Solar dynamo theory – recent progress, questions and answers

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How the solar dynamo works

Dikpati and Gilman, 2006
Solar dynamo theory - questions

- Is it correct?
- Values and variations of the dynamo parameters (diffusivity, meridional flows)
- Regime of operation
- Grand minima
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Predictions of the theory

- The amplitude and period of the sunspot cycle are governed by the speed of the meridional circulation (Wang, Sheeley, Lean (2003), Hathaway (2003), Passos and Lopes, 2009, 2011), Karak (2019), Karak and Choudhuri (2011), ...

- The value of the coefficient of turbulent diffusivity determines the regime of operation of the dynamo (Yeates, Nandy and Mackay, 2000; Hotta and Yokoyama, 2010; Choudhuri, 2010, ...)
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Values of the dynamo parameters

meridional circulation
diffusion

Both largely unknown from observations, especially on long-term scale
Surface poleward meridional circulation has been measured directly during the last 3 sunspot cycles:

- Doppler measurements (Duvall, 1976; Ulrich et al., 1988; Hathaway, 1996 ...)
- Tracers (Komm et al., 1993; Javaraiah, 2006 ...)
- Helioseismology (Giles et al., 1997; Fan and Braun, 1998...)

Estimated velocity: 10-25 m/s
Latitudinal and solar cycle variations of surface meridional circulation

From Doppler shift of gas velocity (Ulrich, 2010)

from magnetic features tracking (Hathaway and Rightmire, 2010)
Cycle to cycle variations of surface meridional circulation

Faster surface circulation in cycle 23

Doppler shift measurements

(Ulrich, 2010)
Limited data for the deep equatorward circulation

Giles (1998) from helioseismology:

Much slower than the surface circulation (2-10 m/s)
Latitudinal dependence;
Hemispheric asymmetry;
Reversal of the flow about 0.8 R
Hathaway et al. (2003) - deep equatorward circulation from the latitude drift of sunspot zones

Latitudinal and temporal dependence

Estimated velocity at sunspot latitudes: 0 – 2 m/s below 30°
Georgieva and Kirov (2007) - estimation from geomagnetic data

Double-peaked cycle of geomagnetic activity:

- one peak in sunspot max,
- the second one on the sunspot decline phase

- Sunspot max peak – max in sporadic solar activity (coronal mass ejections)
- Sunspot decline phase peak – max in recurrent solar activity (high speed solar wind from coronal holes)
When is geomagnetic activity maximum on the sunspot decline phase?

**Sunspot min:**
large polar coronal holes; no coronal holes at low latitudes

**Sunspot max:**
small scattered short-living coronal holes at all latitudes

When the trailing polarity flux reaches the poles, the low latitude holes begin attaching themselves to the polar holes and growing ⇒ long-lasting wide streams of fast solar wind

*(Wang and Sheeley, 1990)*

*CH data compiled by K. Harvey and F. Recely using NSO KPVT observations under a grant from the NSF*
in the absence of polar coronal holes, small short-lived low latitude holes are formed with HSS at high heliolatitudes

big long-lived low latitude coronal holes and HSS in the ecliptic plane are only formed in the presence of polar coronal holes

Wang and Sheeley, 1990
Time from sunspot maximum to geomagnetic activity maximum

= the time for the flow to reach from sunspot max latitudes to the poles

From this time we can calculate the speed of the surface meridional circulation
Long-term variations in surface meridional circulation and the amplitude of the next sunspot maximum

Strong dependence of the polar field and sunspot max on the preceding surface poleward circulation \((r=-0.76)\)

Faster poleward circulation \(\Rightarrow\) weaker polar field

Verification of the theory!
Long-term variations in surface meridional circulation and the amplitude of the next sunspot maximum

Strong dependence of the sunspot max on the preceding surface poleward circulation \((r=-0.7, p=0.03)\)

Faster poleward circulation \(\Rightarrow\) lower sunspot max of the next cycle

Verification of the theory!
Time from geomagnetic activity maximum to next sunspot maximum?

Depends on diffusivity

3 regimes of operation

- Fully advection-dominated
  very low diffusivity

- Intermediate
  higher diffusivity

- Strongly diffusion-dominated
  still higher diffusivity

(Hotta and Yokoyama, 2010)
Time from geomagnetic activity maximum to next sunspot maximum?

