Generation of solar magnetic fields

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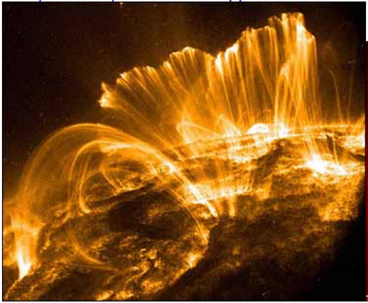
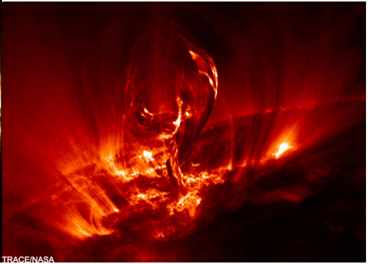
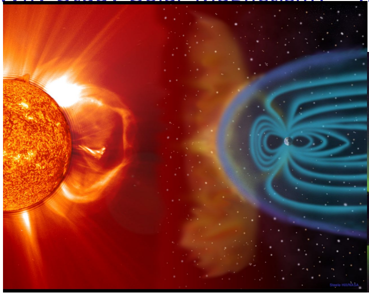
Why Study Solar Magnetism? - I





- Solar Flares and Coronal Mass Ejections are biggest explosions in the solar system – eject magnetized plasma and charged particles.
  Flare Energies $\sim 10^{25}$ 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.

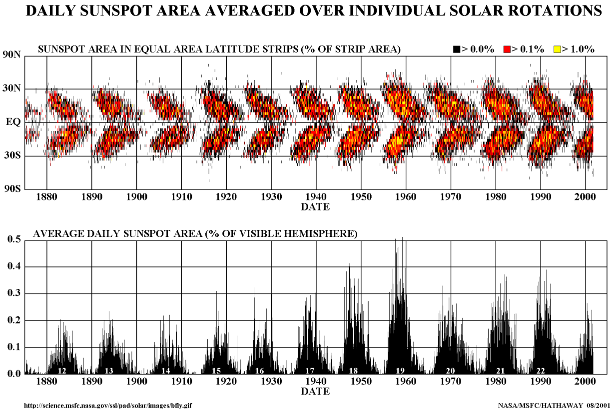
Why Study Solar Magnetism? - II



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*

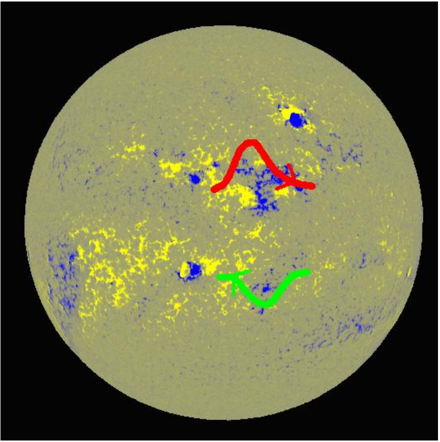


1844: Schwabe discovers solar cycle.

1858: Carrington discovers equatorward latitudinal drift with solar cycle.

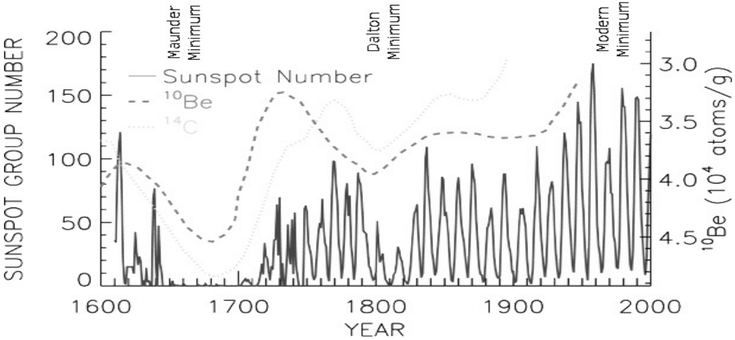
1904: Maunder invents *butterfly diagram*.

