Solar surface magnetism: selected topics

Thaler, I.

Citation for published version (APA):

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations
If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: https://uba.uva.nl/en/contact, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.

UvA-DARE is a service provided by the library of the University of Amsterdam (http://dare.uva.nl)
Chapter 4

Small Scale dynamos on the solar surface: dependence on magnetic Prandtl number

Irina Thaler & H. C. Spruit

submitted to A&A
4.1 Introduction

In laboratory experiments and numerical simulations of hydrodynamic turbulence, it is found that at sufficiently high Reynold’s numbers the statistical properties of the flow become independent of the value of the viscosity ($\nu$). This observation has been enshrined in the standard cascade picture for three-dimensional (but not two-dimensional) turbulence (Kolmogorov 1941). The addition of a magnetic field introduces a second dissipative mechanism, the magnetic diffusivity $\eta$. By analogy with the hydrodynamics case, an assumption suggesting itself is that a turbulent magnetic flow would also be insensitive to the value of $\eta$, such that it would affect only the small scales in the magnetic field. Experience with numerical MHD simulations, however, has shown this assumption to be unexpectedly problematic. The behavior of turbulent MHD flows, including their bulk transport efficiency and the presence or absence of small-scale dynamo action, appears to vary with details of the problem studied, with the numerical methods used, and in particular to depend on the magnetic Prandtl number of the fluid, $\Pr_m = \nu/\eta$.

The magnetic field at the surface of the Sun is dominated by the sunspot cycle, which is believed to have its source near the base of the convective envelope. At sufficient spatial resolution, a weak field of mixed polarity is also observed. Though it is not clear from the observations if it is a truly separate component, rather than some sort of waste product of the spot cycle, it suggests the possibility that a local small scale turbulent dynamo process is operating near in the surface layers (Durney et al. 1993, Petrovay & Szakaly 1993). This suggestion has been addressed with a number of more idealized turbulent dynamo models and simulations (Cattaneo 1999, Cattaneo et al. 2003). In view of the poorly understood dependence of MHD turbulence on details of the problem studied, these simulations do not yield an unambiguous interpretation of the weak field observed on the Sun. With the advent and spectacular successes of realistic 3-D radiative MHD simulations developed for the solar surface layers (Galsgaard & Nordlund 1996), it has become possible to study the problem numerically for conditions much closer to the solar case, where both Vögler & Schüssler (2007) and Pietarila Graham et al. (2010) reported successful small-scale dynamo generation with such simulations. A range in magnetic Prandtl numbers and Reynolds $R_m$ was investigated, but results were still somewhat inconclusive for the combination of large $R_m$ and small $\Pr_m$. In the work presented here we follow up on these results, with emphasis on the dependence on $\Pr_m$ at high resolution.
4.2 DYNAMOS, FLUCTUATING AND NON-, AT LOW Pr_m

The possibility that macroscopic behavior of MHD could depend critically on magnetic Prandtl number was noted already by Balbus and Hawley (1998), in the context of small-scale dynamo action in accretion disks. An often used model for small-scale dynamo action is the ‘fluctuating dynamo’: a flow driven by an assumed external force acting on a large scale and with a random time dependence. It is intended to be generically applicable to MHD turbulence, and believed to be sufficient to prove dynamo action (but not without controversy, see references in Iskakov et al. 2007). Numerical simulations, however (Schekochihin et al. 2002), showed that the presence of self-sustained magnetic field generation in this model depends critically on magnetic Prandtl number, with dynamo action absent when Pr_m ≤ 1 (viscosity smaller than magnetic diffusivity). The magnetic Prandtl number divides astrophysical systems in two very different regimes. It is usually either very small, as in the case of stellar convective cores, or very large, as in the interstellar/intracluster medium (Schekochihin et al. 2007). At higher Reynolds numbers or numerical resolution, Iskakov et al. (2007) found dynamo action below Pr_m = 1 in the fluctuating model, at low growth rates. The growth rate found increases with magnetic Reynolds number, but at the lowest Pr_m achieved, ≈ 0.1, it was still declining with decreasing Pr_m. The authors expressed their belief that the results indicate a flattening of the growth rate to a finite positive value for Pr_m ↓ 0. Functions that decline continuously to zero would equally fit the data shown in their Fig. 3, however.

The question of dynamo action in fluctuating models therefore does not appear to be settled for astrophysically relevant magnetic Prandtl and Reynolds numbers. The question may actually be academic, however, since the assumption of a random driving force on which it is based is of unknown validity for any physically realistic MHD flow.

