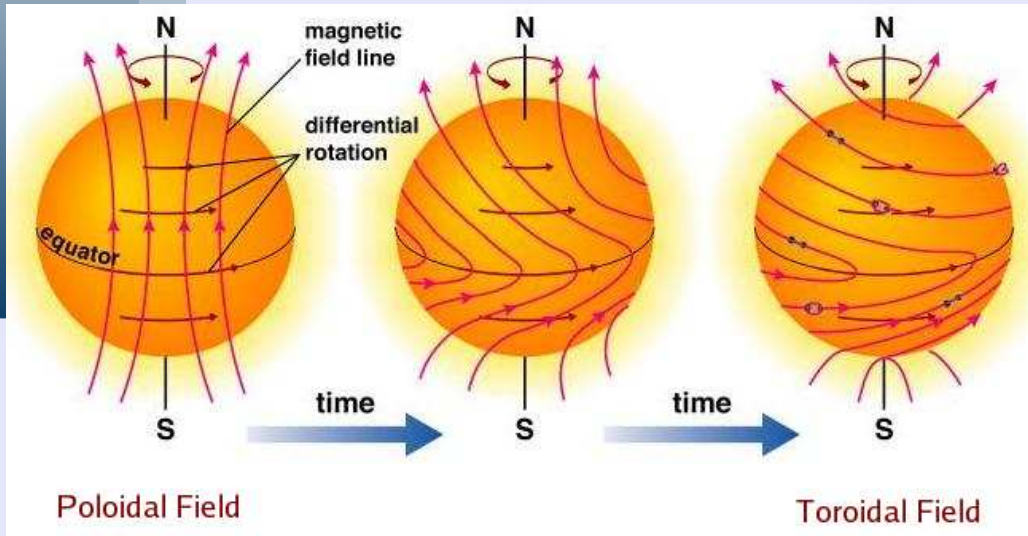
- ★ A rich spectrum of oscillations have been observed for the Sun.
- ★ Eigenfunctions of normal modes
 
$$\xi_{nlm} = R_n(r)Y_l^m(\theta, \phi)e^{i\omega_{nlm}t}$$
- ★ Rotation, Magnetic Fields and departures from spherical symmetry causes splitting
 
$$\omega_{nl(+m)} \neq \omega_{nl(-m)}.$$
- ★ Allows detailed investigation of properties of solar interior, angular velocity distribution and surface flows.
- ★ Detection of **Tachocline** at bottom of convection zone at  $0.7R_{\odot}$  (Spiegel & Zahn 1992).
- ★ Detection of poleward surface flow (Komm, Howard & Harvey 1993; Latushko 1994; Hathaway 1996)

# Basic Idea of the Solar Dynamo



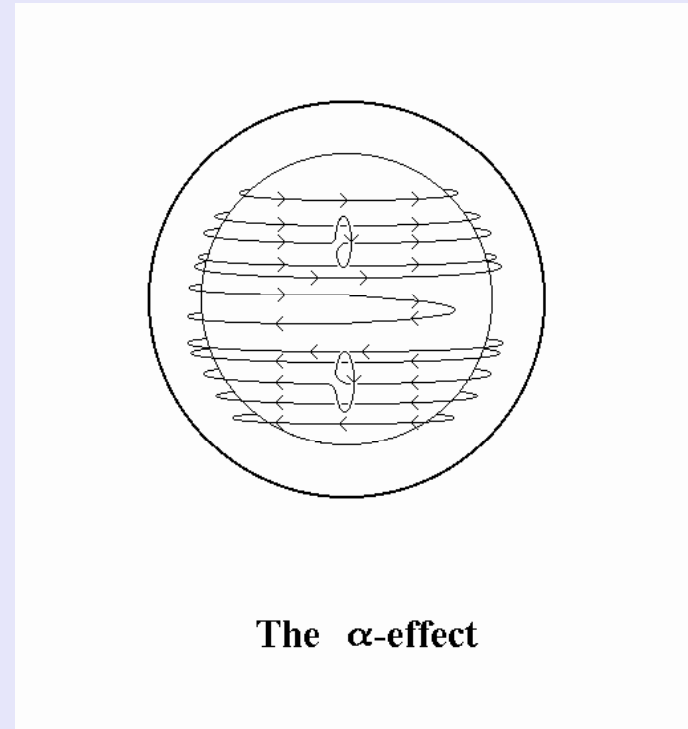
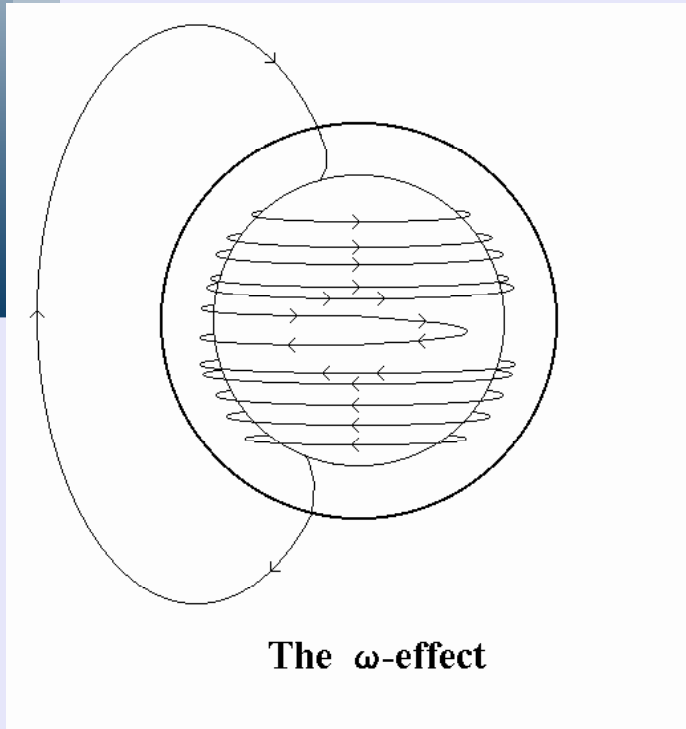
- ★ Toroidal Field  $\Rightarrow B_\phi \hat{e}_\phi$
- ★ Poloidal Field  $\Rightarrow B_r \hat{e}_r + B_\theta \hat{e}_\theta$
- ★ In an axisymmetric model Poloidal Field  $\Rightarrow \nabla \times (A \hat{e}_\phi)$ ,  $A$  is the poloidal field potential.
- ★ Parker (1955) suggested oscillations between poloidal and toroidal fields.

