The Solar Surface Dynamo

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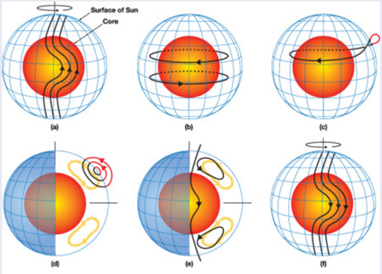
Outline

Solar global dynamo

Global dynamo

- 22 year cycle
- $\approx$ dipolar
- many models (Babcock-Leighton, flux-transport (Dikpati et al.), surface shear (Brandenburg 2005))



M. Dikpati, NCAR

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 $\gg \eta$

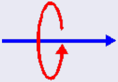
$$\partial_t \mathbf{B} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

$$Re_M = \frac{v_o l_o}{\eta} > Re_M^C \rightarrow \text{dynamo}$$

Turbulent dynamos – well studied

Turbulent dynamos first demonstrated 20 years ago

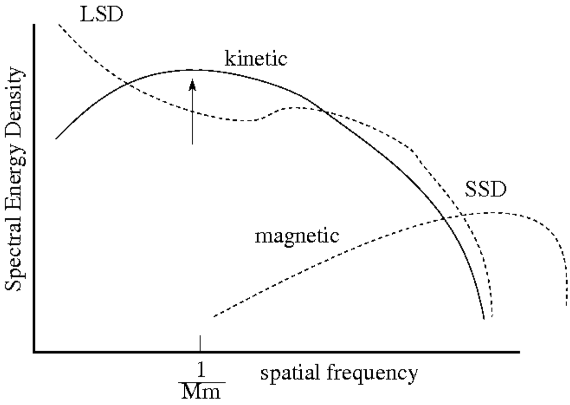
- Realistic: Boussinesq, rotation, convection in spherical shell (Gilman and Miller 1981)
- Idealistic: periodic box
  $N^3 = 64^3$, $Re_M \approx 100$ (Meneguzzi et al. 1981)
    - Homogeneity and isotropy recovered at small scales
    - Helical and Non-helical



Turbulent dynamos – large & small

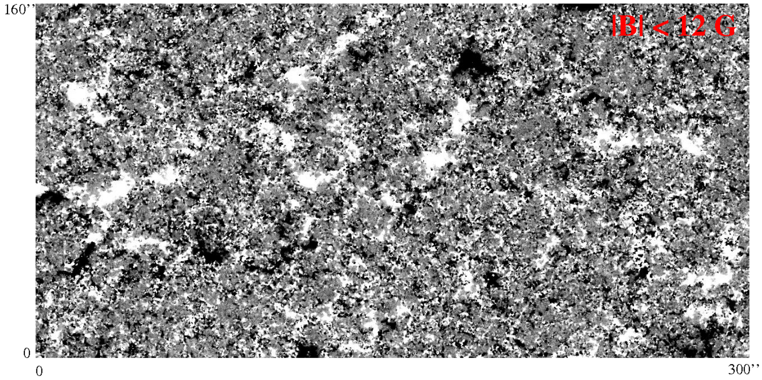
2 types of turbulent dynamos

- Large-scale (LSD; helicity, $\alpha-$effect: mean-field)
- **Small-scale (SSD; non-helical)**
- solar surface dynamo ($\tau_{conv} \sim 10\,\text{min} << \tau_{rotation}$ $\rightarrow$ no net helicity)



Magnetic carpet (Title and Schrijver 1998; Title 2000)

Lites et al. 2008

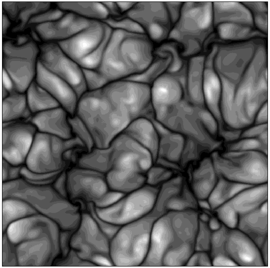


(see also Hagenaar et al. 2003)

