Cyclic amplification of magnetic fields in the solar interior

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

Primordial SMFs

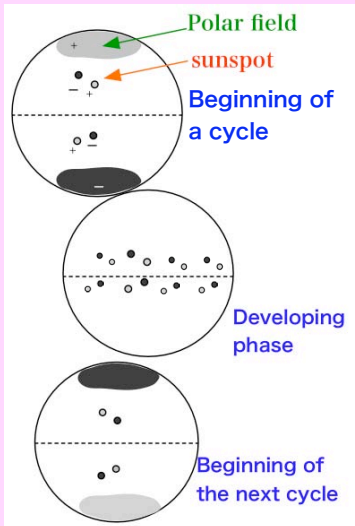
↑

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

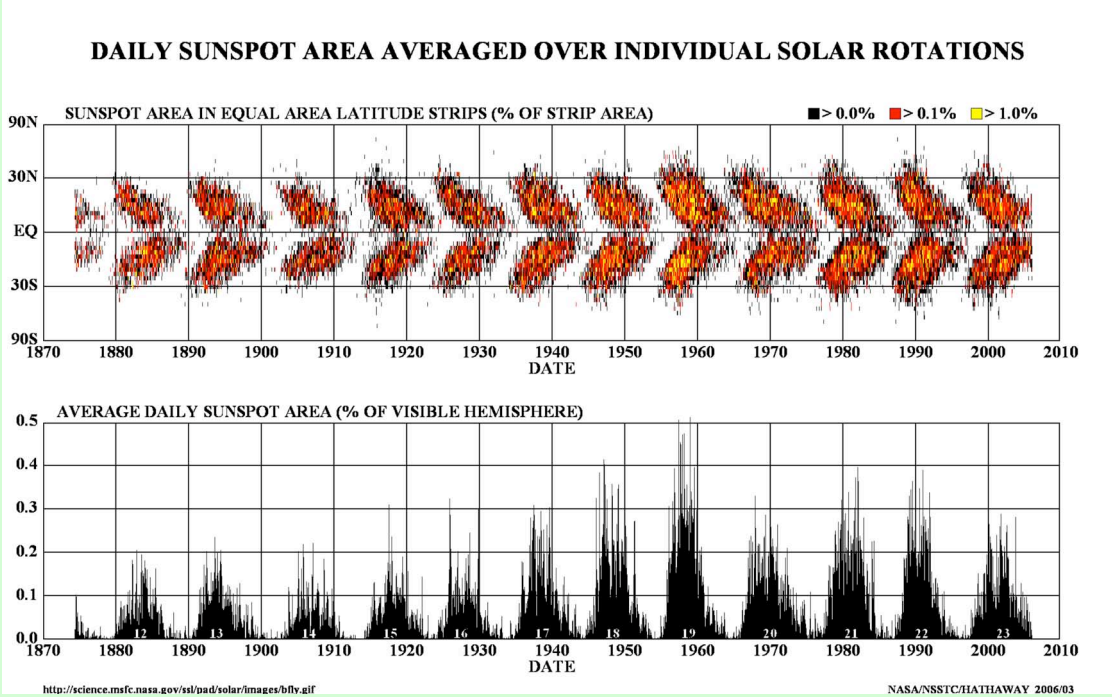
~~Simple diffusion~~ ($t_{diff} \sim 10^8$ yr)

