Universality of the small-scale dynamo mechanism

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Intra-network quiet-Sun magnetic field

Lites et al. 2008

$3\sigma < |B_z| < 24$ G

Magnetic carpet (Title and Schrijver 1998; Title 2000; Hagenaar et al. 2003)

$\langle |B_z| \rangle = 12$ G

$\sigma = 2.4$ G
Sun is a bit too messy

Simplify

- Very large scales, 1391 Mm
- $10^5$ more velocity than magnetic scales
- Mysterious $\sim 22$ yr global dynamo
- Strongly stratified, compressible medium
- Little recirculation
- Ionization/radiation
The MURaM code (Vögler et al. 2005; Vögler 2003)

Realistic magnetoconvection
- Strong stratification
- Fully compressible
- Partial ionization
- Radiative transfer
- Open lower boundary
  (vertical upflows, $\frac{dx}{dz} = 0$ for downflows; $B_{\text{hor}}$ not advected into box)
- High plasma-$\beta$
- No rotation

$B_z$ & brightness
The MURaM dynamo (Vögler & Schüssler 2007)
- Reversed granulation (Cheung et al. 2007)
- Granulation intensity contrast (Danilovic et al. 2008)
- Ratio of vertical to horizontal fields (Schüssler & Vögler 2008)

$5 \times 5 \text{ Mm}$
Tale of two dynamos?
Or one?

Messy, solar case
Ideal case

Messy solar convection

Run 1
MURaM dynamo looks like the Sun (Danilovic et al. 2010)
Tale of two dynamos?
Or one?

Messy, solar case
Ideal case

Homogeneous, isotropic dynamos – well known

\[ N^3 = 64^3, \quad Re_M \approx 100 \]
Meneguzzi et al. 1981

Many studies of small-scale dynamo (SSD)
Childress & Gilbert 1995; Maron & Cowley 2001; Heitsch et al. 2001; Schekochihin et al. 2004; Maron et al. 2004;
Ponty et al. 2005; Schekochihin et al. 2005; Mininni 2006; Ponty et al. 2007; Iskakov 2007, ...
Compare 3 dynamos

Incrementally add realistic physics

- Incompressible, Homogeneous, isotropic Turbulence (HoT) with Ornstein-Uhlenbeck (Langevin equation) forcing at $k \in [2, 3]$
- Boussinesq (incompressible) convection (anisotropic)
- Strongly stratified compressible, partially-ionized, radiative convection (MURaM)
Visually

Tale of two dynamos?  
Or one?

Visual comparison
Fourier comparison
Detailed comparison

**Visually**

**Ideal isotropic, homogeneous**

**Boussinesq convection**

**Solar-like convection**
Spectrally

Tale of two dynamos?
Or one?

Visual comparison
Fourier comparison
Detailed comparison

Ideal isotropic, homogeneous

Boussinesq convection

Solar-like convection
Shell-to-shell transfer analysis

\[ a(x) = \sum_K a_K(x) \quad K < |k| \leq K + 1 \]

\[
\begin{align*}
\partial_t \langle \frac{1}{2} v_K^2 \rangle &+ v \cdot \nabla v_Q + \nabla P = \left( T_{vv}(Q, K) + v \cdot \nabla v_Q + \nabla P \right) \\
\partial_t \langle \frac{1}{2} B_K^2 \rangle &+ v \cdot \nabla B_Q = \left( T_{BB}(Q, K) + v \cdot \nabla B_Q \right)
\end{align*}
\]

\[
T_{vBT}(Q, K) = -T_{BvT}(K, Q)
\]
Direct, local cascade

**$T_{vv}(Q, K)$**

- $Q > K$ - $K$ loses to larger $Q$
- $Q < K +$ $K$ receives smaller $Q$

**$T_{BB}(Q, K)$**

- $Q > K$ - $K$ loses to larger $Q$
- $Q < K +$ $K$ receives smaller $Q$
The dynamo mechanism

Tale of two dynamos? Or one?

Visual comparison
Fourier comparison
Detailed comparison

$T_{vBT}(Q, K) = B_K \cdot (B \cdot \nabla) v_Q$
Tale of two dynamos?  
Or one?  

Visual comparison  
Fourier comparison  
Detailed comparison  

Same kinematic dynamo mechanism  

\[ T_{vBT}(Q, K) \]

Ideal isotropic, homogeneous

Q<K + K receive smaller Q

Boussinesq convection

Solar-like convection

Q<K + K receive smaller Q
Tale of two dynamos? 
Or one?

Same saturation mechanism

Visual comparison
Fourier comparison
Detailed comparison
Conclusions

Ideal results extend to real systems

- Only one small-scale dynamo (SSD)
  - Independent of (isotropy) forcing
  - Same in the face of lots of messy physics
- SSD should work in the Sun as well
  - $P_M 10^{-2}$ OK for SSD (Ponty et al. 2005, Iskakov et al. 2007)
  - $P_M 10^{-5}$ for $\alpha - \omega$??? (Monchaux et al. 2009)
  - Strong stratification/little recirculation, partial ionization, radiation do not change SSD
Summary

Future work

- “Background” field & dominant source
  - “Compressive cascade”
  - Alfvénic turbulent induction
  - SSD

- Lower $P_M$