If the diffusivity is very low

all of the flux makes a full circle

Fully advection-dominated regime

\[ \eta \sim 10^7 \text{ m}^2/\text{s} \]

Jiang, Chatterjee, Choudhuri (2007)

From this time we can calculate the speed of the deep circulation.
Long-term variations in deep circulation and solar cycle amplitude

Strong dependence of the sunspot max on the preceding deep equatorward circulation ($r=0.81$, $p<0.01$)

Faster equatorward circulation $\Rightarrow$ higher sunspot max

Verification of the theory!
Most models assume positive correlation between $V_{surf}$ and $V_{deep}$

actually:

- **Negative correlation** ($r=-0.75$) between $V_{deep}$ preceding it
- No correlation between $V_{deep}$ and $V_{surf}$ following it
What is the physical meaning of the ratio $V_{surf}/V_{deep}$?

The upper half of the convective zone contains 0.5% of the solar mass, and the lower part - 0.25%

The surface poleward flow is much faster than the deep equatorward flow - mass conservation

$V_{surf}/V_{deep} \sim$ reversal depth
Time from geomagnetic activity maximum to next sunspot maximum?

**The other extreme:**
If the diffusivity is very high

flux diffuses directly to the tachocline “shortcircuiting” meridional circulation

Strongly diffusion-dominated regime

\[ \eta \sim 2-9 \times 10^8 \text{ m}^2/\text{s} \]

\[ \eta/u_0 > 2 \times 10^7 \text{ m} \]

*Hotta and Yokoyama (2010)*
Long-term variations in the diffusivity and the ratio $\eta/u_0$

Both $\eta (~1.4-3.10^8)$ and $\eta/u_0 (~5.10^6-3.10^7)$ are not high enough for strongly diffusion-dominated regime and not low enough for fully advection-dominated regime.
Time from geomagnetic activity maximum to the next sunspot maximum?

If the diffusivity is intermediate, a part of the flux short-circuits the meridional circulation, another part makes a full circle.

Intermediate regime

\[ \eta \sim 1 - 2 \times 10^8 \, \text{m}^2/\text{s} \]

Jiang, Chatterjee, Choudhuri (2007)

Diffusivity consistent with our estimation
If the diffusivity is intermediate

a part of the flux short-circuits the meridional circulation, another part makes a full circle

⇒ the sunspot cycle will be a superposition of the two surges of the toroidal field

⇒ double-peaked sunspot max
The 11-year cycle does not contain one but two waves of activity with different physical properties.

During the first maximum, activity increases and subsequently decreases at all latitudes.

The second maximum is only observed at low latitudes, but below 15° it is even bigger than the first one.
Conclusions

2 maxima in all cycles resulting from different physical processes:
- earlier one at all latitudes
- later one at low latitude

Varying timing between them:
- if big enough ⇒ 2 peaks seen
- if small ⇒ 1 peak in lat averaged data

Is this only true for cycle 19?
Georgieva (2011) - two maxima in all cycles from 12 to 23

- Diffusion generated: appears simultaneously in a wide latitudinal band
- Advection generated: moving equatorward with time

Verification of the theory!
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Regime of operation in the upper part of the solar convection zone

Intermediate - neither fully advection dominated, nor strongly diffusion generated

Relative importance of advection versus diffusion

**magnetic Reynolds number**

\[ R_m = \frac{V_{surf} L}{\eta_{surf}} \]

- \( V_{surf} \) - between 5 and 20 m/s
- \( \eta_{surf} \) - between 1.5 and 4.5\( \times \)10^8 m^2/s
- \( L \) \( \sim \) 10^9 m

\[ \Rightarrow R_m \text{ - between 10 and 60} \]

\[ \Rightarrow \text{advection more important than diffusion} \]
Explanation of the negative correlation of $V_{\text{surf}}$ with sunspot max and polar field

- **Advection more important than diffusion**
  Faster $V_{\text{surf}}$ = less time for the leading polarity flux to diffuse across the equator = less uncanceled flux reaching the pole = lower polar field = lower following sunspot max

- **Diffusion more important than advection**
  Faster $V_{\text{surf}}$ = less time for diffusive decay of the flux during its transport to the poles = higher sunspot max

negative correlation between the $V_{\text{surf}}$ and polar field, between $V_{\text{surf}}$ and next sunspot max

