Overview of turbulent dynamo theory
Is there a small-scale solar surface dynamo (SSSD)?
MURaM solar surface dynamo

The Solar Surface Dynamo

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SGS 20.01.09
Outline

1. Overview of turbulent dynamo theory
2. Is there a small-scale solar surface dynamo (SSSD)?
3. MURaM solar surface dynamo
Overview of turbulent dynamo theory
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Solar global dynamo

Global dynamo

- 22 year cycle
- \( \approx \) dipolar
- many models
  (Babcock-Leighton, flux-transport (Dikpati et al.), surface shear (Brandenburg 2005))
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**Solar surface dynamo – turbulent (small-scale) dynamo?**

**Turbulent dynamo**

- Stretching of B-field lines by turbulence (Batchelor 1950, Moffat 1978, Parker 1979)
- “Fast” dynamo for chaotic & sufficiently complex flows (Childress & Gilbert 1995)
- Near the surface layer of the sun? (e.g., Petrovay & Szakaly 1993)

**Stretching $\gg \eta$**

\[
\partial_t \mathbf{B} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}
\]

\[
Re_M = \frac{\nu_0 \lambda}{\eta} > Re_{CM} \rightarrow \text{dynamo}
\]
Turbulent dynamos – well studied

Turbulent dynamos first demonstrated 20 years ago

- Realistic: Boussinesq (no sound waves), rotation, convection in spherical shell (Gilman and Miller 1981)
- Idealistic: periodic box
  \[ N^3 = 64^3, \quad Re_M \approx 100 \] (Meneguzzi et al. 1981)
  - Homogeneity and isotropy recovered at small scales
  - Helical and Non-helical
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Turbulent dynamos – large & small

2 types of turbulent dynamos

- Large-scale (LSD; helicity, $\alpha -$ effect: mean-field)
- Small-scale (SSD; non-helical)
- Solar surface dynamo ($\tau_{\text{conv}} \sim 10 \text{ min}$ $< < \tau_{\text{rotation}}$ $\rightarrow$ no net helicity)
Magnetic carpet (Title and Schrijver 1998; Title 2000)

(see also Hagenaar et al. 2003)
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**Convectively-Driven Small-Scale Dynamo (Cattaneo 1999)**

- Boussinesq convection (no sound waves)
- no Coriolis force (SSD)

**Temperature**

\( B_z \)

\( Re \approx 200 \)
\( Re_M \approx 1000 \)

\[
512 \times 512 \times 97 \approx 5 \cdot Re_M^{9/4}
\]

**Kinetic Energy**

**5 * Magnetic Energy**

\[
u_0 = 200
\]

(see also Cattaneo et al. 2003)
1. Shredding of large-scale field by turbulence?

**Induced small-scale field**

- **Observation:** Very small-scale bipolar regions ($\Phi < 30 \cdot 10^{18} \text{ Mx}$) independent of the solar cycle and latitude (for low latitudes) (Hagenaar et al. 2003; Trujillo Bueno et al. 2004)

- **Timescale for SSD much faster** (e.g., Kulsrud & Anderson 1992; Kulsrud 1999) for open questions see Iskakov et al. (2007)
  
  - $\tau_{SSD} \sim 10 \text{ min (theoretically)} \ll \text{ other dynamos}$

- **Shredding is algebraic-in-time, SSD is exponential-in-time** (e.g., Schekochihin et al. 2005)
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**Evidence for SSSD**

**Arguments against SSSD**

2. \( \text{Re} \gg \text{Re}_M \) (i.e., \( P_M \equiv \frac{\text{Re}_M}{\text{Re}} = \frac{\nu}{\eta} \ll 1 \) )

\[
P_M > 1 \rightarrow l_\eta < l_\nu
\]

Schekochihin et al. 2004

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**Fig. 1.**—Sketch of scale ranges and energy spectra in a large-Pr\(_m\) medium.

eddies \( l > l_\eta \) stretch B

eddies \( l < l_\eta \) diffuse B
2. \( \text{Re} \gg \text{Re}_M \) (i.e., \( P_M \equiv \frac{\text{Re}_M}{\text{Re}} = \frac{\nu}{\eta} \ll 1 \))