Sunspots: Tracers of solar activity - *II*



- 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 - *III*

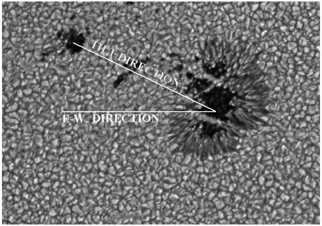


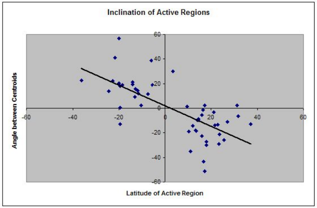
- ⋆ Number of sunspots observed on the Sun vary with time.
- ⋆ Time variation is predominantly cyclic, mean period is 11 years.
- ⋆ However, there are large amplitude fluctuations.

Sunspots: Tracers of solar activity-*IV*: Hale's polarity rule (1908)

- ⋆ 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)

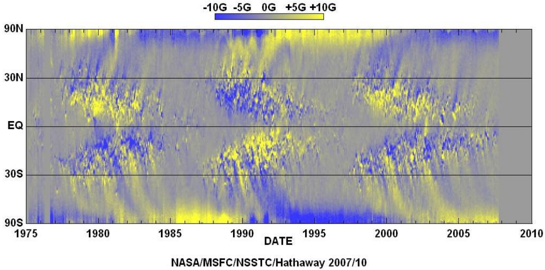




Together they imply:During an odd cycle the leading spot in NH (SH) has 'N' ('S') polarity
and lies nearer the equator than the following spot.

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

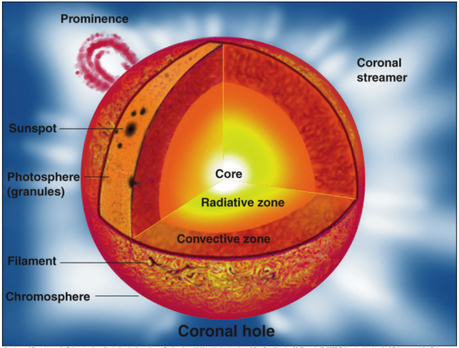
Polar Fields: Tracers of solar activity - *I*



- Babcock & Babcock developed the solar magnetograph in 1948.
- They report presence of weak diffuse magnetic fields on the Sun restricted to latitudes $> 55^o$.
- 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 N and S hemispheres.

Summary of observations

1. Equatorward migration of Sunspot belts (dynamo wave) but poleward transport of poloidal field.
2. 22-year magnetic cycle
3. Phase shift of $\pi/2$ between Toroidal and poloidal fields.
4. **Dipolar parity** of magnetic field in the poles.
5. Predominantly negative (positive) current helicity in northern (southern) hemisphere 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.

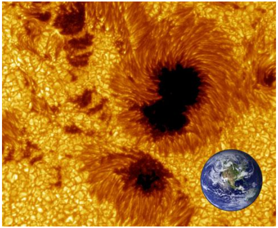
- The Induction Equation

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

- 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).

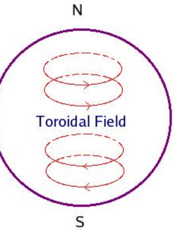
Magnetoconvection

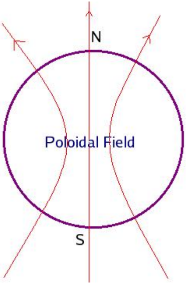
- Magnetoconvection – *Theory of interaction between magnetic field and thermal convection* (Chandrasekar 1952; Weiss 1981).
- Partitioning of space between magnetic field and convection – Magnetic fields excluded from regions of vigorous convection.
- Magnetic fields probably exist as fluxtubes rather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