$\Rightarrow$ advection-dominated regime
Regime of operation in the lower part of the solar convection zone

Two possible regimes in the base of the convection zone:

- **Diffusion-dominated:**
  Faster $V_{\text{deep}}$ = less time for diffusive decay of the field = higher sunspot max

- **Advection-dominated:**
  Faster $V_{\text{deep}}$ = less time for toroidal field generation = lower sunspot max

(Yeates, Nandy & Machay, 2008)

Positive correlation between the $V_{\text{deep}}$ and sunspot max

$\Rightarrow$ diffusion-dominated regime
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Long-term variations in Vdeep (ESAI database)

higher Vdeep = lower sunspot max during the Maunder minimum

Confirmed by 10Be data (Beer et al., 1998)

⇒ advection-dominated regime
Still longer reconstruction (ESAI)

higher $V_{\text{deep}} = \text{lower sunspot max}$ during all grand minima

= advection dominated regime during grand minima
What is the difference between a “normal” period and a Grand minimum?

- $V_{\text{deep}}$, diffusivity - about the same
- $V_{\text{surf}}$ drops to very low values
- Ratio $V_{\text{surf}}/V_{\text{deep}} \approx 1$

Maunder minimum

Sporer minimum
A we entering a new grand minimum?

- The answer is **NO!** – that is, **NOT RIGHT NOW**
- Because $V_{surf}$ is relatively high, $V_{deep}$ is very low $\rightarrow$ $V_{surf}/V_{deep}$ is high
Thank you for your attention
Solar dynamo theory - questions

• Is it correct?
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• Long-term variations and irregularities
• Predictability
What is the reason for the long-term solar activity variability?

The sequence of relations

- Good negative correlation \((r=-0.75)\) between \(V_{surf}\) and the following \(V_{deep}\)
The sequence of relations

- Good correlation ($r=0.81$) between $V_{\text{deep}}$ and the following sunspot max (≡ toroidal field)
- Indication that solar dynamo operates in diffusion dominated regime
The sequence of relations

**NO correlation** between the sunspot max (≡ toroidal field) and the speed of the following surface poleward circulation $V_{\text{deep}}$
The sequence of relations

\[ \text{Vsurf} \rightarrow \text{Bpol} \rightarrow \text{Vdeep} \rightarrow \text{Btor} \not\rightarrow \text{Vsrf} \]

The “kick” acts upon Vsurf
Is the “kick” random?

Not likely: systematic variations in the sunspot cycle magnitude (Gleissberg cycle)
This dynamo mechanism works for all stars with convective envelopes.

What if the star has a planet?

The simplest case: one planet on a circular orbit in the star’s equatorial plane.

But we are interested in the horizontal, not in the vertical component of the tidal force.

In the case of the Sun, the elevation caused by all planets together is very small (~ 1 mm).

The elevation is due to the vertical component of the tidal force.

For one only planet, all vectors directed to the planet’s subpoint.
the case of the Sun with a number of planets

The tidal forces depend on the distance and relative positions of the major tide-creating planets (Jupiter, Earth, Venus, Mercury) which change with time.
Tidal acceleration in the horizontal plane

Meridional acceleration can change the meridional circulation speed \( \sim 10 \text{ m/s} \)
evaluation of the magnitude

\[
\cdot a = \frac{F}{\rho} \\
\cdot F \sim 10^{-10} \text{ N/kg} \\
\cdot \rho \sim 10^{-5} \text{ gr/cm}^3 = 10^{-2} \text{ kg/m}^3 \\
\implies a \sim 10^{-8} \text{ m/s}^2
\]

\[
\cdot t \sim 10^8 \text{ s} \\
\implies \text{dVsurf} \sim \text{ m/s}
\]

Corresponds to the observed variation of Vsurf
The average tidal force is important in the period when the surface meridional circulation carries the flux to the poles.
bigger meridional tidal force
= slower poleward surface circulation
= higher sunspot number of the next cycle
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= slower poleward surface circulation
= higher sunspot number of the next cycle
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How far ahead can we predict?

$V_{surf} \Rightarrow B_{pol} \Rightarrow V_{deep} \Rightarrow B_{tor} \not\Rightarrow V_{surf}$

$\Rightarrow$ No more than 1 cycle memory

Can we predict from planetary influences?
Forecast???
Thanks for your attention