2 Theoretical possibilities

- Clusters
- Galaxies
- Stars (Sun)
- Protostellar disks
- Planets
- Laboratory dynamos

\( \text{Re} = \text{Re}_M P_M^{-1} \)

(Rogachevskii & Kleeorin 1997)

Schekochihin et al. 2005
2. $Re \gg Re_M$ (i.e., $P_M \equiv \frac{Re_M}{Re} = \frac{\nu}{\eta} \ll 1$)

Dynamo at low $P_M$

Iskakov et al. 2007
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Evidence for SSSD

Arguments against SSSD

2. \( \text{Re} \gg \text{Re}_M \) (i.e., \( P_M \equiv \frac{\text{Re}_M}{\text{Re}} = \frac{\nu}{\eta} \ll 1 \))

Dynamo at low \( P_M \)

\[ P_M \approx 10^{-5} \]

Iskakov et al. 2007
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\[ P_M \approx 10^{-5} \text{ – No Problem} \]

VKS experiment (Monchaux et al. 2007)

CEA-Saclay – CNRS – ENS-Lyon – ENS-Paris
3. Strong stratification & little recirculation

“Last” argument against SSD (Stein et al. 2003)

- Strong stratification
- Little plasma is recirculated in the near-surface layers
- Realistic magneto-convection with open boundaries
  (Stein et al. 2003): $253 \times 253 \times 163 \rightarrow Re_M \sim 600$
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The MURaM code (Vögler et al. 2005; Vögler 2003)

Realistic magnetoconvection

- Strong stratification
- Fully compressible
- Partial ionization
- Radiative transfer
- Open lower boundary
  
  \[ \frac{\partial v}{\partial z} = 0 \text{ for downflows; } B_{\text{hor}} \text{ not advected} \]
  
  into box

- No rotation
- Parallelized

\( B_z \) & brightness
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Turbulent solar surface dynamo
Comparing MURaM with obs.: Strong horizontal field
Prevalent weak vertical field
Estimating true unsigned vertical flux

Strong stratification & little recirculation – No Problem

<table>
<thead>
<tr>
<th>Run</th>
<th>$N_{hor}^2 \times N_Z$</th>
<th>$Re_M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$288^2 \times 100$</td>
<td>300</td>
</tr>
<tr>
<td>B</td>
<td>$576^2 \times 100$</td>
<td>1300</td>
</tr>
<tr>
<td>C</td>
<td>$648^2 \times 140$</td>
<td>2600</td>
</tr>
</tbody>
</table>

1300 $\lesssim Re^C_M \lesssim 2600$

Run C: $E_M \approx 3\% E_K$
Turbulent small-scale solar surface dynamo for $Re_M > Re_M^C$

Simulation Comparison

<table>
<thead>
<tr>
<th>Result</th>
<th>Grid pts.</th>
<th>$Re_M$</th>
<th>$P_M$</th>
<th>BC</th>
<th>SSD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run A</td>
<td>$288^2 \times 100$</td>
<td>$\approx 300$</td>
<td>$\approx 1$</td>
<td>open</td>
<td>N</td>
</tr>
<tr>
<td>Stein+</td>
<td>$253^2 \times 163$</td>
<td>$\approx 600$</td>
<td>$\approx 1$</td>
<td>open</td>
<td>N</td>
</tr>
<tr>
<td>Run B</td>
<td>$576^2 \times 100$</td>
<td>$\approx 1300$</td>
<td>$\approx 1$</td>
<td>open</td>
<td>N</td>
</tr>
<tr>
<td>Cattaneo</td>
<td>$512^2 \times 97$</td>
<td>$\approx 1000$</td>
<td>$\approx 5$</td>
<td>closed</td>
<td>Y</td>
</tr>
<tr>
<td>Run C</td>
<td>$648^2 \times 140$</td>
<td>$\approx 2600$</td>
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</tbody>
</table>