A physically realistic yet simple model that does not need an assumed fluctuating forcing is the shearing box model for the flow in an accretion disk. Strong ‘magnetorotational’ turbulence develops in rotating shear flows which are stable in the absence of a magnetic field (such as Keplerian shear). Lesur & Longaretti (2007) and Fromang et al. (2007)(further investigated by Fromang 2010, 2010b, Simon 2011) studied the dependence of magnetorotational turbulence on Pr_m through simulations with explicit viscosity and magnetic diffusivity. The results show that the amount of angular momentum transported increases with the magnetic Prandtl number. A crucial factor was found to be the presence or absence of a (weak) ‘mean vertical field’ (a net flux crossing the disk). In the absence of such a field no dynamo action found at the values Pr_m < 1 that are relevant for most accretion disks.

Since most codes used in astrophysics do not include explicit viscosity or magnetic diffusivity but leave it to the discretization errors or the stabilization algorithms of the
code, the value of $\Pr_m < 1$ to be associated with a simulation is not obvious a priori. The rates of diffusion of momentum and magnetic field can be measured with independent tests of a code, however. Though neither of these represents a physically realistic diffusion coefficient, their ratio would represent an effective magnetic Prandtl number characterizing the numerics. The value found in Fromang et al. (2007) is $\Pr_m \approx 2$; similar numbers have been reported for other codes. This value, in the range where dynamo action is also observed in simulations with explicit diffusivities, explains that magnetorotational turbulence has been obtained in most astrophysical codes. For the results reported below, the code used includes an explicit process for modifying its effective value $\Pr_m$.

The reason for the strong dependence on $\Pr_m$ has been discussed in terms of the ordering of the viscous and resistive length scales (cf. Moffatt 1961). For $\Pr_m \gg 1$, the viscous length scale, where the field stretching takes place, is much larger than the resistive one, which plays then a negligible role (Batchelor 1950, Schekochihin et al. 2004). The situation is quite different for $\Pr_m \ll 1$, when the resistive scale is much larger than the viscous scale. In the limit of large conductivity the field stretching as well as the magnetic dissipation grow exponentially and estimating which of these processes develops faster is hardly possible (Finn & Ott 1988).

### 4.2.1 Transient behavior

A remarkable observation of possible relevance also for the solar case has been made by E. Rempel et al. (2010), who studied the classical shearing box model of magnetorotational dynamo action at $\Pr_m > 1$, for the case where the mean field through the disk vanishes. Dynamo action saturates rapidly (a few orbital time scales) to a statistically steady state, but after a finite time switches off again on an equally fast time scale. Since onset of dynamo action requires a finite seed field to overcome magnetic diffusion, this inactive state is final. The duration of the active phase increases approximately exponentially with increasing $R_m$.

This kind of behavior has been observed in other chaotic systems and is called type-II supertransient behavior. The switch-off is explained as happening when decay-facilitating fluctuations are by chance simultaneously present in all statistically independent subvolumes of the simulation. This happens more readily at low spatial resolution or Reynolds number. In the presence of a finite net flux threading the disk this effect does not take place, since this flux cannot change (cf. Spruit & Uzdenksy 2005 in connection with net flux in accretion disks). Provided it exceeds the minimum value required for MRI instability to grow, it is sufficient to restart the dynamo process when it happened to start decaying in a supertransient accident. The result would just be a
large fluctuation instead of a switch-off.

Generalizing from this experience, the presence of some low level of magnetic flux from an external source may be essential for small-scale dynamo action at any value of the magnetic Prandtl number. Possible relevance for the Sun is discussed in sect. 4.5.

4.2.2 Experimental evidence

Liquid metals have low magnetic Prandtl numbers (of order $10^{-5}$), conveniently in the astrophysically relevant range. Reaching the high Reynolds numbers expected to be needed for dynamo action has been more challenging. The most successful experiment so far has been reported by Monchaux et al. (2007). In a turbulent shearing flow between counter-rotating plates in liquid sodium these authors obtained dynamo action at $R_m \approx 50$ in the form of a steady field with superposed strong fluctuations. This success appeared to be related to a peculiarity of the experimental device. Dynamo action was absent until one of the rotating parts, made of stainless steel (low magnetic permeability), was replaced by an iron part (high permeability and magnetic remanence). The remanent magnetization of the iron part may have played a role. Once magnetized by the steady component of the magnetic field, the iron part would have maintained a minimum field strength in its neighborhood. This is significant in view of the experience (for example in the shearing box simulations mentioned above) that even a weak externally imposed field component strongly facilitates dynamo action. Whatever the precise interpretation, however, the relevance of this experimental result for astrophysics is questionable since astrophysical fluids with the magnetic properties of solid iron are unknown.