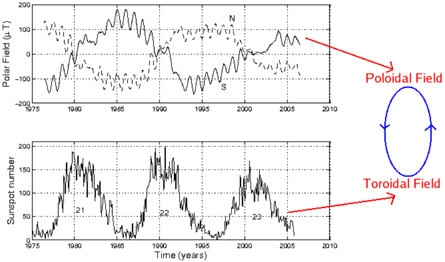


Picture courtesy Swedish Solar Telescope

Basic Idea of the Solar Dynamo







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

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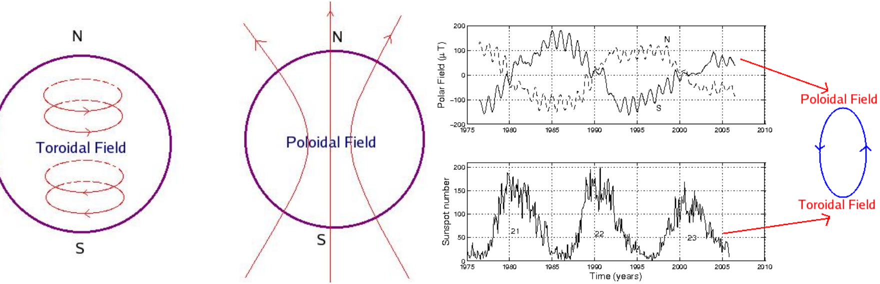

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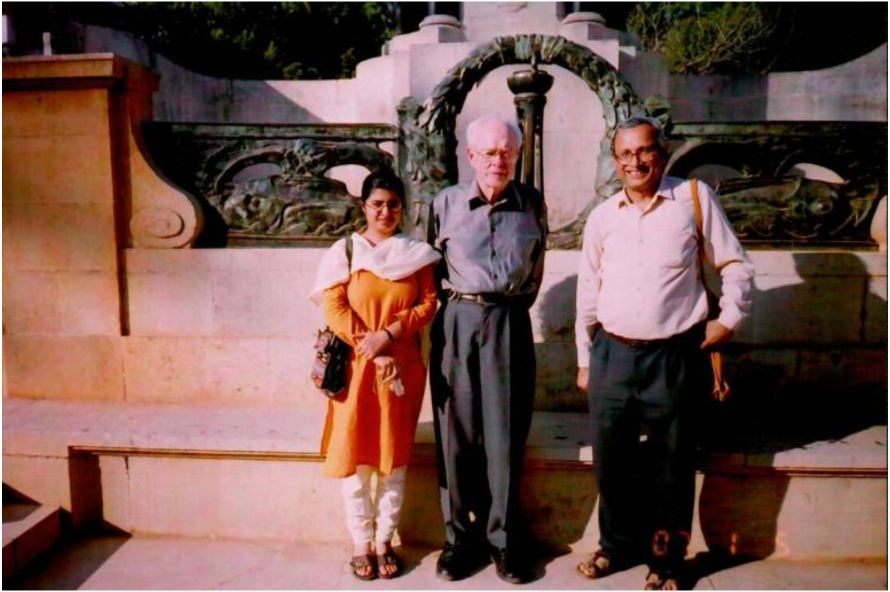
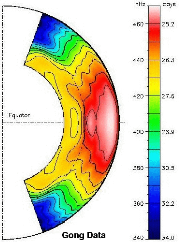
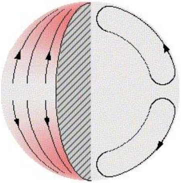
An old picture



Angular Velocity Distribution and meridional flow

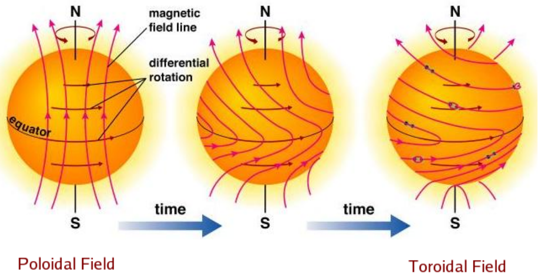


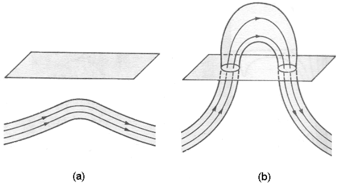


Helioseismology

- ⋆ A rich spectrum of oscillations have been observed for the Sun. standing waves
- ⋆ Eigenfunctions of normal modes $\xi_{nlm} = R_n(r) Y_l^m(\theta, \phi) e^{i\omega_{nlm}}$
- ⋆ 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)

