The solar dynamo (critical comments on)
The solar dynamo (critical comments on)

- what observations show
- what they show is not the case
- what is known from theory
- interesting open questions

quantitative models $\leftrightarrow$ `figuring things out'
- clues about deep layers from things happening at the surface
- role of the ‘tachocline’
- dynamo driven by magnetic instability, not ‘convective turbulence’
Things happening on the surface

- Emergence of active regions: clues to the cycle’s workings
- strength and location of the cycle field
- role (?) of convective turbulence
Active region emergence

Fields move independent of surface flow.

+,− in opposite directions: ‘antidiffusion’.

Hinode JAXA/NASA  The Hinode ‘trilobite’

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Active region emergence

Fields move independent of surface flow.
+,- in opposite directions: ‘antidiffusion’.
Active region emergence

Properties

- regularity of Hale’s polarity law
- emerging fields move independent of surface flows (Vrabec 1974), ‘antidiffusion’
- sunspot proper motion time scales - a few days (Herdiwijaya et al. 1997)
- tilt of AR continues to settle after emergence (Howard 1991a)
- mean meridional drift or AR < 0.5 m/s (Howard 1991b)
active region emergence  
(Cowling 1953)

W. Elsaesser 1956

Fig. 5. Showing a strand of the solar toroidal field lifted locally and giving rise to a bipolar sunspot group.

the ‘rising tree’

Zwaan 1978

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Q1: why does the field erupt?
A: (Babcock) when its reaches a critical strength

Q2: from which depth?
A: base convection zone.

‘Winding-up’ by differential rotation with latitude

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Interpretation (ct.'d)
- active region tilt produced by emergence is the ‘α-effect’ of the cycle


Q: which flows (where) produce the Coriolis displacement?
A: look at tilt development

Interpretation (ct.'d)
Q: where is the tilt produced?

look at tilt development (Howard 1992)

- most tilt **after** main flux emergence,
- during separation of polarities

Effect is **not** caused at the surface

- mass ($\rho$) energy density ($B^2, P$) is at the **base**
Stable interior

Coriolis force on spreading AR

\[ F_{\text{cor}} = 2v \times \Omega \]
Equatorward drift (Babcock 1961)

\[ \frac{\partial}{\partial t} B_\varphi \sim \sin 2 \Lambda (1 + 1.51 \sin^2 \Lambda) \]

Equatorward drift+‘Polar branch’

[B_{\text{inst}} \sim 10^5 \text{G} \quad \text{(Schüssler et al. 1994)}]
Questions:
- location 
- strength } of the azimuthal field

Location?
Field of 3000G (spots @ surface) is buoyant.
buoyant rise time $z/v_A = 2d$ ($z=50$ Mm)
$\rightarrow$ spots are ‘anchored’ deeper than 50 Mm
$\rightarrow$ they are not a surface effect

Magnetic buoyancy can be compensated by lower temperature
Buoyant (Parker-)instability
Convection zone itself unstable } $\rightarrow$

stable location: base of the convection zone
Rising flux tubes: 1D simulations

Choudhuri & d’Silva 1993,
Fan & Fisher 1994
Schüssler et al. 1994

Model for fields rising from base of the CZ
- 1D: flows along and across tube
- including thermal and magnetic buoyancy
- free parameter: $B$ at base

data to fit:
- latitude of emergence
- time scale
- AR tilt

convergence with these three obs. for $B \sim 100 \text{kG}$

$\frac{B^2}{2\pi} \gg \frac{1}{2} \rho v_{\text{conv}}^2$

$\Rightarrow$ emergence process only weakly influenced by convection
**Why at base CZ?**
- field is not passively carried by flow → stronger than equipartion
- stratification of convection zone has no restoring forces
- fields can not ‘float midway’ for as long as years
- floats to top or sinks to bottom (if heavy enough ...)
---> winding-up during cycle must happening @ base

- **If at base CZ:**
  - field becomes unstable (Parker instab.) at $\approx 10^5 G$ (Schüssler et al. 1994)

`rising tube` simulations:
- rise time $\approx$ days
- in the observed latitude range
- with right AR tilt

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Interpretation (ct.'d)

-> contact made between MHD of interior and observations @ surface.

Explains:
- Hale’s & Joy’s laws
- time scale of spot proper motions (Alfvén travel time)

consequences:
- Field is stronger than convection
- → direct connection between surface and interior
- B not generated by ‘interaction with turbulent convection’:
  cycle operates on differential rotation and instability of B. (compare: field generation in accretion disks)
- Differential rotation with latitude (not radius)

Theories
- turbulent mean field models
- superficial sunspots
- flux transport models

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The need to produce quantitative models

- mean field alfa-omega:
  - interaction turbulent convection - magnetic field
  - kinematic
  - operating in bulk of CZ

variations:

- tachocline dynamos
- flux transport dynamos
Responds to the need for quantitative, computable models

Little or no contact with observations:
- inconsistent with emergence process, sunspot formation
- kinematic.