## Dynamo Process: Toroidal Field Creation



- ↪  **$\Omega$ -effect:** Faster rotating equator winds up the poloidal field in the direction of rotation to create toroidal fields.
- ↪ **Seat of  $\Omega$ -effect:** Magnetic buoyancy rules out amplification in the convection zone (Parker 1975). Conjectured to be at the overshoot layer at the bottom of the convection zone (Spiegel & Wiess 1980; van Ballegoijen 1982).

## Dynamo Process: Poloidal Field Creation



- ↪ Mean Field  $\alpha$  effect: small scale helical turbulence (Parker 1955).
- ↪ Helical turbulence twists the buoyantly rising toroidal field into loops in poloidal plane.
- ↪ Numerous such small scale loops diffuse to form the large scale poloidal field.

## Flux tube simulations & crisis in dynamo theory

- ↪ Simulations done with thin flux-tube approximations (Choudhuri & Gilman 1987)  
⇒ Coriolis force is dominant for  $B_{BCZ} < 10^5 \text{ G}$ .
- ↪ Flux tube simulations match Joy's Law (observed tilt angles) iff  $B_{BCZ} \sim 10^5 \text{ G}$  (D'Silva & Choudhuri, 1993; Fan, Fisher & DeLuca 1993).
- ↪ Only Flux tubes with  $B < 10^5 \text{ G}$  can be stored in the overshoot layer; stronger flux tubes escape due to buoyancy.
- ↪ Mean Field turbulent  $\alpha$ -effect can twist flux tubes having equipartition values ( $\sim 10^4 \text{ G}$ ). For super equipartition fields  $\alpha_{turb}$  gets quenched!



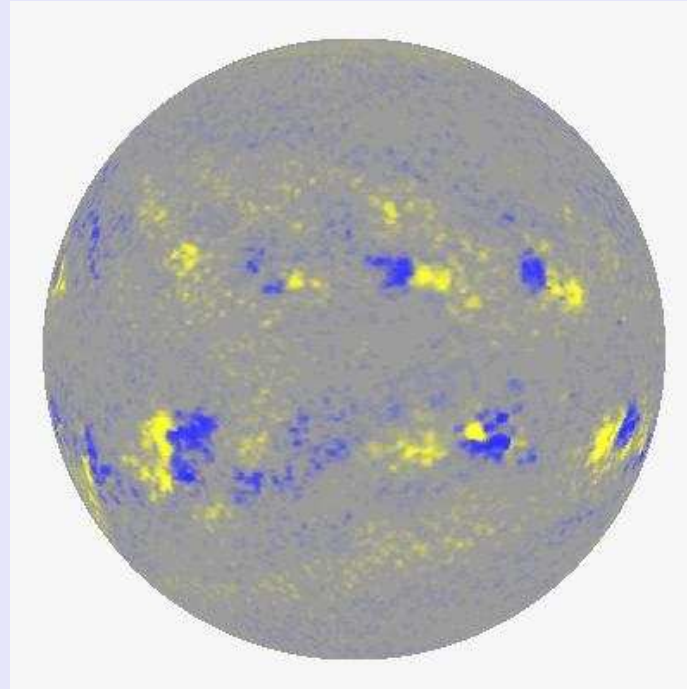
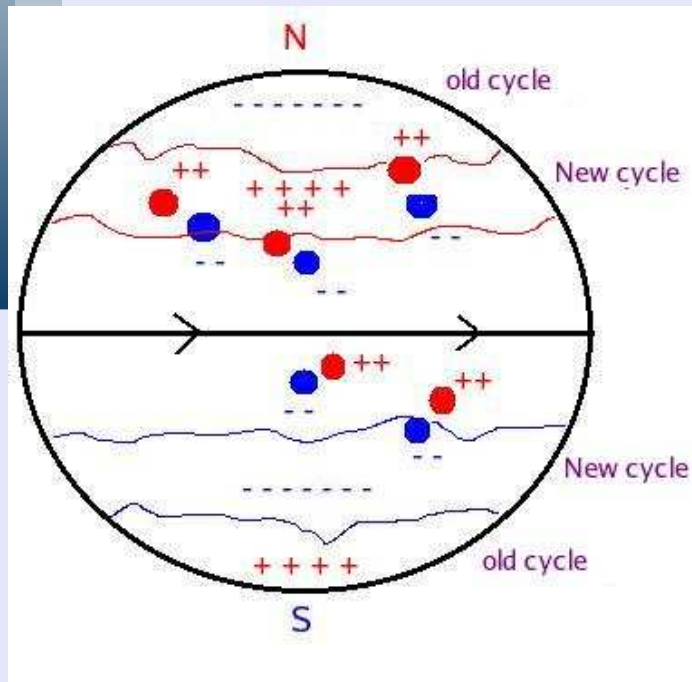
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### Alternative?

