Solar dynamo frontiers workshop: Helioseismology, 3D modeling, and data assimilation, June 9-12, 2015 at Boulder, USA

The most important figures are at 17th slide, don’t miss it.

Small- and Large-Scale Dynamo in the Solar Convection Zone

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Solar magnetism

The sun shows large temporal and spatial ranges of magnetic field from the granulation scale (∼1 Mm) to the global dipole field (∼1000 Mm).

Magnetic field is thought to be maintained by the dynamo action in the convection zone.

(Lites+2008, Hinode)
Small- and large-scale dynamos

**Small-scale dynamo (SSD):** Dynamo operating with non-helical turbulence in the scale smaller than energy carrying scale generating **no net magnetic flux** (Local dynamo, fluctuation dynamo). Origin of the **photospheric** magnetism (Catteneo 1999). Time scale is less than 1 minute (Rempel, 2014), determined by the smallest scale of the turbulence.

**Large-scale dynamo (LSD):** Dynamo with large-scale shear and/or mean turbulent electromotive force by helical turbulence generating **net magnetic flux** (Global dynamo). Origin of the features related to solar cycle (e.g. **polar reversal**, **Hale’s law**). Time scale is about 10 years in the solar case.

Sometimes there is no clear separation between them. Combination of these constructs the solar magnetism. (See also Brandenburg+2005, Physics Report, Section 5)
Kinematic and non-kinematic phase of small-scale dynamo

In the kinetic phase of the small-scale dynamo, where the Lorentz feedback can be ignored, the dynamo is most efficient in the smallest scale. Stretching there has shortest time-scale. Thus the magnetic energy peaks at the smallest scale. e.g., high-resolution photospheric calculation by Rempel, 2014

When the dynamo can reach the non-kinematic phase, the magnetic energy reaches the small-scale kinetic energy and suppresses it. The peak of the magnetic energy shifts to large scale. Enough resolution to resolve turbulent inertial scale is required to reach this stage. This is difficult in global dynamo calculation.
Small- vs. Large-scale dynamos

A lot of large scale dynamo simulations succeed in reproducing the coherent mean field with cycle (ASH, EULAG, FSAM, and pencil...)

**In the most of large-scale dynamo simulations in the convection zone, the small-scale dynamo is not efficient**, since the small-scale dynamo requires enough resolution for resolving the inertial range of turbulence.

On the other hand, when the small-scale dynamo begins to be effective with small magnetic diffusivity, the large-scale (mean) magnetic field is destroyed.

We should not forget that the sun has very small magnetic diffusivity ($10^4$ cm$^2$ s$^{-1}$ at the base)

$$\Omega_0 = 3 \Omega_{\text{sun}}, \ Pm = 0.25$$

$$\eta = 2.6 \times 10^{12} \text{ cm}^2 \text{ s}^{-1}$$

$$\eta = 1.2 \times 10^{12} \text{ cm}^2 \text{ s}^{-1}$$

Mean magnetic energy is decreased by factor of 3. (Nelson+2013)
Do we need suppression of small-scale dynamo in the solar convection zone?

2D kinematic dynamo in high $R_m \sim 2500$
(Tobias+2013, Cattaneo+2014)

Mean $B$ normalized for removing the exponential growth.

- helical, no shear
- non-helical, with shear
- helical, with shear

The shear suppresses the growth rate of the SSD. Note that the non-linear effect is ignored.

Interesting argument is that suppressing the small-scale dynamo is required for achieving the large-scale dynamo.
Open questions

1. Efficiency of the small-scale dynamo in the solar convection zone
   ✓ Strength of the turbulent magnetic field in the convection zone.
   ✓ Influence on the convective flow. Is it reduced? (Hanasoge+ 2012)
   ✓ Influence on the energy transport.