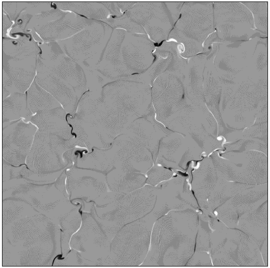
Convectively-Driven Small-Scale Dynamo (Cattaneo 1999)

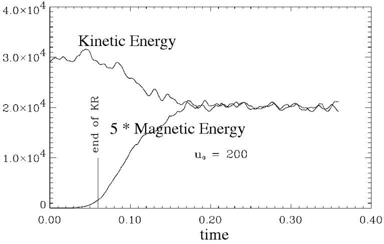
$$Re \approx 200$$
$$Re_M \approx 1000$$
$$512 \times 512 \times 97 \approx 5 \cdot Re_M^{9/4}$$

Temperature



B_z





- Boussinesq convection
- no Coriolis force (SSD)

(see also Cattaneo et al. 2003)

1. Shredding of large-scale field by turbulence?

Induced small-scale field

- Timescale for SSD much faster (e.g., Kulsrud & Anderson 1992; Kulsrud 1999)
  - $\tau_{SSD} \sim 10\,\mathrm{min}$ (theoretically) $\ll$ other dynamos
- Shredding is algebraic-in-time, SSD is exponential-in-time (e.g., Schekochihin et al. 2005)
- **Observation:** Very small-scale bipolar regions ($\Phi < 30 \cdot 10^{18}\,\mathrm{Mx}$) independent of the solar cycle and latitude (for low latitudes) (Hagenaar et al. 2003)

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

$\underline{P_M > 1}$

Schekochihin et al. 2004

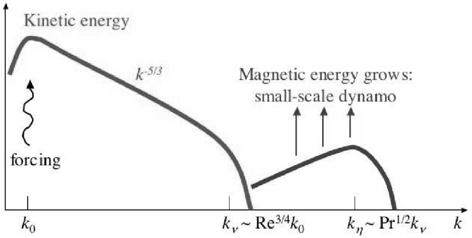
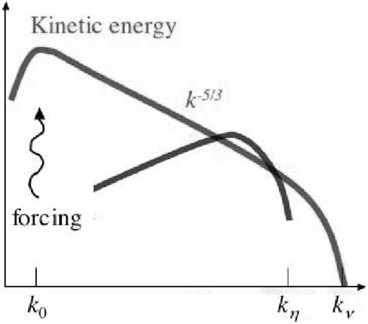


FIG. 1.—Sketch of scale ranges and energy spectra in a large-Pr_m medium.

