Cyclic amplification of magnetic fields in the solar interior

Solar magnetic fields (SMFs) are maintained via cyclic amplification...

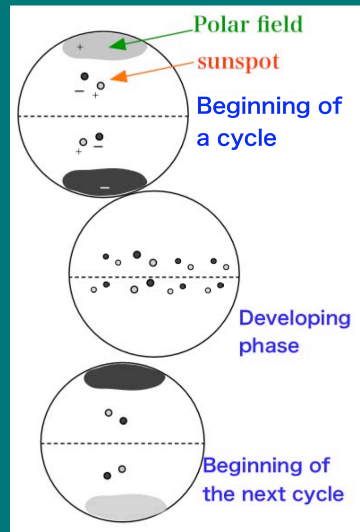
Primordial SMFs → ~~Simple diffusion~~ $(t_{diff} \sim 10^8\ \mathrm{yr})$

↑ $\updownarrow$

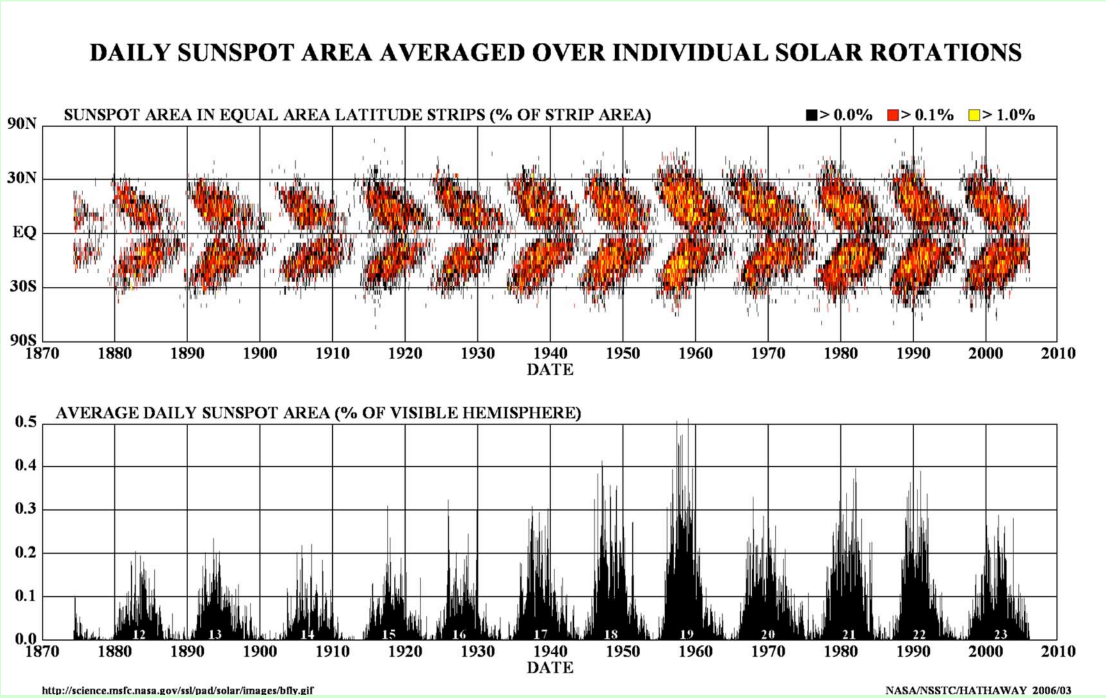
Concentration of
interstellar magnetic fields (**IMFs**)

$t_{solar\ age} \sim 4.6 \times 10^9\ \mathrm{yr}$

Hale's law

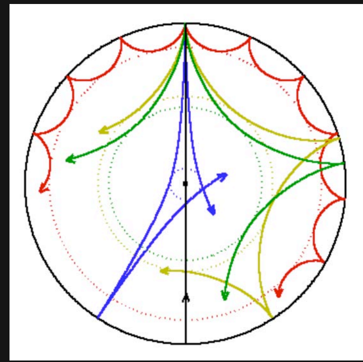


Maunder's butterfly diagram... latitudinal distribution of sunspots



Helioseismology provides observational information on the solar interior…

(see http://163.180.179.74/~magara/page31/Topics/Seismology/seis2.html)