2. Influence of the small-scale dynamo on the large-scale dynamo
   ✓ Does small-scale dynamo destroy large-scale dynamo in the sun?
   ✓ How the sun maintain large-scale magnetic field with very small viscosity and magnetic diffusivity?
We carry out two series of calculations:

1. HD and MHD calculations in restricted Cartesian geometry exploring the possibility of small-scale dynamo in the convection zone without the rotation in high resolution which currently cannot be achieved in any global settings. (Hotta et al., 2015, ApJ, 803, 42)

2. MHD calculations in full spherical geometry exploring the interaction between small- and large-scale dynamos using rather low resolution. (Hotta et al., 2015 in prep)
Numerical setting

- Calculation domain 
  \((0.715,0,0)<(x,y,z)/R_{\text{sun}}<(0.96,1,1,1)\)

<table>
<thead>
<tr>
<th>Cases</th>
<th>(N_x \times N_y \times N_z)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H256D,M256D</td>
<td>72x256x256</td>
</tr>
<tr>
<td>H2048, M2048</td>
<td>576x2048x2048</td>
</tr>
</tbody>
</table>

Solar luminosity at the base of the convection zone is adopted. Only H(M)256D have explicit diffusivities \(\kappa = \nu = \eta = 1 \times 10^{12} \text{ cm}^2 \text{ s}^{-1}\) in order to compare it with ordinary global calculations (Fan+2014). In the highest resolution, the grid spacing is smaller than 350 km. Hydrodynamic cases (H****) are calculated 100 days. Then weak random magnetic field is added with no net magnetic flux (M****).
Contours for two cases

Values at $r=0.95R_{\text{sun}}$

$v_x$ in HD  $v_x$ in MHD  $B_x$ in MHD

H256D  M256D
H2048  M2048

$t=0.0[\text{day}]$
Energy evolution

Saturated magnetic energy for M256D is $2 \times 10^5$ erg cm$^{-3}$, which is 10 times smaller than that in M2048.
Spectra in two cases at the base

In the case M256D, the magnetic energy does not reach the kinetic energy indicating a less efficient small-scale dynamo. The Lorentz feedback to the flow is insignificant in the low resolution case.

In the case M2048, the magnetic energy exceeds the kinetic energy in the small-scale. The RMS convection velocity is reduced by factor of 2 due to the Lorentz feedback.
The magnetic energy reaches more than 90% ($0.95 B_{eq}$) of kinetic energy at the convection zone in M2048, while M256D can maintain 5% of kinetic energy.
Entropy perturbation

Entropy at $r=0.8R_{\text{sun}}$

Magnetic field suppresses the mixing of heat between up- and downflow regions. This makes upflow hotter and downflow cooler than HD case. As a result the energy transport is not significantly suppressed even with strong Lorentz feedback.
Next series in spherical geometry

In order to investigate the interaction between small- and large-scale dynamo, we carry out a series of high-resolution calculations in the spherical geometry.

<table>
<thead>
<tr>
<th>Cases</th>
<th>$N_r \times N_\theta \times N_\phi$</th>
<th>$\eta, \nu$ [cm$^2$ s$^{-1}$]</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low_D</td>
<td>64x192x384</td>
<td>$1 \times 10^{12}$</td>
<td>Fan+2014</td>
</tr>
<tr>
<td>Medium</td>
<td>64x192x384</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>256x768x1536</td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>

Initially, we put random and small fluctuation on the entropy and weak (100 G) antisymmetric toroidal field. Then integrate the equation for 50 years. When without the character D, we only use slope limited diffusion. M256 costs 800,000 core hours.
Comparison of resolutions

Less diffusive

**Low_D**
\[ \nu = \kappa = 1 \times 10^{12} \text{ cm}^2 \text{ s}^{-1} \]

**Medium**
64x192x384

**High**
256x768x1536

\[ v_r \text{ at } 0.95R \]

\[ B_\phi \text{ at } 0.72R \]

In Low_D (Fan+2014), the coherent magnetic field is generated and concentrated around the base of the convection zone. Using higher resolution (M64) large scale magnetic field looks destructed. In the highest resolution calculation, we again see the indication of large-scale magnetic field at the bottom of the convection zone.
Summary

1. Small-scale dynamo (SSD) is very efficient with small magnetic diffusivity throughout the convection zone.
   ✓ $0.95B_{eq}$ is achieved at the base of the convection zone.
   ✓ The flow is reduced by the factor of 2.
   ✓ The small-scale magnetic field suppresses the mixing between up- and downflows and increases the efficiency of energy transport.

2. Large-scale dynamo (LSD) is influenced by the small-scale dynamo
   ✓ LSD is suppressed by SSD with using “medium” turbulent diffusivity.
   ✓ LSD is supported by SSD in the higher resolutions.