eddies $l > l_\eta$ stretch B

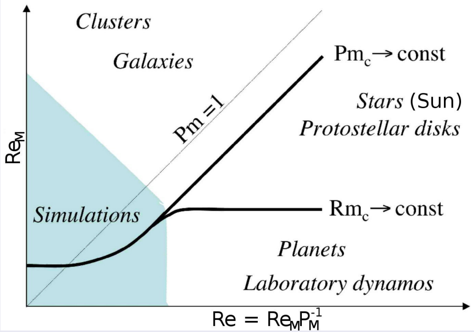
$\underline{P_M < 1}$



eddies $l < l_\eta$ diffuse B

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

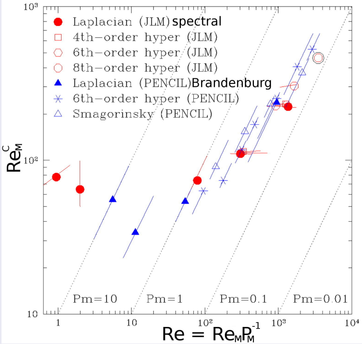
2 Theoretical possibilities



Schekochihin et al. 2005

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

No dynamo at low P_M



Schekochihin et al. 2005

Dynamo at low P_M

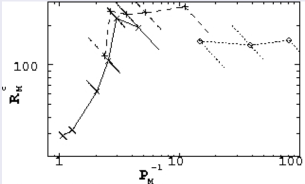
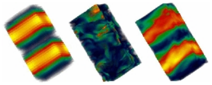
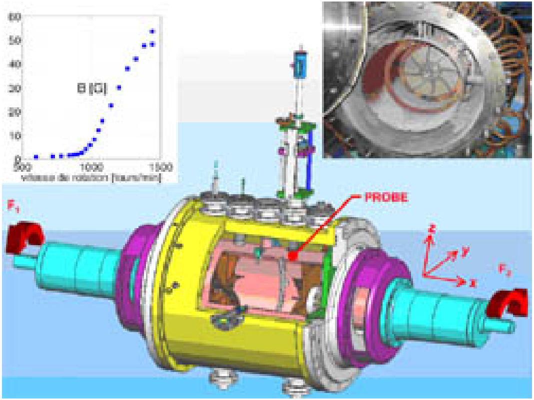


FIG. 1: R_M^c for dynamo action versus inverse P_M. Symbols are: × (DNS), + (LAMHD), and ◇ (LES). Transverse lines indicate error bars in the determination of R_M^c, as the distance between growing and decaying runs at a constant R_V.

Ponty et al. 2005



$P_M \approx 10^{-5}$ – 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): $253 \times 253 \times 163 \rightarrow Re_M \sim 600$

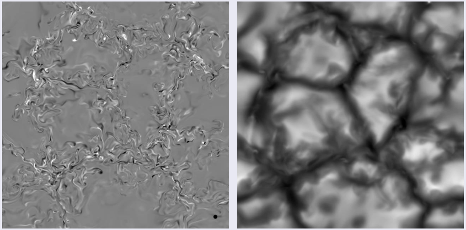
The MURaM code (Vögler et al. 2005; Vögler 2003)

Realistic magnetoconvection

- Strong stratification
- Fully compressible
- Partial ionization
- Radiative transfer
- Open lower boundary

  (vertical upflows, $\frac{dv}{dz} = 0$ for downflows; B_{hor} not advected into box)
- No rotation
- Parallelized

B_z & brightness

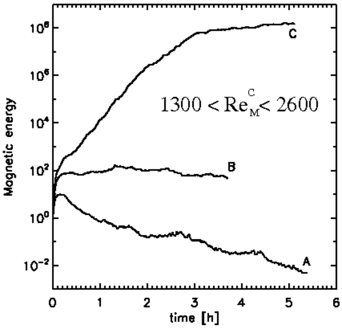


Strong stratification & little recirculation – No Problem

Vögler & Schüssler 2007

Run	$N_{hor}^2 \times N_Z$	Re_M
A	$288^2 \times 100$	300
B	$576^2 \times 100$	1300
C	$648^2 \times 140$	2600

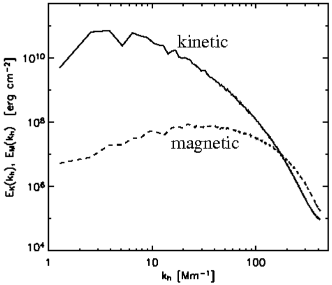
$1300 \lessapprox Re_M^C < 2600$



Run C: $E_M \approx 3\% E_K$

Turbulent small-scale solar surface dynamo for $Re_M > Re_M^C$

Run C



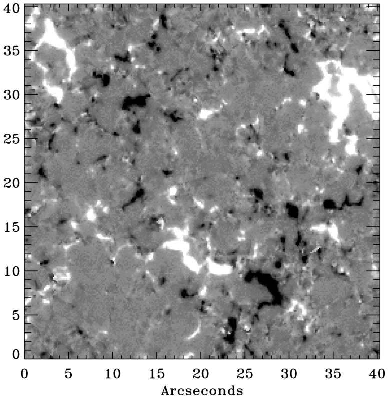
(Vögler & Schüssler 2007)