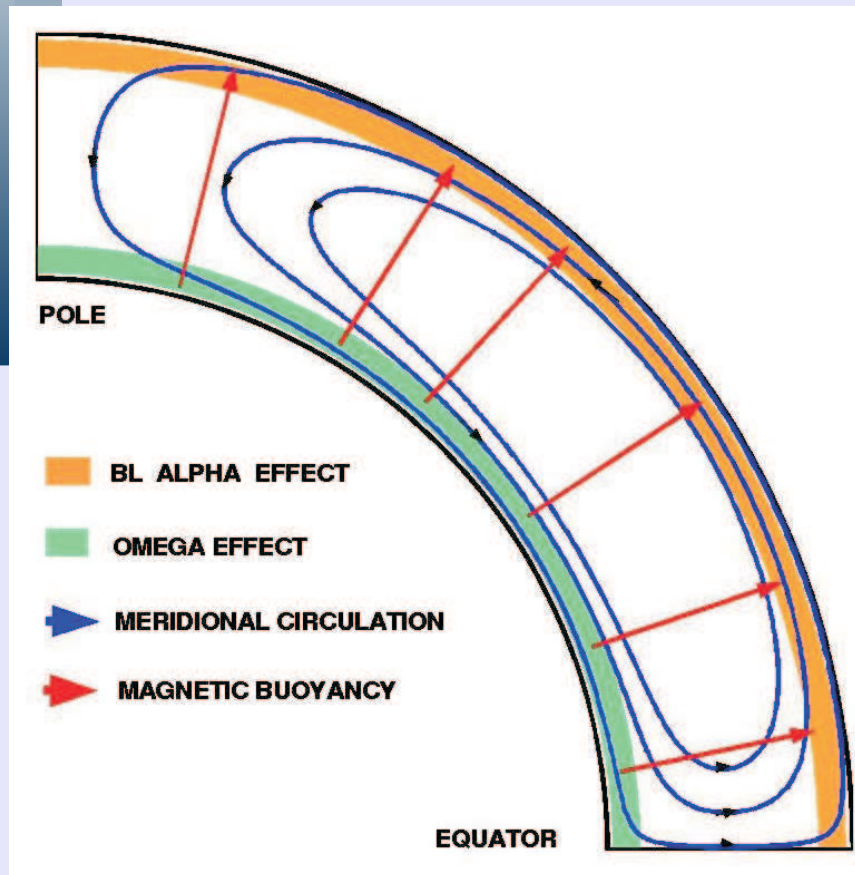
Phenomenological  $\alpha$ -effect proposed by Babcock (1961) & Leighton (1969) revisited

## The Babcock–Leighton $\alpha$



- ✓ Decay of tilted bipolar regions generate poloidal flux.
- ✓  $\alpha_{BL}$  confined to narrow layer near the surface.
- ✓ Tilts are monotonic function of latitude ( $\sim \cos \theta$ ), poloidal flux production dominated by active regions at higher latitude.

# Flux Transport Dynamos.



Modern Solar Dynamo Models incorporate THREE basic processes.

1. *The poloidal field gets converted to the strong toroidal field by stretching due to the differential rotation.*
2. *The toroidal field generated in the tachocline rises to the surface due to magnetic buoyancy and forms active regions. The tilted bipolar active regions decay to produce poloidal field by Babcock-Leighton mechanism*
3. *The meridional circulation carries the poloidal field first to the poles and then to the tachocline situated at  $0.7R_{\odot}$ .*

## The Basic Equations

All our calculations are done with a code for solving the **axisymmetric kinematic dynamo** problem. An axisymmetric magnetic field in spherical coordinate system can be represented in the form

$$\mathbf{B} = B(r, \theta) \hat{\mathbf{e}}_\phi + \nabla \times [A(r, \theta) \hat{\mathbf{e}}_\phi], \quad (1)$$

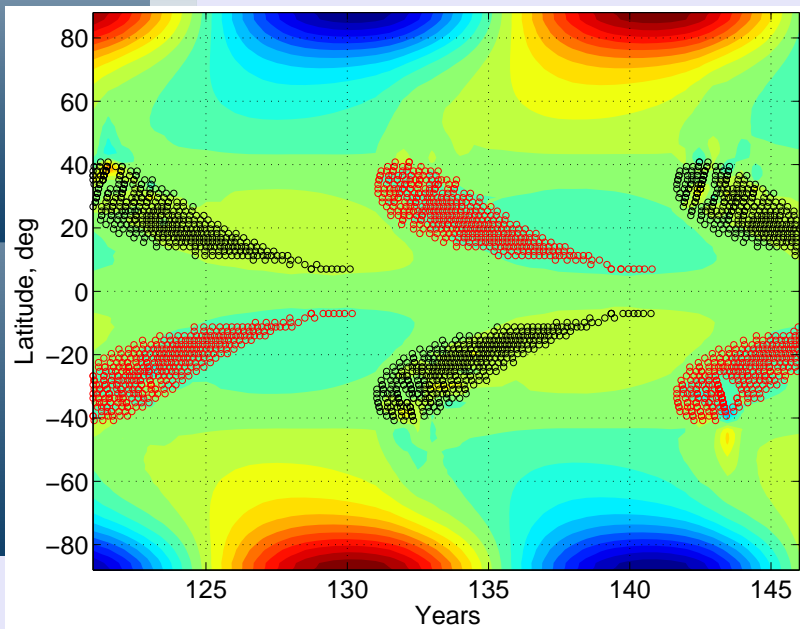
The coupled PDEs representing the  $\alpha\Omega$  dynamo are:

$$\frac{\partial A}{\partial t} + \frac{1}{s} (\mathbf{v} \cdot \nabla)(sA) = \eta_p \left( \nabla^2 - \frac{1}{s^2} \right) A + \underbrace{\alpha B}_{\text{Source term for A}}, \quad (2)$$