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

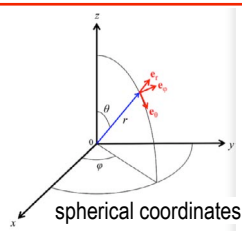
Hale's law



Maunder's butterfly diagram => spatial variations of SMFs



Theoretical models of periodically varying SMFs



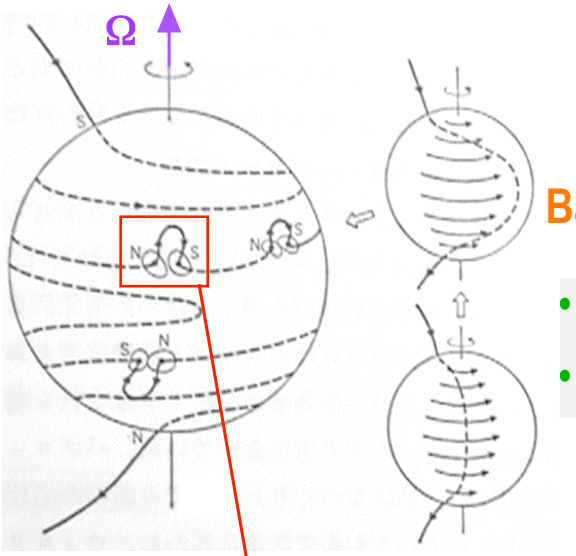
$$\boldsymbol{B} = \boldsymbol{B}_p + \boldsymbol{B}_t = \begin{pmatrix} B_r \\ B_\theta \\ 0 \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ B_\phi \end{pmatrix}$$

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

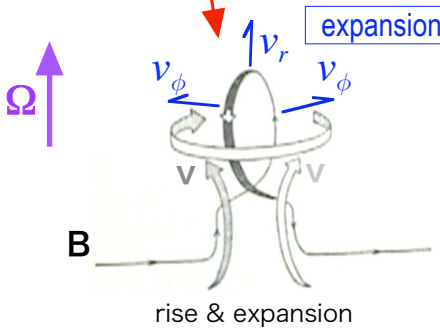
· Poloidal component (B_p) => Toroidal component (B_t)



Babcock's model

- Differential rotation (v_ϕ)
- Frozen-in condition

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



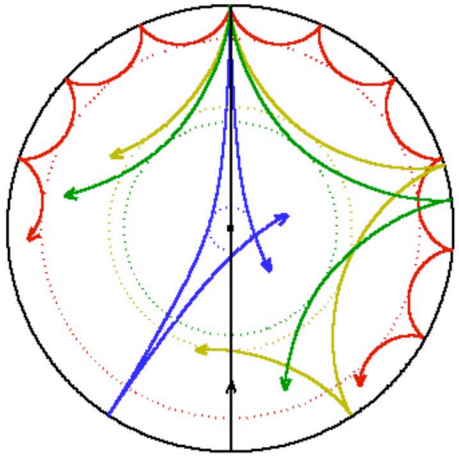
rise & expansion

Parker's cyclone model (α - effect)

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

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

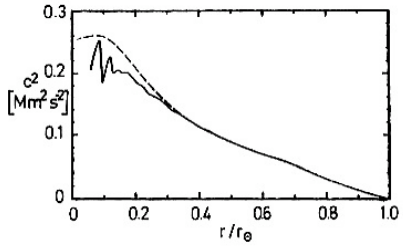
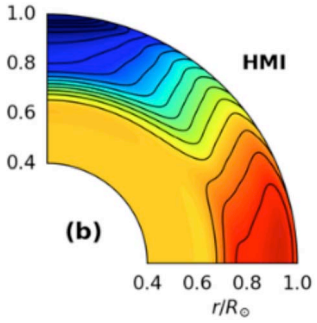
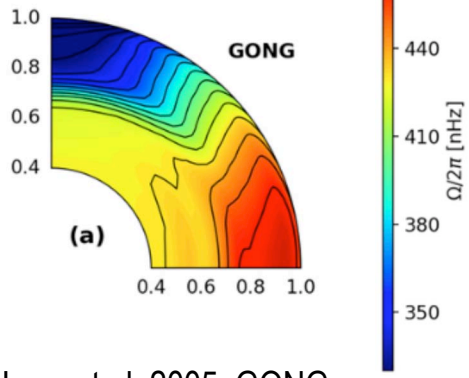


Fig. 5.17. Square of the sound speed in the Sun. *Continuous line*: inversion of the data in Fig. 5.16; *dashed*: theoretical solar model. From Christensen-Dalsgaard et al. (1985)