Simulation Comparison

Result	Grid pts.	Re_M	P_M	BC	SSD
Run A	$288^2 \times 100$	≈ 300	$\lesssim 1$	open	N
Stein+	$253^2 \times 163$	≈ 600	≈ 1	open	N
Run B	$576^2 \times 100$	≈ 1300	$\lesssim 1$	open	N
Cattaneo	$512^2 \times 97$	≈ 1000	≈ 5	closed	Y
Run C	$648^2 \times 140$	≈ 2600	$\lesssim 1$	open	Y

Pervasive horizontal magnetic flux (Lites et al. 2008)

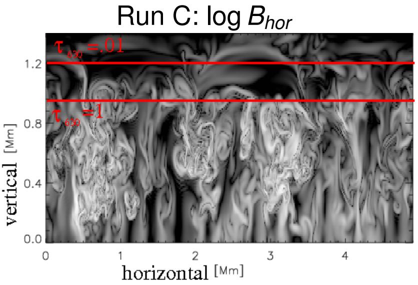
$< |B^L_{app}| > \approx 11\,\mathrm{Mx\,cm}^{-2}$ $< B^T_{app} > \approx 55\,\mathrm{Mx\,cm}^{-2}$



$|B^L_{app}| \leq 50\,\mathrm{Mx\,cm}^{-2}$ $B^T_{app} \leq 200\,\mathrm{Mx\,cm}^{-2}$

Strong horizontal photospheric magnetic field in SSD

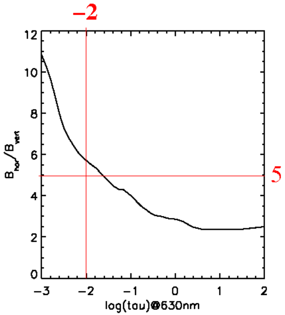
(Schüssler & Vögler 2008)



Shallow narrow loops (integranular lanes)

Extended loops (above granules)

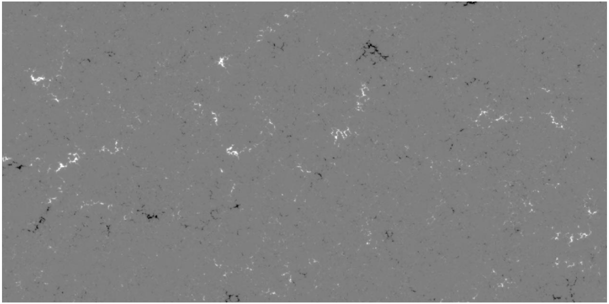
(see also Steiner et al. 2008)



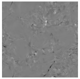
Average vertical field decreases faster with height than horizontal field