Assumptions:
- Active regions are ‘turbulence’ (‘to be averaged out’)
- Field strength dictated by interaction w. convection
  (contradicted by strength of sunspots)
- Takes place by interaction between convection and B
  (contradicted by phenomenology of AR emergence)

Predictions
- rotation rate depends more on depth than latitude
  (contradicted by helioseismology)

Theoretical Justification
- high $R_m$ : $B$ intrinsically non-local (↔ scale separation)
Tachocline dynamos

1. Why the tachocline is not what operates the solar cycle

‘Tachocline’ ↔ ‘base of convection zone’ (not same thing)
- radial shear in CZ predicted by convective mean field electrodynamics absent,
- shear is in latitude
- move dynamo into tachocline?

\[ v \rightarrow T_{r\phi} \text{ stress} \rightarrow \phi \rightarrow r \uparrow \]

Turbulence, dynamo ...

\[ -v \rightarrow -T_{r\phi} \]

‘shear between moving plates’
- radial shear in CZ predicted by convective mean field absent
- shear is in latitude
- move dynamo into tachocline?

\[ -v \quad Tr\phi \quad stress \quad \phi \quad \rightarrow \quad r \uparrow \]

Turbulence, dynamo?

\[ -v \quad Tr\phi = 0 \quad \text{no stress} \]

\textit{convectively stable interior}
convection zone,
\[
\text{Re stress } < \nu_r \nu_\phi > \rightarrow \nu_t \sim 10^{13} \text{ cm}^2/\text{s}
\]

\[\nu \rightarrow T_{r\phi} \text{ stress} \quad \phi \rightarrow r \uparrow\]

Turbulence, dynamo?

\[\nu \leftarrow -\nu \quad T_{r\phi} = 0 \quad \text{no stress}\]

**convectively stable interior:** \(\nu \sim 10 \text{ cm}^2/\text{s}\)

viscous stress vanishes
convection zone,

\[ \text{Re stress} \quad < v_r v_\phi > \quad \rightarrow \quad \nu_t \sim 10^{13} \text{ cm}^2/\text{s} \]

\[ v \quad T_{r \phi} \quad \text{stress} \quad \phi \quad \rightarrow \quad r \uparrow \]

base of CZ, 
\[ T=2.0 \text{ MK} \]

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Li burns here, 
\[ T=2.6 \text{ MK} \]

\[ \nu \sim 10^3 \text{ cm}^2/\text{s} \]

from Li - depletion constraint

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Q:
1. What causes the thin tachocline?
2. What operates the solar cycle?

A:
1: Tachocline is an imprint of the latitudinal differential rotation into the interior. (Spiegel & Zahn 1992, McIntyre 2007)

2: $\Omega(\theta)$

Consequences for all models that use $\Omega(r)$. 

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flux transport dynamos

- mean field alfa-omega equations  (kinematic ...)
- sources of alfa-effect at surface  (observational illusion ...)
- flux transport at surface  
- latitude drift of active zone by return flow  (not observed ...)
Solar cycle: open issues

1 ‘Thermodynamic problem’: strength of the field @ base requires low temperatures

\[ B = 10^5 \approx \delta T / T \sim 10^{-4} \]

2 Flux disappearance rate (Labonte & Howard 81: AR flux lives 10d)

- turbulent diffusion: not an explanation.
- reconnection: where?
  
  (c.f. Parker 2009)
Flux disappearance rate: how long does the flux of the cycle stay around?

- TSI decline during last (extended) minimum
- how much does the quiet Sun magnetic flux contribute to TSI?
Magnetic brightening of the Sun

‘quiet Sun’: \( \langle |B_z| \rangle \approx 10 \text{ G} \)

Q: - dependence on cycle phase?
   - effect on brightness?
   - long term variation?
Magnetic brightening of the Sun

Average of minima: 1365.440 ± 0.014 Wm⁻²
Difference of minima to average: +0.124; +0.071; −0.195 Wm⁻²
Cycle amplitudes: 0.928 ± 0.019; 0.919 ± 0.020; 1.040 ± 0.017 Wm⁻²

C. Fröhlich et al. 2011

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Magnetic brightening of the Sun

- brightness of small scale field dominates over spot darkening
- 0.08% cycle variation of TSI has no climate effect

- possibly larger longer term variations?
  * magnetic fields
  * as yet unknown mechanisms

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Magnetic brightening of the Sun

‘bright wall effect’:

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Magnetic brightening of the Sun

‘bright wall effect’:

- small scale field causes heat leaks in surface → enhanced cooling → geostrophic flows around AR → ‘torsional oscillation’

HCS 1977
HCS 2003

important epicycle skipped here ...