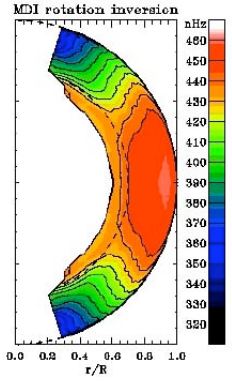
Distribution of angular velocity (=> v_ϕ) in the solar interior



Larson and Schou 2018, HMI



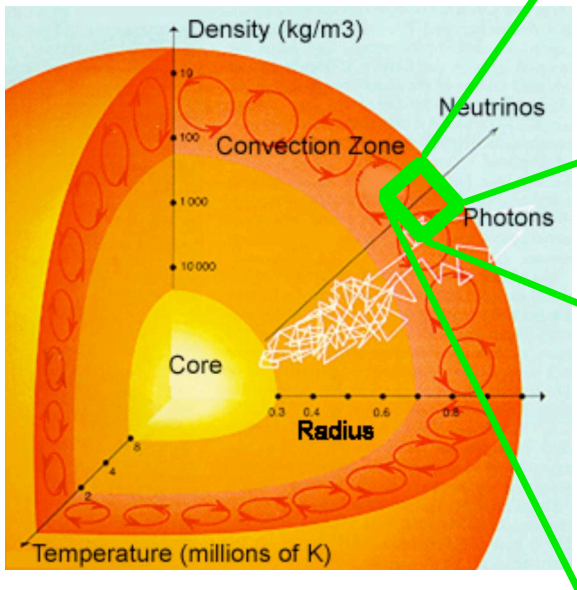
Howe et al. 2005, GONG



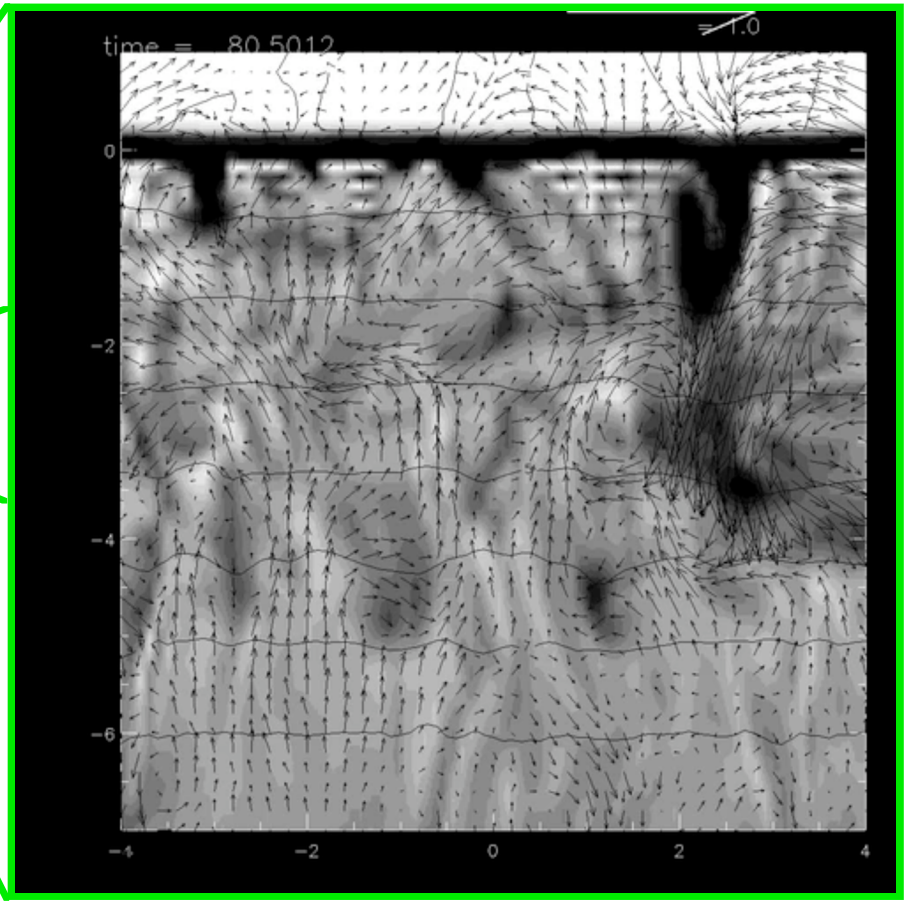
Schou et al. 1998, MDI

Transport of magnetic fields through the convection zone

Convective motions...