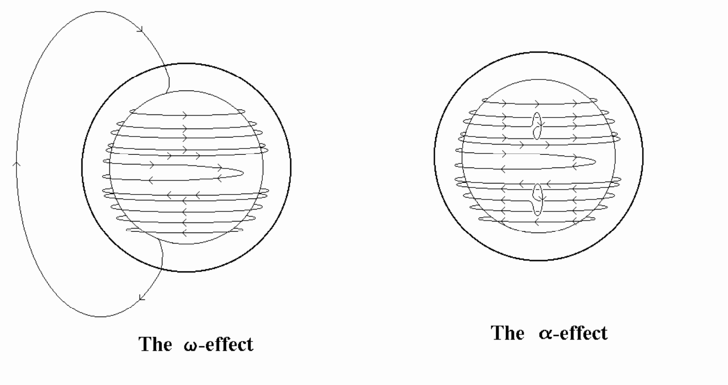
Dynamo Process: Toroidal Field Creation





- Ω-effect: Faster rotating equator winds up the poloidal field in the direction of rotation to create toroidal fields.
- Seat of Ω-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 Ballegooijen 1982).

Dynamo Process: Poloidal Field Creation



- Mean Field α effect: small scale helical turbulence (Parker 1955).
- Helical turbulence twists the buoyantly rising toroidal field into loops in poloidal plane. Positive (negative) in NH (SH).
- Numerous such small scale loops diffuse to form the large scale poloidal field.

The Mean Field dynamo equations: axisymmetric kinematic problem

An axisymmetric magnetic field in spherical coordinate system can be represented in the form

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

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

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

$$\frac{\partial B}{\partial t} + \frac{1}{r}\left[\frac{\partial}{\partial r}(rv_r B) + \frac{\partial}{\partial \theta}(v_\theta B)\right] = \eta_t \left(\nabla^2 - \frac{1}{s^2}\right) B$$

$$+ \underbrace{s(\mathbf{B}_p.\nabla)\Omega}_{\text{source term for B}} + \frac{1}{r}\frac{d\eta_t}{dr}\frac{\partial}{\partial r}(rB), \tag{3}$$

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

1. Dynamo wave propagation obeying Parker-Yoshimura rule,

$$\overrightarrow{k} = \alpha \nabla \Omega \times \hat{e}_{\phi}.$$

   For solar-like rotation profile, if overshoot layer is the seat of toroidal field generation then,
   dynamo wave propagates poleward at lower latitude and equatorward at high latitudes.

This is opposite to that observed!

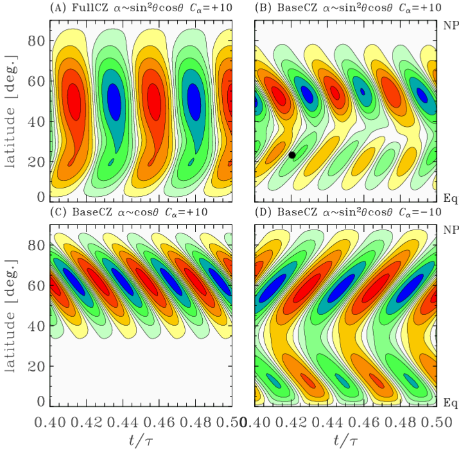


Fig. 7 from "Dynamo Models of Solar Cycle" in lrsp-2005-2 by P. Charbonneau. No meridional circulation.

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

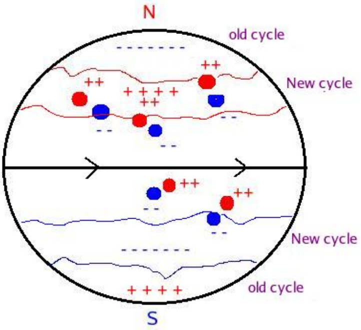
2. α quenching and limits on growth
   - Mean field reaches equipartition $\rightarrow \frac{\alpha_0}{(1+|B/B_{eq}|^2)}$. weak form
   - Small scale field reaches equipartition $\rightarrow \frac{\alpha_0}{(1+R_m|B/B_{eq}|^2)}$. strong form
   - Dynamical equation for α using helicity conservation (Brandenburg & Subramanian, 2005) .