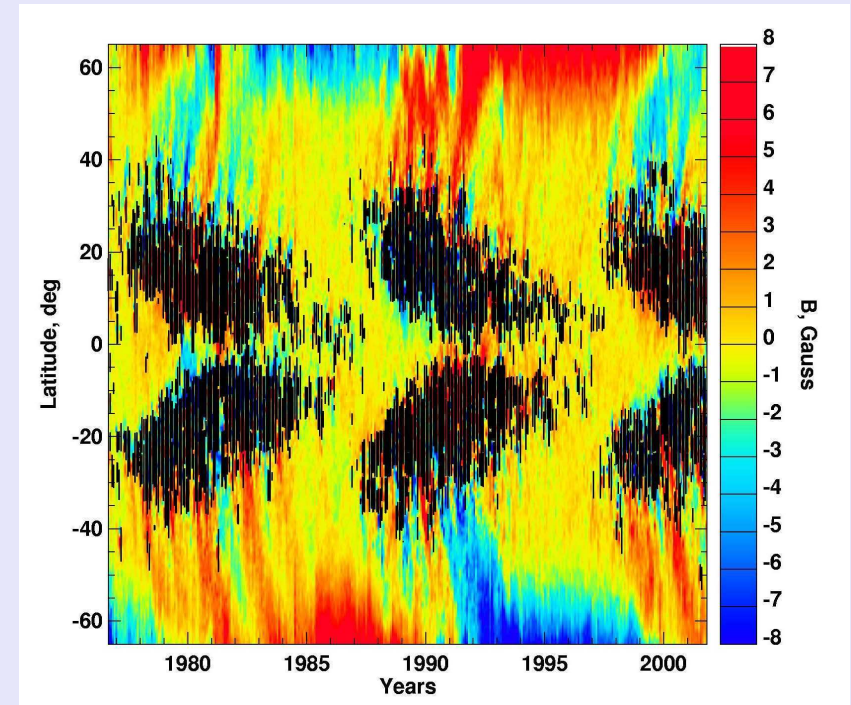
$$\begin{aligned} \frac{\partial B}{\partial t} + \frac{1}{r} \left[ \frac{\partial}{\partial r} (rv_r B) + \frac{\partial}{\partial \theta} (v_\theta B) \right] &= \eta_t \left( \nabla^2 - \frac{1}{s^2} \right) B \\ &+ \underbrace{s(\mathbf{B}_p \cdot \nabla)\Omega}_{\text{source term for B}} + \frac{1}{r} \frac{d\eta_t}{dr} \frac{\partial}{\partial r} (rB), \end{aligned} \quad (3)$$

where  $s = r \sin \theta$ , and meridional circulation  $\mathbf{v} = \nabla \times [\psi(r, \theta) \hat{\mathbf{e}}_\phi]$

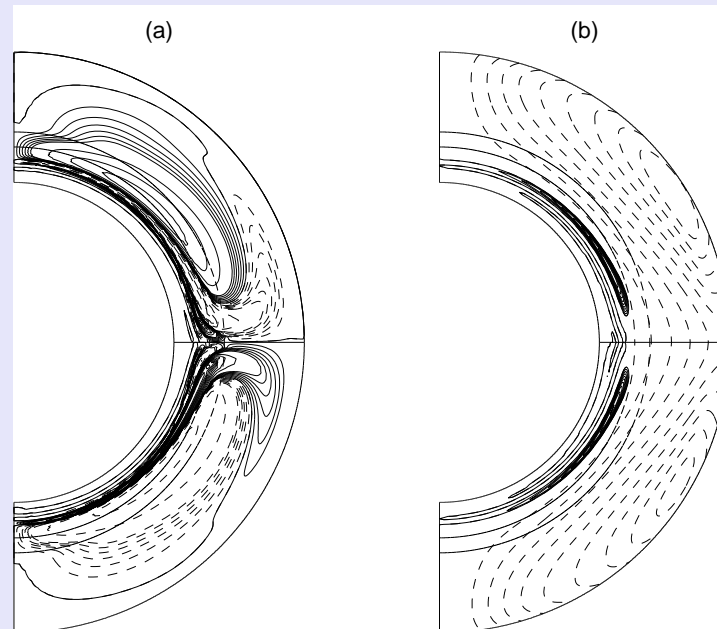
# Theoretical results from Surya



Theoretical Butterfly diagram of sunspot eruptions from *Surya*.