(Vögler & Schüssler 2007)
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Pervasive horizontal magnetic flux (Lites et al. 2008)

\[ \langle |B^L_{app}| \rangle \approx 11 \text{ Mx cm}^{-2} \]
\[ \langle B^T_{app} \rangle \approx 55 \text{ Mx cm}^{-2} \]

\[ |B^L_{app}| \leq 50 \text{ Mx cm}^{-2} \]
\[ B^T_{app} \leq 200 \text{ Mx cm}^{-2} \]
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**Strong horizontal photospheric magnetic field in SSD**
(Schüssler & Vögler 2008)

Run C: $\log B_{\text{hor}}$

- $\tau_{\text{hor}} = 0.1$
- $\tau_{\text{hor}} = 1$

Shallow narrow loops (integranular lanes)
Extended loops (above granules)

Average vertical field decreases faster with height than horizontal field

(see also Steiner et al. 2008)
Distribution of vertical field strength

Hinode $B^L_{\text{app}}$ 220 Mm $\times$ 110 Mm (Lites et al. 2008)

Run C: $B_{\text{ave}}$ 4.9 Mm $\times$ 4.9 Mm
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Prevalent weak vertical field

Simulated PDFs

Simulations have prevalent weak field
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Prevalent weak vertical field

Observed PDF derived from Stokes V (Lites et al. 2008)

Simulated PDFs

Synthetic observation is also peaked
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Prevalent weak vertical field

Observed PDF derived from Stokes V (Lites et al. 2008)

Simulated PDFs

Observed PDF is compatible with monotonic PDF of the actual field
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Vertical radiative transfer & turbulence

Vertically averaged field = 0

Absorption profiles Doppler shifted
Synthetic Magnetogram

Effect increases with variance \((v_z)^{1/2}\) along line of sight

\[
B_{\text{ave}} < 0.1 \text{ G}
\]

\(B^L_{\text{app}}\) vs \(\sigma_v \text{ (km/s)}\)
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From fractal geometry to true unsigned vertical flux

Fractal = self-similar = power-law

\[ N(l) \propto l^{-D} \]

Koch fractal

\[ \chi(l) \equiv \frac{\sum_i \int_{A_i} B_z \, da}{\int_{A} B_z \, da} \]

\[ \chi(l) \sim l^{-\kappa} \]

(Ott et al. 1992)

\( \chi(l) \) measures the portion of flux remaining after averaging over boxes of length \( l \)

(Sorriso-Valvo et al. 2002)
Cancellation is self-similar

\[ \kappa = 0.26 \pm 0.01 \]

\[ \langle |B_Z| \rangle \equiv \int_A |B_z| \, da / \int_A da \]

\[ \langle |B_Z| \rangle_l \equiv \frac{\sum_i \int_{A_i(l)} B_z \, da}{\int_A da} = \chi(l) \cdot \langle B_z \rangle \]

\[ \langle |B_Z| \rangle = \langle |B_Z| \rangle_l \cdot \frac{\chi(l \eta)}{\chi(l)} = 11G \cdot \left( \frac{220 \text{ km}}{l \eta} \right)^{0.26} \]

\[ \eta \sim 1 \times 10^8 \text{ cm}^2 \text{s}^{-1} \] (Kovitya & Cram 1983)

K41 \rightarrow \eta \sim 80 \text{ m} < 800 \text{ m}

\[ \rightarrow \langle |B_Z| \rangle \geq 46 \text{ G} \]
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Better agreement with Hanle estimates

The flux remaining at $l = 200$ km follows a power-law scaling. Extrapolation to solar values, $Re_M \sim 3 \cdot 10^5$, yields $\chi(200 \text{ km}) = 0.2$.

$\langle |B_Z| \rangle \sim 50 \text{ G}$

$\langle |B_Z| \rangle \sim 50 \text{ G}$

$\langle B_{\text{hor}} \rangle > \langle |B_Z| \rangle$ (Lites et al. 2008)

$\langle B \rangle \sim 130 \text{ G Hanle}$ (Trujillo Bueno et al. 2004)
Conclusions

- A small-scale solar surface dynamo (SSSD) is likely
  - Evidence seen in observations
  - MURaM dynamo simulations in agreement with observations
  - Arguments against fail: stratified, compressed, little recirculation, $P_M \ll 1$ all seem OK

- Whatever its source, small-scale B-field is turbulent & fractal
  - we should use this to interpret observations

- arXiv:0812.2125