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Fossil fields versus dynamos

Two types of fossil field:

- Field trapped in star during its collapse from parent molecular cloud
  - During fully-convective phase this field is amplified by dyanamo activity…little trace of it remains
- Field trapped in radiative core during its formation
  - Decay time in core is very long
  - But...only the steady component of a field will persist

Does the Sun have a fossil field?

Classical decay time $\tau_D \approx R_{Sun}^2/\eta \approx 10^{10}\ years$

(cf age of Sun: 4.6 x 10^9 years). This may be appropriate for core, but in the convection zone, the true timescale is likely to be much shorter due to:

- resistive instabilities producing shorter lengthscales
- buoyancy removing flux from the solar interior
- fluid turbulence giving an effective (eddy) diffusivity acting over the depth L of the convective region

$$\eta_{eddy} = \mathrm{v}\, d \approx 10^9\, m^2 s^{-1}$$
$$\tau_D \approx L_{Conv}^2/\eta_{eddy} \approx 10\ years$$

- Hence the field in the convective zone must be dynamo generated...
- but there may still be a fossil field in the core (some theoretical arguments suggest it must be at least 1G).

NB: Mt Wilson survey showed that some stars showed no evidence of cyclic variations in spot coverage... fossil fields or “Grand minima?”

A solar dynamo must explain

- The 11 year sunspot cycle
- The restriction of spots to two latitude belts
- The drift of these belts towards the equator
- The inclination of sunspot groups (about ten degrees to the equator)
- The polarity laws for bipolar spot groups (the leading spot is always of the same polarity which reverses over a cycle)
- The large-scale field polarity reversal.
- Changes in the morphology of the white-light corona over a cycle

How does a dynamo work?

We need a feedback mechanism:

A flow v across B gives an induced electric field

$\underline{v} \times \underline{B}$ which drives a current $\underline{j}$ $(\sigma(\underline{E} + \underline{v} \times \underline{B}) = \underline{j})$

which gives an induced magnetic field B $(\mu\, \underline{j} = \nabla \times \underline{B})$

This magnetic field creates an electric field

$\nabla \times \underline{E} = -\frac{\partial \underline{B}}{\partial t}$ and a Lorentz force $\underline{j} \times \underline{B}$

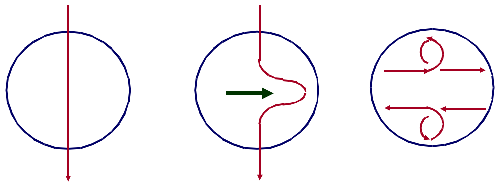
which can provide the force that drives the motion.

Dynamo models

- Full solution requires solving MHD equations to demonstrate that:
  1) there is a motion (v) which can maintain an oscillating magnetic field B
  2) this motion is itself maintained by the available forces
- Difficult problem: kinematic models prescribe the velocity field and simply show that it gives an oscillating or growing magnetic field
- A fully self-consistent dynamo model would describe a velocity field that not only gave rise to an oscillating magnetic field but was itself maintained by the available forces.

•The essential ingredients for a dynamo to work are a velocity shear to stretch the magnetic field and a force (such as the Coriolis force) to twist it.

Initially north-south field | shear flow stretches field | Coriolis forces twist field



In cylindircal polars, field has toroidal component (azimuthal) and poloidal component

ω-effect turns poloidal field into toroidal field

α-effect turns toroidal field into poloidal field

Dynamo models – The Sun

- ω-effect takes place at the base of the convection zone.
- Rising flux tubes are subject to Coriolis forces which give the flux tubes a twist α-effect
- α-effect can also turn poloidal field back into toroidal field, but the ω-effect is the dominant mechanism for this ⟶ $\alpha\omega$ dynamo

Fixed location for ω-effect enables us to predict latitude bands for emergent spots

Dynamo models

- If the ω-effect decreases, the importance of the alpha effect may increase ⟶ $\alpha^2\omega$ dynamo
- Fully convective stars (e.g. M Dwarfs) have no radiative core and so no location where the ω–effect can generate toroidal field ⟶ α^2 dynamo
- α^2 effect is distributed throughout the convection zone, so we may expect to see magnetic flux and therefore starspots at all latitudes

Doppler images of M dwarfs appear to show spots distribted uniformly at all latitudes