Distribution of vertical field strength

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

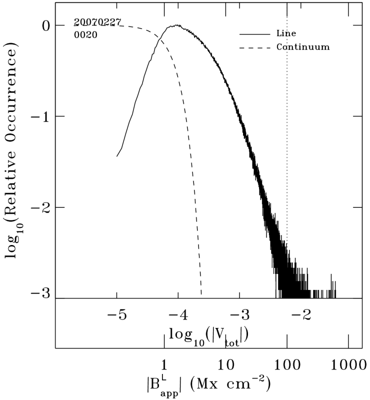


Run C: B_{ave} 4.9 Mm $\times$ 4.9 Mm

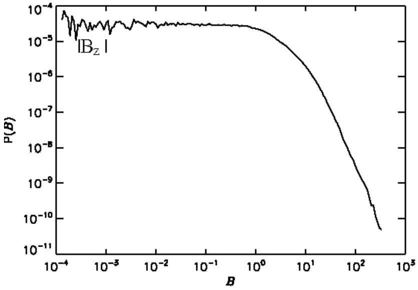


Prevalent weak vertical field

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



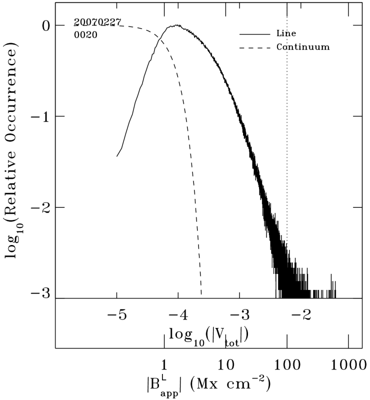
Simulated PDFs



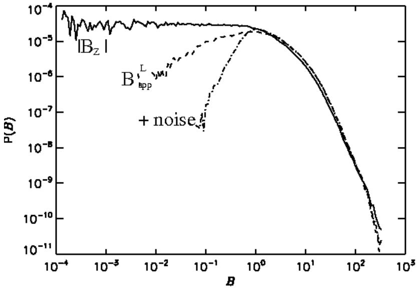
Simulations have prevalent weak field

Prevalent weak vertical field

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



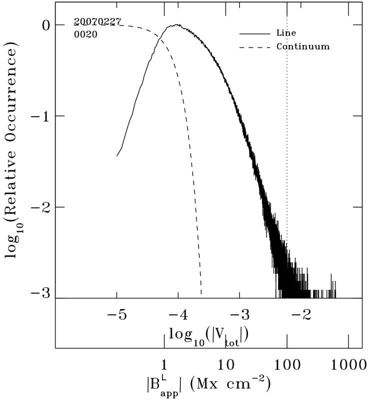
Simulated PDFs



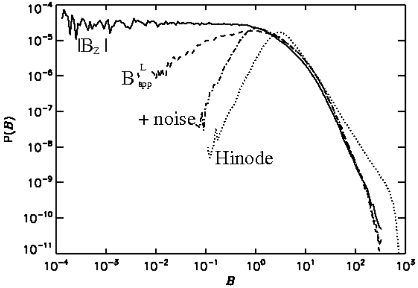
Synthetic observation is also peaked

Prevalent weak vertical field

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

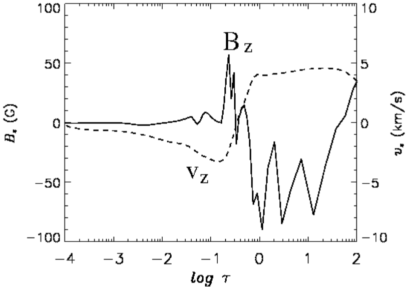


Simulated PDFs



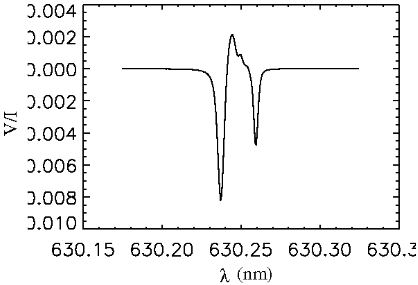
Observed PDF is compatible with monotonic PDF of the *actual* field

Vertical radiative transfer & turbulence



Vertically averaged field = 0

Fe I 6302.5 Å (a *Hinode* SP line)