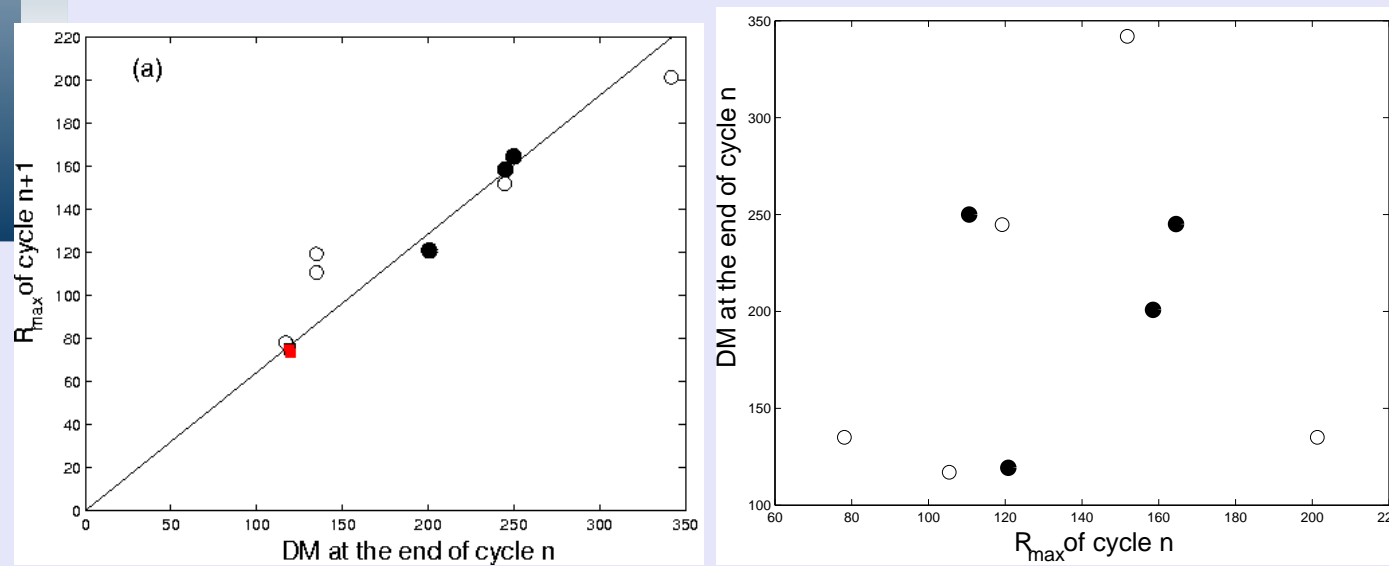
Observed Butterfly diagram of sunspot eruptions.



*Meridional cross-section of the Sun showing (a) toroidal and (b) poloidal fields during the epoch of solar minimum.*

## Observational support for precursor methods.

Polar field at the minimum gives an indication of the strength of the next solar maximum (Schatten, Scherrer, Svalgaard & Wilcox 1978).  $DM$  or the solar magnetic dipole moment is the difference between N-S polar field at a given minima.



**Left panel:** Strengths of solar cycles plotted against  $DM$  values of the preceding minima. The solid circles are based on actual polar field data whereas the open circles are based on polar field inferred from position of  $H\alpha$  filaments (Makarov et al 2001).

**Right panel:**  $DM$  values of polar fields plotted against the strengths of previous solar cycles

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

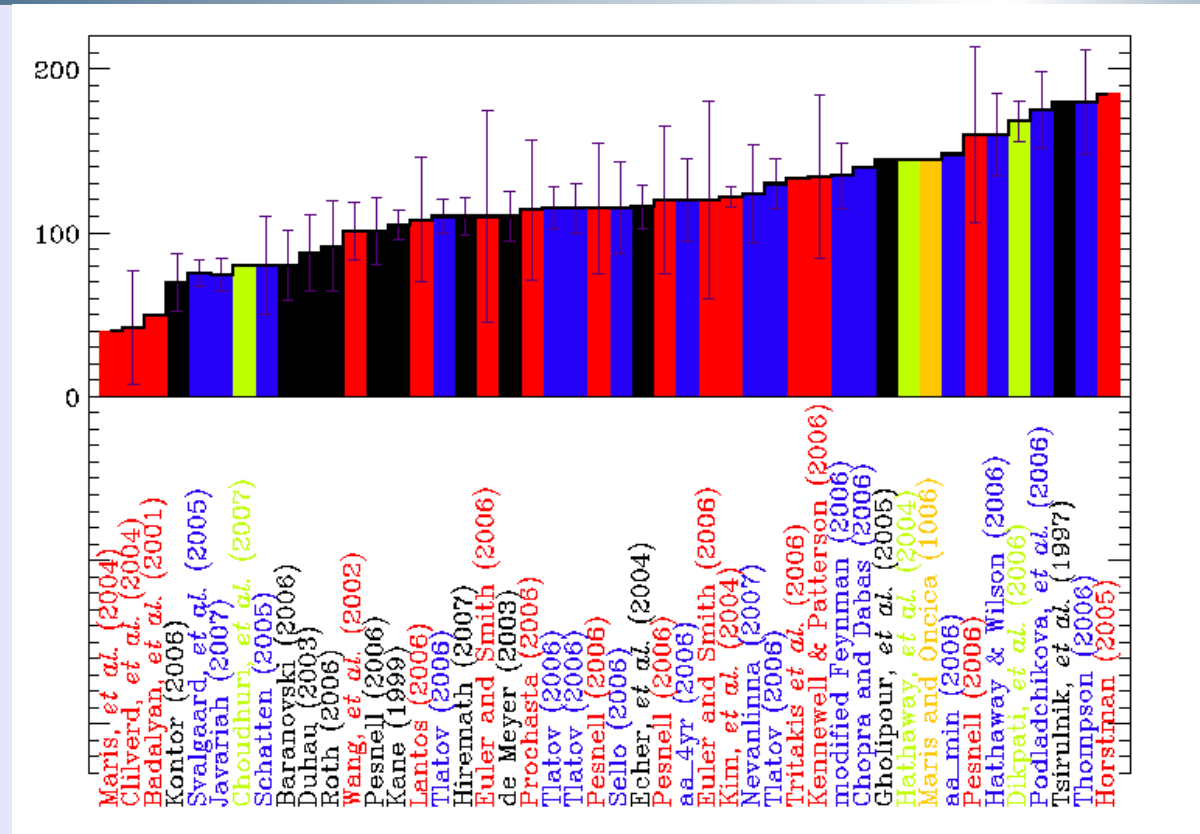
*What can we say from theoretical solar dynamo models?*

Dikpati & Gilman (2006) predict a strong cycle 24!  
They took Toroidal  $\implies$  Poloidal as *deterministic*

Tobias, Hughes & Weiss (Nature 442, 26, 2006) comment:  
"Any predictions made with such models should be treated with extreme caution (or perhaps disregarded), as they lack solid physical underpinnings."