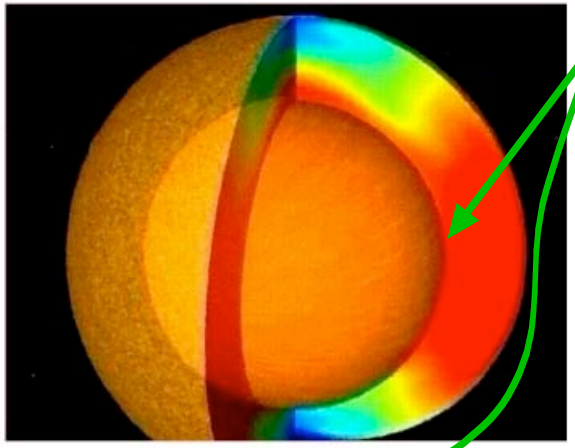


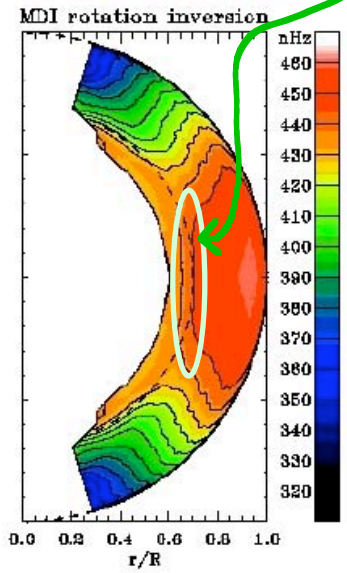
Mixture of upflows, downflows, circulating flows



Vertical slice of a 3D simulation

SMFs rise via magnetic buoyancy...





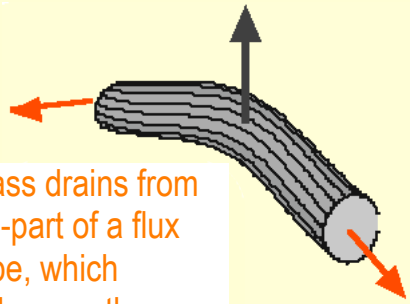
Distribution of angular velocity in the solar interior

Tachocline (bottom of the convection zone)

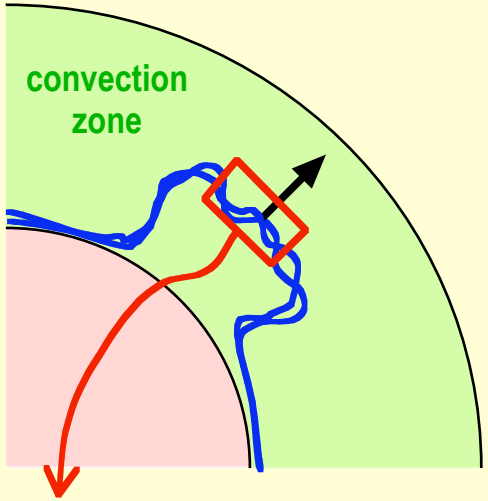
... sharp change of angular velocity => **shear flow**

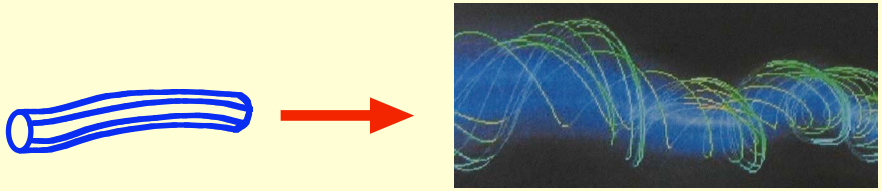
magnetic fields are deformed by the shear flow, which may produce flux tubes of intense magnetic flux.