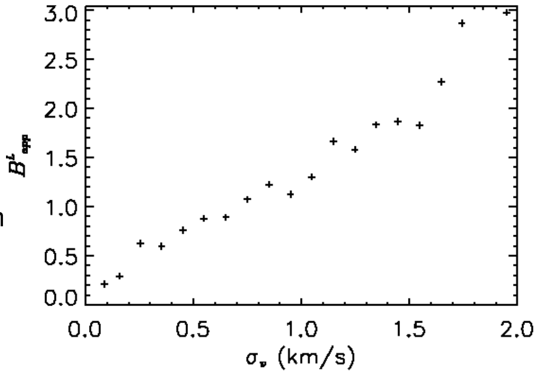


Absorption profiles Doppler shifted

Vertical radiative transfer & turbulence

$B_{ave} < 0.1\,\mathrm{G}$

Synthetic Magnetogram

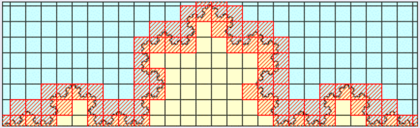


Effect increases with variance$(v_z)^{1/2}$ along line of sight

From fractal geometry to true unsigned vertical flux

Fractal = self-similar = power-law

$$N(l) \propto l^{-D}$$



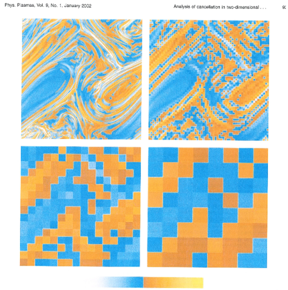
Koch fractal

$$\chi(\mathbf{l}) \equiv \frac{\sum_{\mathbf{i}} \left| \int_{\mathcal{A}_{\mathbf{i}}(\mathbf{l})} \mathbf{B_z da} \right|}{\int_{\mathcal{A}} |\mathbf{B_z}| \mathbf{da}}$$

$$\chi(l) \sim l^{-\kappa}$$

(Ott et al. 1992)

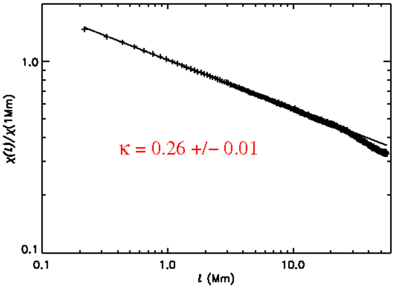
(Sorriso-Valvo et al. 2002)



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

Cancellation is self-similar

Hinode B_{app}^{L} (Lites et al. 2008)



$$\chi(\mathbf{l}) \equiv \frac{\sum_i \left| \int_{\mathcal{A}_i(\mathbf{l})} \mathbf{B_z da} \right|}{\int_{\mathcal{A}} |\mathbf{B_z}| \mathbf{da}}$$

Fractal extrapolation

$$< |\mathbf{B_z}| > \equiv \int_{\mathcal{A}} \left| \mathbf{B_z} \right| \mathbf{da} / \int_{\mathcal{A}} \mathbf{da}$$

$$< |\mathbf{B_Z}| >_\mathbf{l} \equiv \frac{\sum_i \left| \int_{\mathcal{A}_i(\mathbf{l})} \mathbf{B_z da} \right|}{\int_{\mathcal{A}} \mathbf{da}} = \chi(\mathbf{l}) \cdot < \mathbf{B_Z} >$$

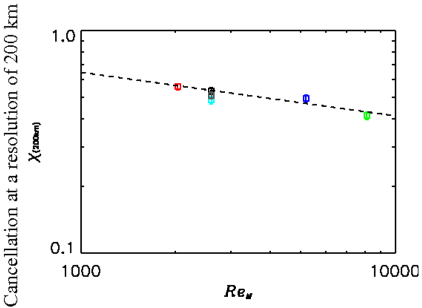
$$< |\mathbf{B_Z}| > = < |\mathbf{B_Z}| >_\mathbf{l} \cdot \frac{\chi(\mathbf{l}_\eta)}{\chi(\mathbf{l})} = 12\mathrm{G} \cdot \left(\frac{100\mathrm{km}}{\mathbf{l}_\eta} \right)^{0.26}$$

$\eta \sim 10^8\,\mathrm{cm}^2\mathrm{s}{-1}$ (Kovitya & Cram 1983)