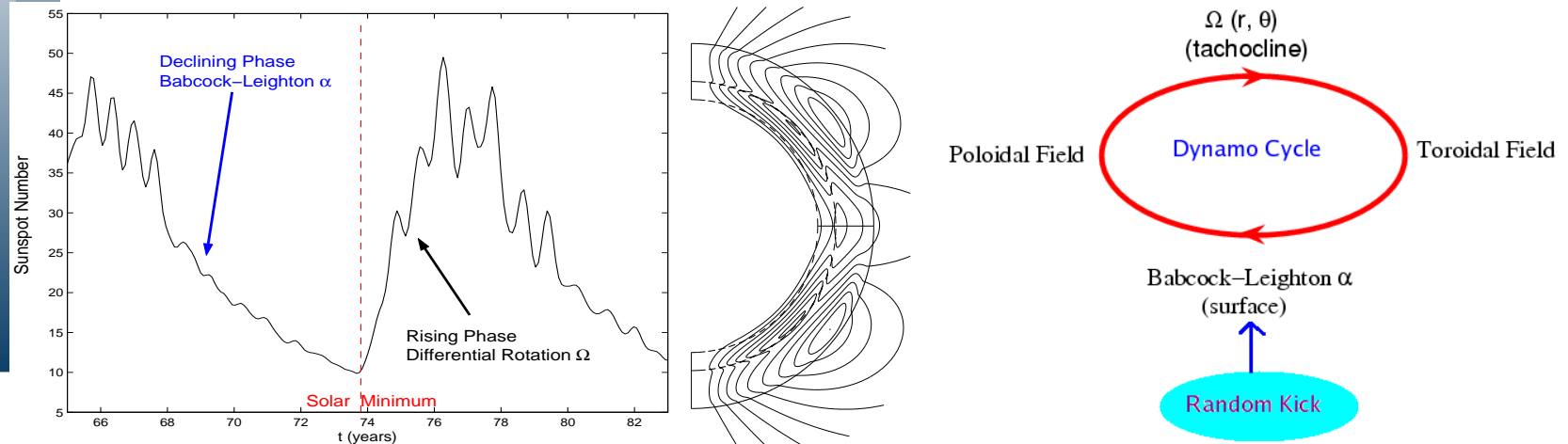


## Cycle 24 predictions so far...



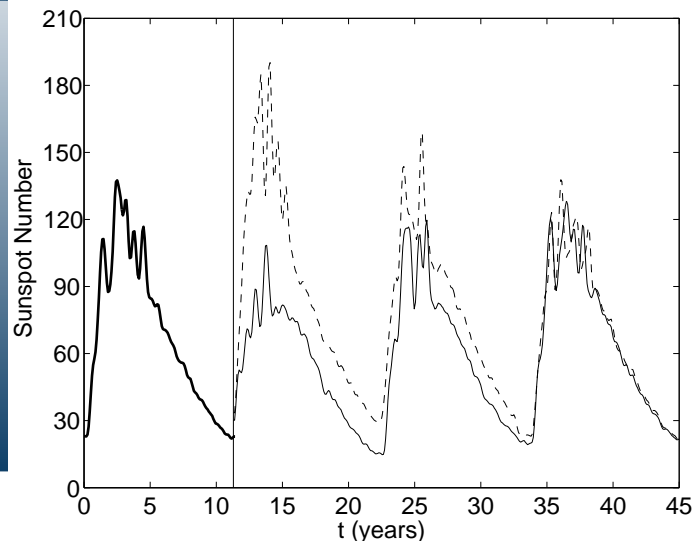
- ↪ The official NOAA, NASA, and ISES Solar Cycle 24 prediction was released by the Solar Cycle 24 Prediction Panel on April 25, 2007.
- ↪ The 45 independent predictions used to arrive at a consensus. Combination of spectral, climatological, neural network, dynamo model-based, precursor methods.

## Our Methodology for Predicting Solar Cycle 24



- ↪ *Poloidal field generated from an active region by the Babcock–Leighton process depends on the tilt, the scatter in the tilts introduces a randomness in the poloidal field generation process.*
- ↪ *The polar field at the solar minimum produced in a mean field dynamo model is some kind of ‘average’ polar field during a typical solar minimum. The polar field during a particular solar minimum may be stronger or weaker than this average field.*
- ↪ *We propose the following methodology for modelling the solar cycles with a mean field dynamo model. We run the dynamo code in the usual way from one solar minimum to the next. Then, at the time of the minimum, we change the amplitude of the polar field suitably to make it agree with the observed value of the polar field and run the code again to the next minimum.*

## Persistence in our model



Monthly smoothed sunspot number plots by increasing (dashed line) and decreasing (solid line) the poloidal field by 30% above  $0.8R_{\odot}$  at a solar minimum (indicated by the vertical line), based on our model.