Distribution of sound speed (=> temperature) in the solar interior

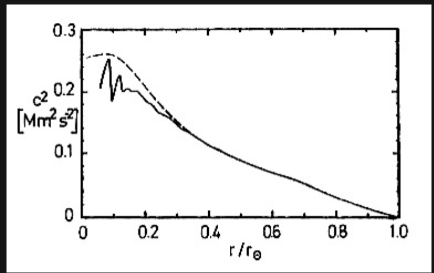
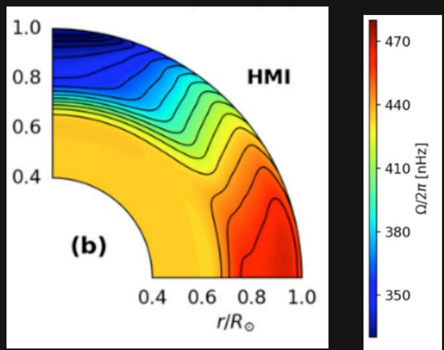
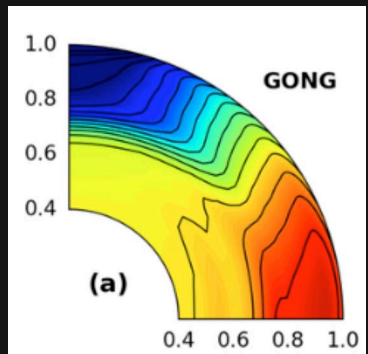


Fig. 5.17. Square of the sound speed in the Sun. *Continuous line*: inversion of the data in Fig. 5.16; *dashed*: theoretical solar model. From Christensen-Dalsgaard et al. (1985)

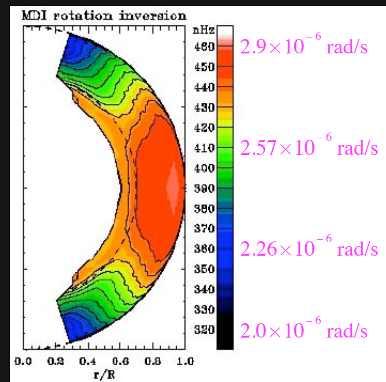
Distribution of angular velocity (=> Ω) in the solar interior



Larson and Schou 2018, HMI



Howe et al. 2005, GONG

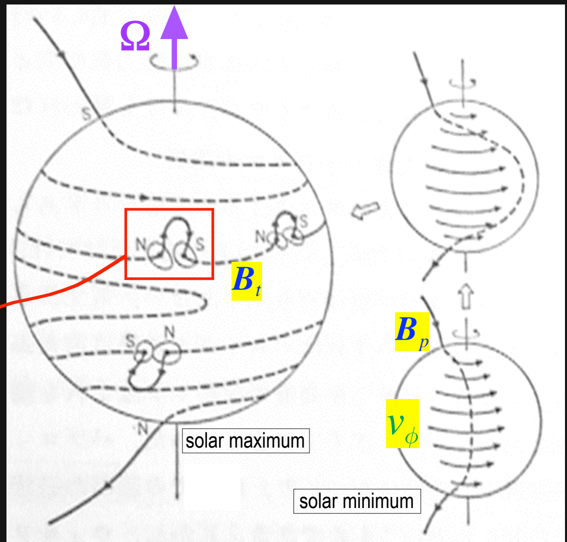


Schou et al. 1998, MDI

Theoretical models of periodically varying SMFs

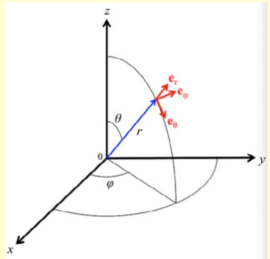
- Poloidal component (B_p) => Toroidal component (B_t)

solar minimum — solar maximum



Babcock's model

- Differential rotation (v_ϕ)
- Frozen-in condition



$$\boldsymbol{B} = \boldsymbol{B}_p + \boldsymbol{B}_t = \begin{pmatrix} B_r \\ B_\theta \\ 0 \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ B_\phi \end{pmatrix}$$