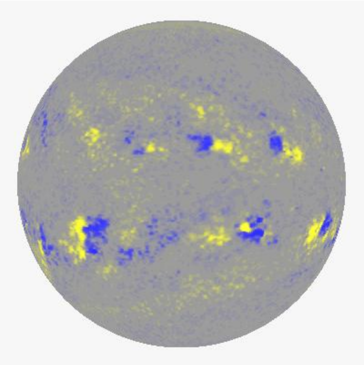
$$\rightarrow \frac{\alpha_0 + \eta_t R_m < \overline{J}.\overline{B} > /B_{eq}^2}{(1 + R_m|B/B_{eq}|^2)}.\text{strongest form}$$

Alternative?

- Interface dynamos (Parker 1993). α-effect is separated from the region of storage of toroidal flux.
- Phenomenological α-effect proposed by Babcock (1961) & Leighton(1964; 1969) revisited
- Magnetostrophic instability of flux tubes (Schmitt 1987; Thelen 2000).
- Hydrodynamical shear instabilities of the tachocline (Dikpati & Gilman 2001)

The Babcock–Leighton α





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

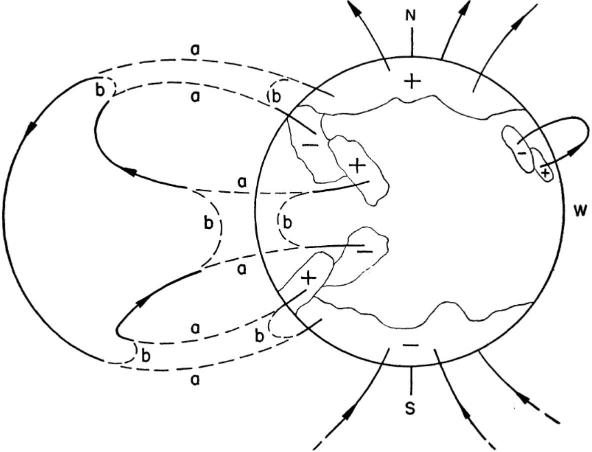
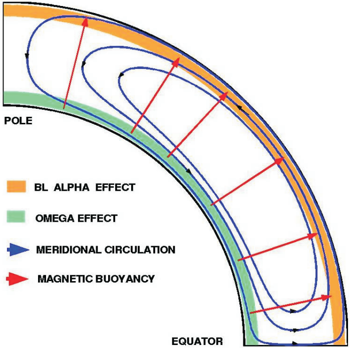


FIG. 8.—The expanding lines of force above older BMR's move out to approach the lines of force of the main dipole field. Severing and reconnection gradually occur, so that parts *a* are replaced by parts *b* and a portion of the main field is neutralized. Also a large flux loop of low intensity is liberated in the corona Continuation of the process results in the formation of a new main dipolar field of reversed polarity.

Flux Transport Dynamos.

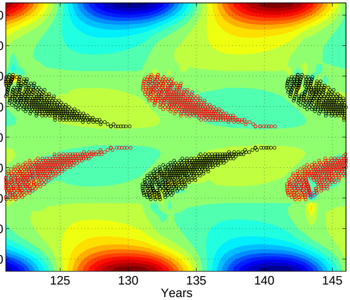


Modern Solar Dynamo Models incorporate THREE basic processes.

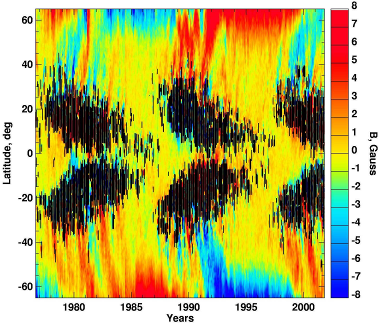
1. *The poloidal field gets converted to the strong toroidal field by stretching due to the differential rotation.*
2. *The toroidal field generated in the tachocline rises to the surface due to magnetic buoyancy and forms active regions. The tilted bipolar active regions decay to produce poloidal field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

- Deeply penetrating meridional circulation to push toroidal field little below the overshoot layer (Nandy & Choudhuri 2002)
- Different diffusivities for toroidal(η_t) and poloidal (η_p) fields, with $\eta_p \sim 50\eta_t$.

Theoretical results from *Surya*



Theoretical Butterfly diagram of sunspot eruptions from Surya(Chatterjee, Nandi & Choudhuri 2004).



Observed Butterfly diagram of sunspot eruptions.