Using regression analysis, Svalgaard, Cliver and Kamide (2005) propose a relation,

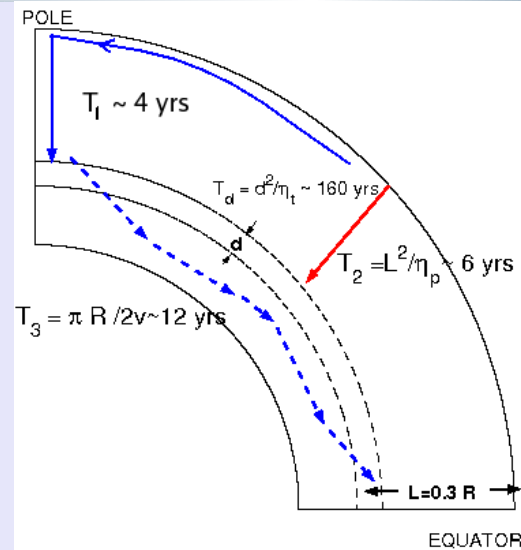
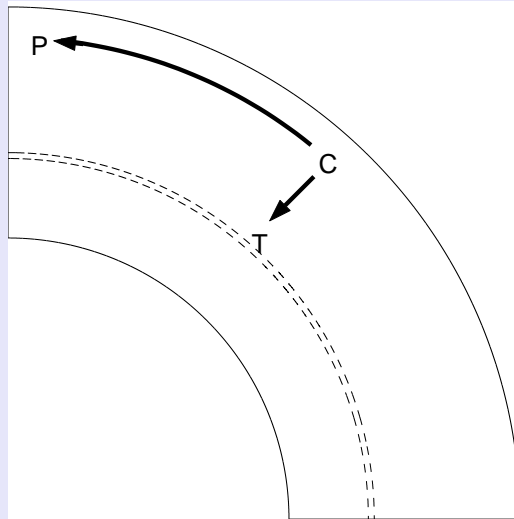
$$R_{max}^{n+1} \propto DM_n \quad (4)$$

On the basis of our model we expect a more complicated relation,

$$R_{max}^{n+1} \propto f(DM_n, DM_{n-1}) \quad (5)$$

This might mean that for  $DM_n$  quite different from  $DM_{n-1}$ , the  $R_{max}^{n+1}$  forecasted from our model is likely to be different from that expected from equation(4).

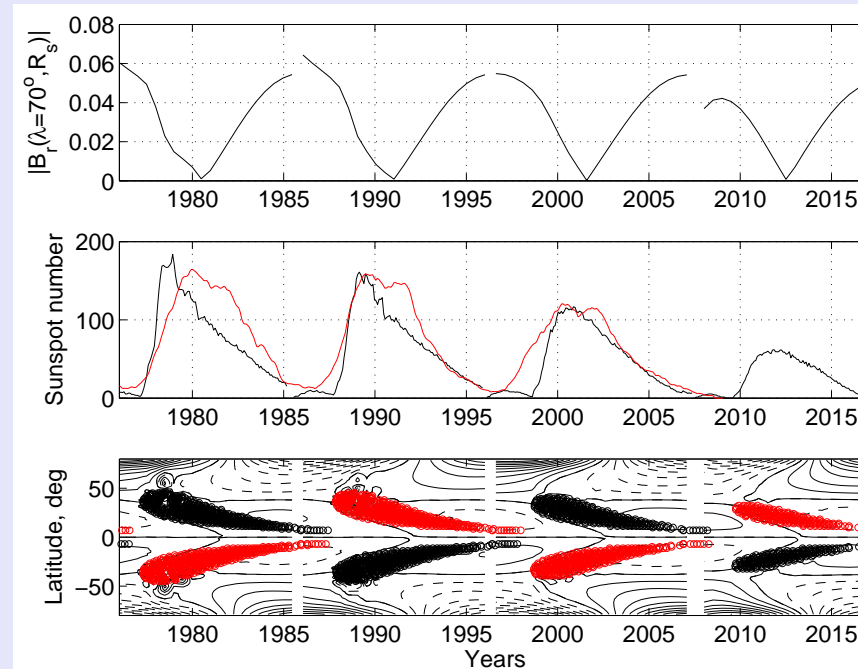
## Typical Time Scales in the Dynamo model.



A sketch indicating how the poloidal field produced at **C** during a maximum gives rise to the polar field at **P** during the following minimum and the toroidal field at **T** during the next maximum.

Correlation arises if  $C \rightarrow T$  diffusion takes 5-10 years. It is 5-6 years in our model and 250 years in Dikpati-Gilman model. Our diffusion coefficient is of order  $\sim 1/3\nu l$

## Cycle–24: Weak or Strong?



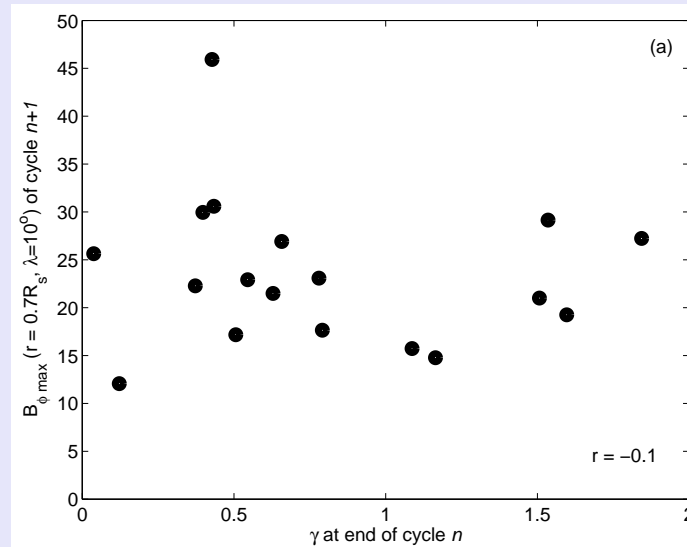
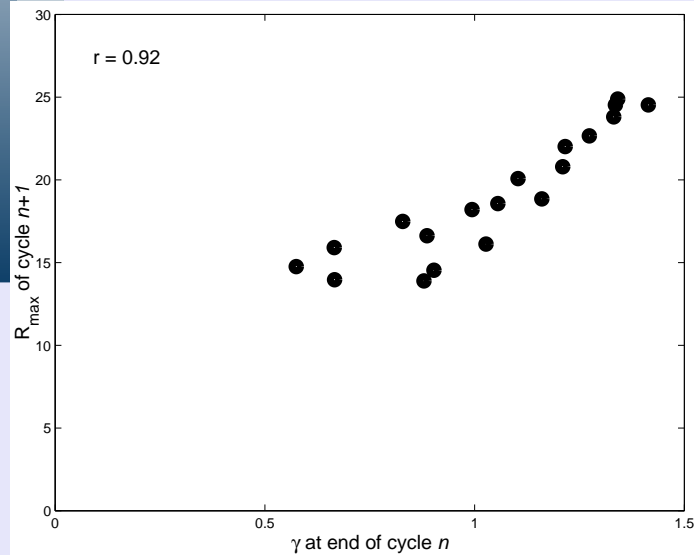
Our model predicts that cycle 24 will be **40% weaker** than cycle 23 in contrast to Dikpati et al, 2006, who predict that cycle 24 will be **50% stronger** than the present cycle .