poloidal component + toroidal component

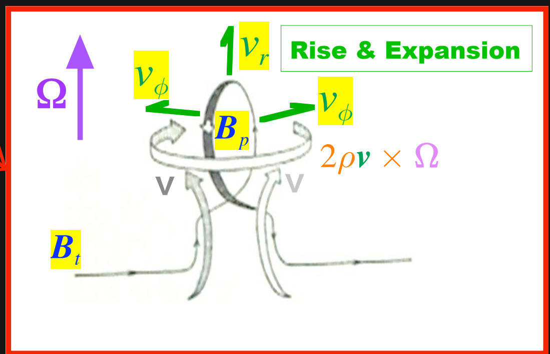
$$\boldsymbol{v} = \boldsymbol{v}_{mer} + \boldsymbol{v}_{azi} = \begin{pmatrix} v_r \\ v_\theta \\ 0 \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ v_\phi \end{pmatrix}$$

meridional flow + azimuthal flow

- Toroidal component (B_t) => Poloidal component (B_p)

solar maximum — solar minimum

local frame

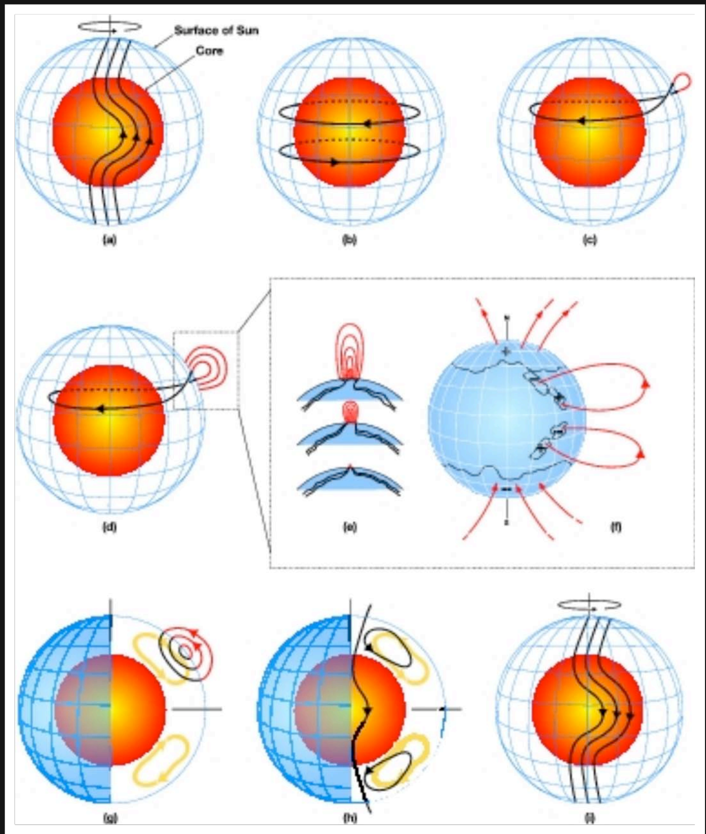


Parker's cyclone model (α-effect)

- Rising & expanding motions (v_r, v_ϕ)
- Coriolis force ($2\rho \boldsymbol{v} \times \Omega$)

Flux-transport model (poloidal component => toroidal component => poloidal component)

combines **Babcock's model** and **Parker's model** with *prescribed* **meridional flow** (v_r, v_θ)



From Dikpati

(a) Shearing of poloidal field by the Sun's differential rotation near convection zone bottom. The Sun rotates faster at the equator than the pole.

(b) Toroidal field produced due to this shearing by differential rotation.

(c) When toroidal field is strong enough, buoyant loops rise to the surface, twisting as they rise due to rotational influence. Sunspots (two black dots) are formed from these loops.

(d,e,f) Additional flux emerges (d,e) and spreads (f) in latitude and longitude from decaying spots (as described in figure 5 of Babcock (1961)).