K41 $\rightarrow l_\eta \approx 80\,\mathrm{m} < 800\,\mathrm{m}$

$\rightarrow < |B_Z| > \geq 40\,\mathbf{G}$

Better agreement with Hanle estimates



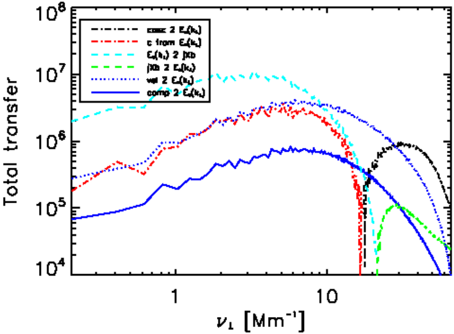
The flux remaining at $l = 200\,\mathrm{km}$ follows a power-law scaling. Extrapolation to solar values, $Re_M \sim 3 \cdot 10^5$, yields $\chi(200\,\mathrm{km}) = 0.2$.
$\rightarrow < |B_Z| > \sim 50\,\mathbf{G}$

$< |B_Z| > \sim$ **40 or 50 G**
$< B_{hor} > \, > < |B_Z| >$ **(Lites et al. 2008)**
$< B > \sim 130$ **G Hanle (Trujillo Bueno et al. 2004)**

Conclusions

- A small-scale solar surface dynamo (SSSD) is likely
  - Seen in *Hinode* observations
  - 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

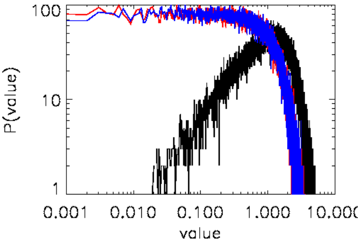
Future Work



Effect of noise

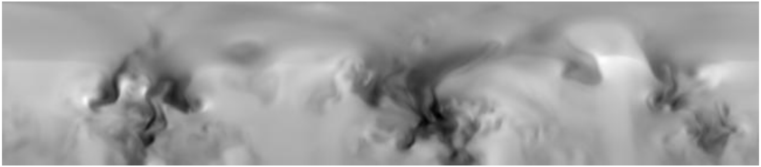
Sum of absolute values of 2 random vars

- $B^L_{app} = f(V_{tot})$
- $V_{tot} = sgn(V_{blue}) \cdot \frac{1}{I_c N}\left(\left|\sum_{i=1}^{N_b}(V(\lambda_i) + \sigma_i)\Delta\lambda\right| + \left|\sum_{i=1}^{N_r}(V(\lambda_i) + \sigma_i)\Delta\lambda\right|\right)$
- $|V_{tot}| = |V^{true}_{tot}| + \frac{1}{I_c N}(|\sigma_b| + |\sigma_r|)$
- For $|V^{true}_{tot}| \approx 0 \rightarrow |V_{tot}| > 0$ (artificially high flux)



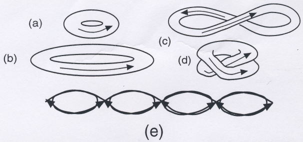
Mean flow

Instantaneous flow



Time-averaged mean flow

Pictures of Dynamos



Childress & Gilbert 1995

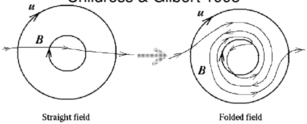
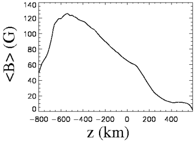
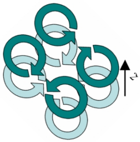


FIG. 2.—Stretching and folding of field lines by turbulent eddies.

Schekochihin et al. 2004

$$N^3 \propto Re_M^{9/4}$$

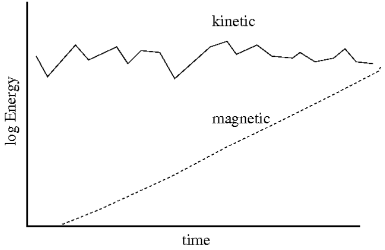




What is dynamo action?

1. Kinematic/exciting

- Kinematic – generates B-field from seed (non-magnetic state is unstable)



2. General/sustaining

- General – maintains B-field against losses of ohmic dissipation: $\eta\nabla^2 B$