Our model shows a strong correlation between the polar field strength at the end of the cycle and the sunspot number in the following maxima in accordance with observations.

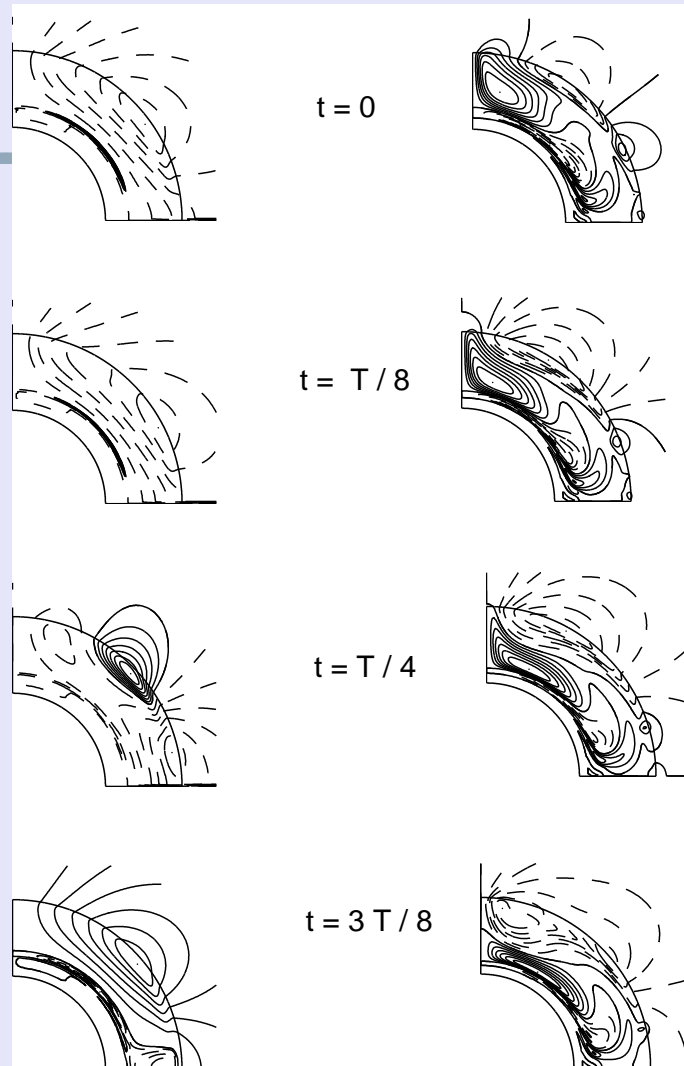
If our identification of the polar field generation mechanism as the only random process in the dynamo cycle is correct then that limits the predictive capability of solar cycles to

7–8 years.

## Validation of precursor method from our model



The strength of the maximum of cycle  $n+1$  plotted against the randomly chosen value  $\gamma$  at the end of cycle  $n$ .  $\gamma$  is the factor by which the average poloidal field produced at the end of a cycle by the regular model is corrected. *Left Panel:* For our model 'surya'. *Right Panel:* For a low diffusivity model as described in Dikpati & Charbonneau (1999).



Transport of poloidal field for high diffusivity model (left) and low diffusivity model (right)

## Probable cause of conflicting predictions

- ↪ Conceptual difference: Dikpati & Gilman (2006) treat the Babcock-Leighton  $\alpha$  process as deterministic unlike ours.
- ↪ Model difference: They use a diffusivity 50 times smaller than ours inside the convection zone.
- ↪ Their model works in the advection dominated regime unlike ours which lies at the interface of advection and diffusion dominated regimes.
- ↪ Less diffusivity means longer memory for fluctuations.  $T_{n+1}$  depends not only on  $P_n$  but also on  $P_{n-1}, P_{n-2}, \dots$  etc.



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The final verdict will come from the **SUN GOD** himself in 2-3 years .



## Acknowledgements



### Collaborators

1. Arnab Rai Choudhuri (Indian Institute of Science, Bangalore).
2. Dibyendu Nandi (IISER, Kolkata).
3. Jie Jiang (MPS, Lindau)



### Discussions

1. H. M. Antia (Tata Institute of Fundamental Research, Mumbai).
2. Kristof Petrovay (Eötvös University, Budapest).
3. Piet Martens (Cfa Harvard).