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Magnetic brightening of the Sun

'bright wall effect':

- small scale field causes heat leaks in surface (HCS 1977)
  → enhanced cooling
  → geostrophic flows around AR → ‘torsional oscillation’ (HCS 2003)

most of the brightening effect due to the 'curved rims'
Steiner 2005, Carlsson et al. 2004

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Measuring magnetic brightening of the Sun

R. Schnerr & HCS, 2011

Hinode

$\langle |B_z| \rangle = 11 \text{ G}$

$\delta I_{\text{mag}} / I = 1.2 \times 10^{-3}$

SST

$\langle |B_z| \rangle = 10 \text{ G}$

$\delta I_{\text{mag}} / I = 1.5 \times 10^{-3}$

relation with `inner network' fields
(Livingston & Harvey 1975, S. Martin)

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measured (disk center): $\delta I_{\text{mag}} \approx 1.5 \times 10^{-3}$

$\langle B_z \rangle = 10 \text{ G}$

does not include:
- dark rims (compensation)
- effect on surrounding granulation
Measuring magnetic brightening with numerical simulations

Bolometric flux \( <B_z> = 50 \text{ G} \)

\( B_z \)

Irina Thaler & Remo Collet @ MPA

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Measuring magnetic brightening with numerical simulations

Bolometric flux $<B_z> = 50$ G

Irina Thaler & Remo Collet @ MPA

Opposite polarities develop. Inner network field? (Livingston & Harvey 1975) ‘surface dynamo’? (Schüssler et al. 2007)

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Granulation \((B=0, 6\times 6 \text{ Mm})\)
result (preliminary):
\[ \langle B_z \rangle = 50 \text{ G} \rightarrow \frac{\delta F}{F_{\text{bolometric}}} < 0.5\% \]

Q: - cycle dependence?
   - is the background field a ‘local dynamo’?
Summary

- solar dynamo is not kinematic.
- it operates on differential rotation and magnetic instability, not convective turbulence.
- underappreciated observational clues in existing observations of AR.
- cycle does not operate on tachocline shear

- open questions:
  • thermodynamics of field @ base CZ
  • the ‘turbulent diffusion step’ (‘annealing’)
- an effect of quiet Sun flux on TSI ??
Other examples of field generation operating on magnetically driven instabilities

1 Magnetorotational (‘MRI’) field generation in accretion disks
2 Field generation in stably stratified zones of stars

1: - Angular momentum distribution in a Keplerian disk 
   \[ j \sim r^{1/2} \] hydrodynamically stable
   - seed field unstable to growth of magnetorotational
   - \( B \) breaks a hydrodynamic constraint:
     ‘magnetically enabled’ shear instability
   - flows are consequence of \( B \), not its source
Field generation in a stably stratified stellar interior

Energy source: differential rotation from
- spindown by stellar wind torque,
or
- change of internal structure by stellar evolution

field amplification cycle:
- seed field $B_p$
- field line stretching by $\Omega(r)$, $\rightarrow B_\phi \sim t$
- instability driven by magnetic energy sets in,
- $v_r$ acting on $B_\phi \rightarrow$ new $B_p$

which instability?
- pinch type inst.
- magnetic buoyancy
- magnetorotational (MRI)
First to set in: an $m=1$ pinch type instability. ‘Tayler inst.’ (R.J. Tayler 1956 ... 1980 ... 1986)

Stable stratification dominates dynamics

Radial length scale  \[ \frac{l}{r} \approx \frac{\omega_A^2}{N^2} = \frac{\nu^2}{r^2 N^2} \ll 1 \]

horizontal  \( l \sim r \)
Need to include: thermal diffusion, magnetic diffusion

Instability conditions from Acheson’s (1978) dispersion relation for azimuthal fields in stars

Simple model for a field amplification cycle: \((HCS 2002)\)

- ‘shellular’ rotation \(\Omega(r)\)
- ignore \(\theta\) - dependence of inst.
- \(e = \pi = 2 = 1\)

Solar interior \((\Delta\Omega/\Omega \sim 0.05)\)
- field amplification 10-100 x critical
- magnetic stress sufficient to keep up with spindown torque

(Schüssler et al. 1994)

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Field generation can happen in a global, hydrodynamically stable velocity field.

Closing of amplification cycle possible by different forms of magnetic instability:
• in solar convection zone: magnetic buoyancy
• in accretion disks: MRI, buoyancy
  in convectively stable zones of ✶✶: Tayler inst.

nearly uniform rotation solar interior due
to a (weak form of) dynamo action