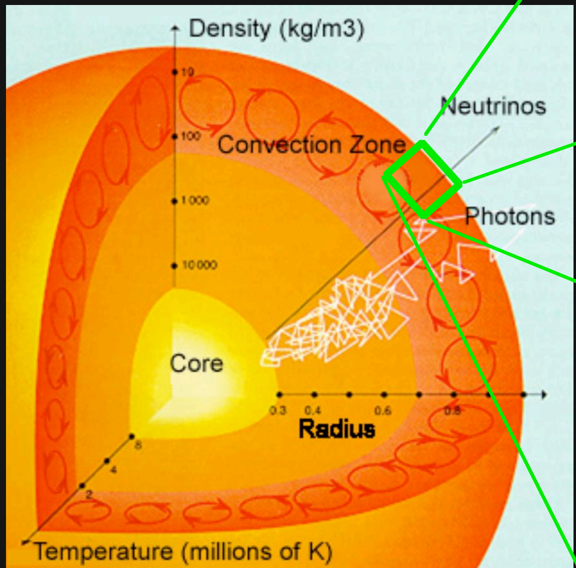
(g) Meridional flow (yellow circulation with arrows) carries surface magnetic flux poleward, causing polar fields to reverse.

(h) Some of this flux is then transported downward to the bottom and towards the equator. These poloidal fields have sign opposite to those at the beginning of the sequence, in frame (a).

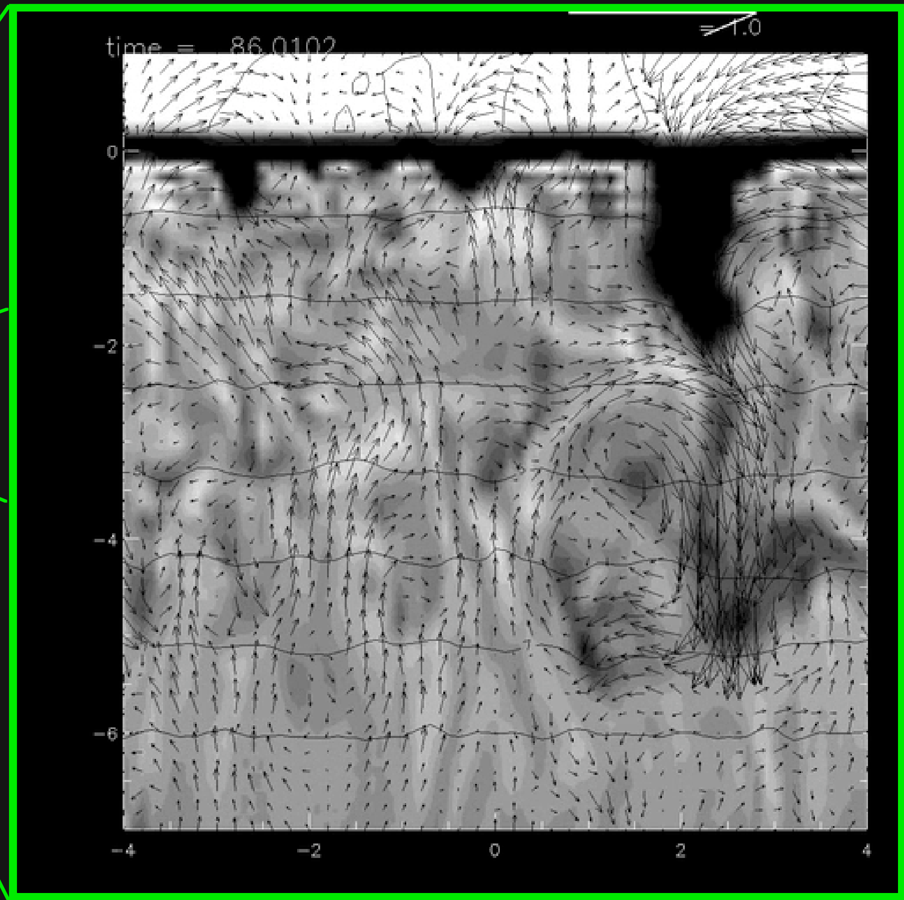
(i) This reversed poloidal flux is then sheared again near the bottom by the differential rotation to produce the new toroidal field opposite in sign to that shown in (b).

Transport of magnetic fields through the convection zone

Convection zone (CZ)... full of convective motions



Mixture of upflows, downflows, circulating flows



Vertical slice of a 3D simulation