Cyclic amplification of magnetic fields in the solar interior

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

Primordial SMFs

↑

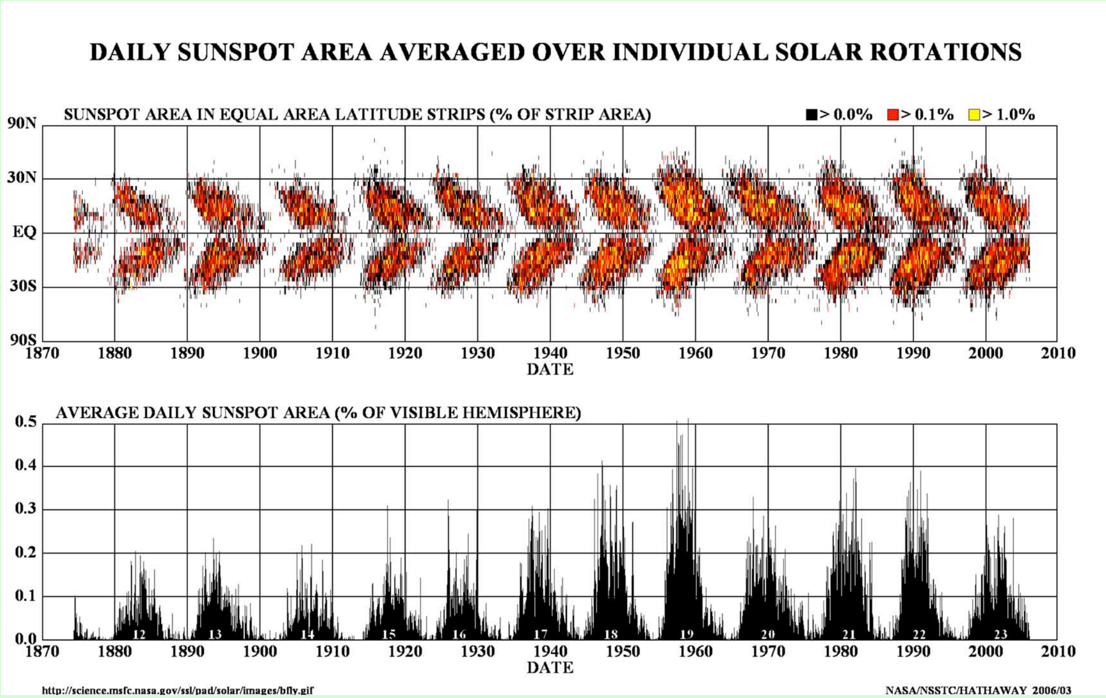
concentration of
interstellar magnetic fields (**IMFs**)

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

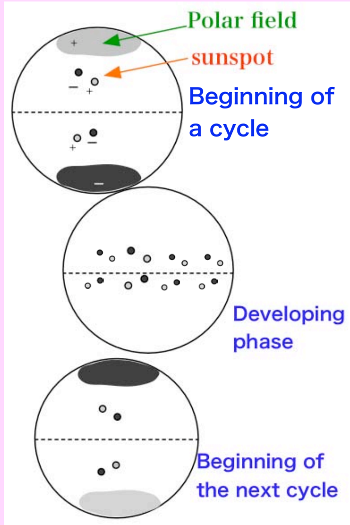
↕

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

Maunder's butterfly diagram => spatial variations of SMFs

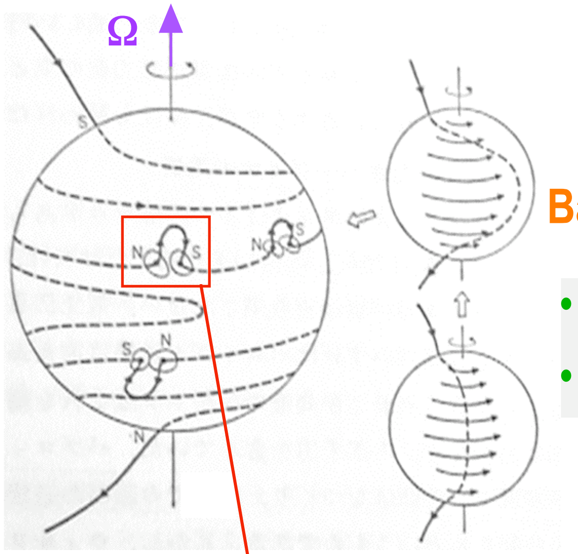


Hale's law



Theoretical models of periodically varying SMFs

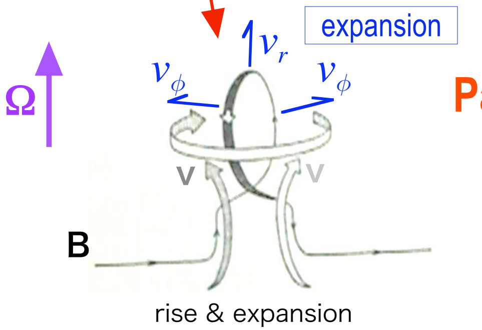
- **Poloidal component (B_p) => Toroidal component (B_t)**



Babcock's model

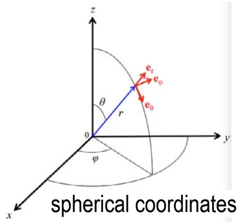
- **Differential rotation (v_ϕ)**
- **Frozen-in condition**

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



Parker's cyclone model (α - effect)

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



spherical coordinates (r, θ, ϕ)

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

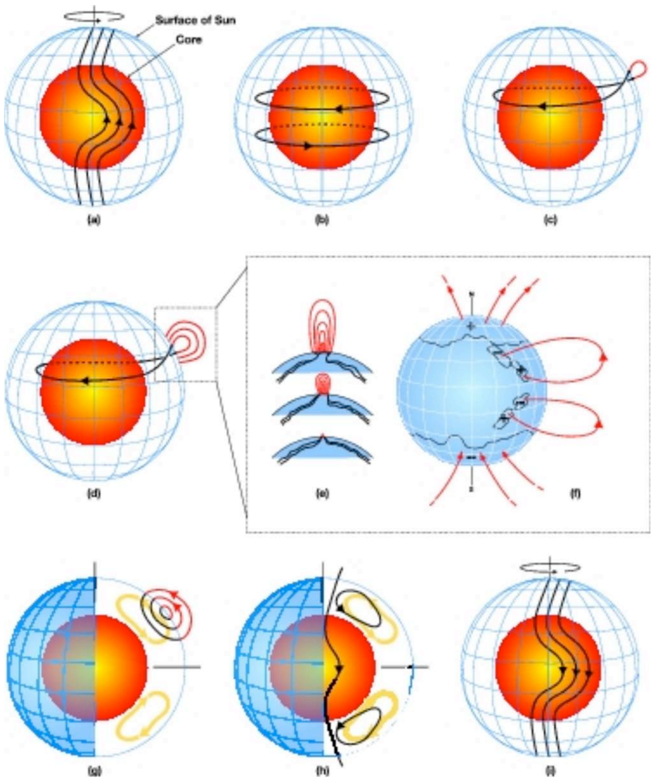
poloidal component + toroidal component

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

meridional flow + rotational flow

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).