Magnetic buoyancy



mass drains from Ω-part of a flux tube, which enhances the buoyancy of that part.



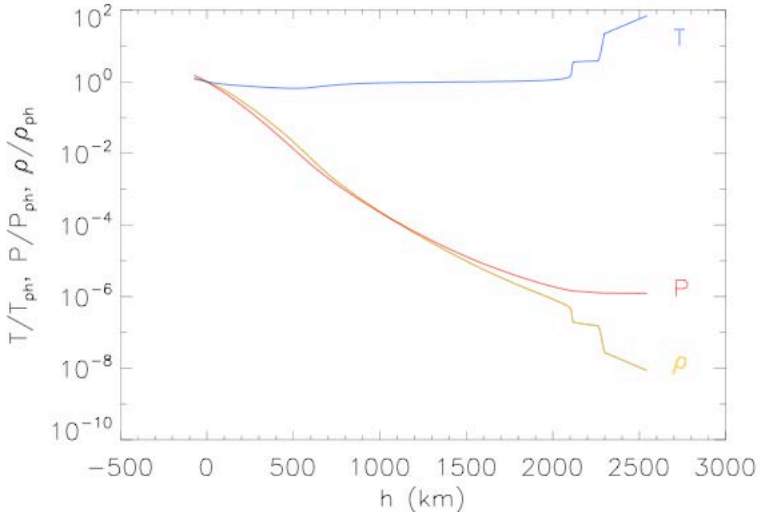


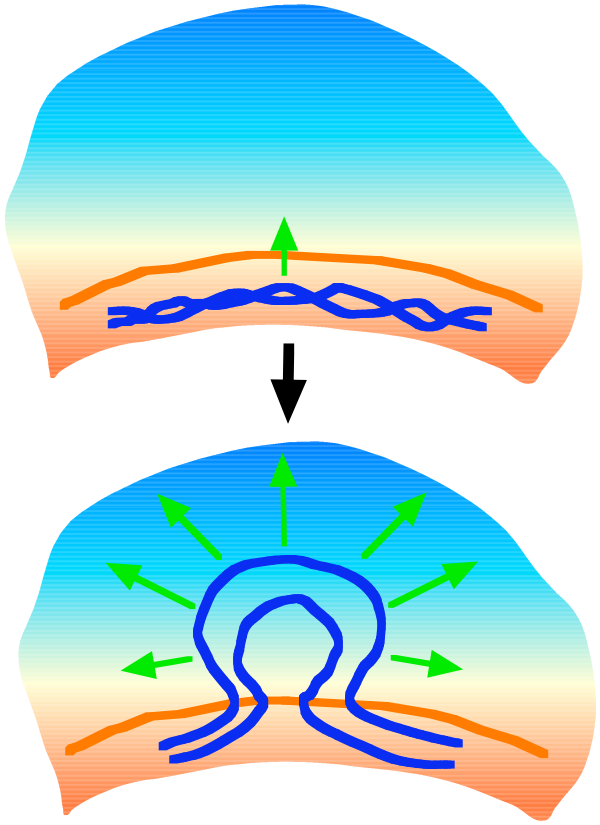
Twisted flux tube

Emergence of magnetic fields into the solar atmosphere

Flux emergence...

A magnetic flux tube emerges to the solar atmosphere and then expands rapidly due to the sharp decrease of gas pressure of a surrounding plasma across the solar surface.





Photosphere	Chromosphere	Corona
P ~ 2×10^5 dyn/cm^2	P ~ 1×10^2 dyn/cm^2	P ~ 2×10^(– 2) dyn/cm^2

840 km (0.001 Rs)

6000 km (0.01 Rs)