Situation for the Sun

Magnetic Prandtl numbers $Pr_m \approx 1$ are accessible with realistic 3D MHD solar surface simulations, and for these values small scale dynamo action has been found (Vögler & Schüssler 2007, Pietarila Graham et al. 2010). In terms of dynamo behavior, $Pr_m = 1$ still belongs to the large magnetic Prandtl number limit, however. In view of the inconclusive results discussed above, the question whether low-$Pr_m$ small scale dynamo action is to be expected on the solar surface is still open.

4.2.3 Indications of solar small-scale dynamo action

Livingston & Harvey (1971) discovered an intrinsically weak small-scale internetwork field on the Sun. It is spread approximately uniformly across the solar disk, and seems
to be independent of the solar cycle. Its properties have been studied in detail by Martin (1988), Martin (1990) and Zirin (1985). Durney et al. (1993) and Petrovay & Szakaly (1993) suggested that this component is due to small scale dynamo action, locally near the solar surface. Alternatively, the weak field component could represent fragments of active regions rising through the convection zone, or as a by-product of the decay of active regions (e.g. Spruit et al. 1987). In this 'decay' hypothesis a correlation between the quiet sun magnetic field and the solar cycle would be expected. The fact that this is not evident in the observations would therefore require that the decay from the large scale magnetic field to the smallest scales exceeds the solar cycle time, in this interpretation (Lites 2011). Parnell et al. (2009) on the other hand find that the magnetic flux distribution between $10^{17} - 10^{23}$ Mx can be described by a single power law function. This would indicate that the whole field is produced by the same process.

Since weak fields tend to be compressed to strong fields by the granulation flow, there is the possibility that (some fraction of) the intrinsically strong small scale magnetic field is unrelated to the sunspot cycle but instead result from a small scale dynamo mechanism. The origin and possible variation of the strong field component is of special interest due to its brightness contribution to the TSI (Schnerr & Spruit 2011, Foukal et al. 2006, Afram et al. 2011, Thaler & Spruit 2014a).

4.3 Calculations

4.3.1 Numerical methods

The numerical simulations were realized with the 3D magnetohydrodynamics code STAGGER, which was developed by Galsgaard & Nordlund (1996). The code solves the time-depended magnetohydrodynamics equations by a 6th order finite difference scheme using 5th order interpolations for the spatial derivatives, while the time evolution is done using a 3rd order Runge-Kutta scheme. For every time step the radiative transfer equation is solved at every grid point assuming local thermal equilibrium. This is done by using a Feautrier-like scheme along the rays with two mu angles plus the vertical and four phi angles horizontally, which adds up to nine angles in total. To incorporate the wavelength dependence of the absorption coefficient, the Planck function is sorted into four opacity bins. The equation of state table is calculated using a standard program for ionization equilibria and absorption coefficients (Gustafsson et al. 1973) and using opacity distribution functions identical with the ones used by Gustafsson et al. (1975) and are further described in Stein & Nordlund (1998), Nordlund (1982), Nordlund & Stein (1990). For a more detailed description of the STAGGER code see Beeck et al. (2012). The horizontal boundaries are periodic, while on the top and
bottom we have open transmitting boundaries. To get the right effective temperature, the density and internal energy of gas flowing in at the lower boundary are kept fixed to control the entropy value. The magnetic field is kept vertical at the lower boundary, thus allowing horizontal displacements of the field lines. At the top boundary the horizontal field components are determined from the vertical component by a potential field extrapolation.

### 4.3.2 Setup

The setup used consists of a box with horizontal dimensions of $3 \text{ Mm} \times 3 \text{ Mm}$ and $1.3 \text{ Mm}$ vertical, extending to $475 \text{ km}$ above the photosphere and $836 \text{ km}$ below. The initial magnetic field configuration consists of a checkerboard pattern with a vertical magnetic field of alternating polarity and strength of $10 \text{ mG}$ or $1 \text{ mG}$. This setup is similar to the one used in Vögler & Schüssler (2007), Pietarila Graham et al. (2010), where in parts of their experiments they used a $4 \times 4$ checkerboard in a box with horizontal dimensions of $6 \text{ Mm} \times 6 \text{ Mm}$ with a vertical depth of $1.4 \text{ Mm}$.

### 4.3.3 Implementation of the magnetic Prandtl parameter in the STAGGER code

The numerical magnetic Prandtl parameter $P_m$ is defined as the ratio between hyper-viscosity and magnetic diffusivity and these are implemented in the STAGGER code in the following way:

\[
\begin{align*}
\frac{\partial \rho}{\partial t} &= -\nabla \cdot \rho \mathbf{u} & (4.1) \\
\frac{\partial \mathbf{B}}{\partial t} &= -\nabla \times \mathbf{E} & (4.2) \\
\mathbf{E} &= - (\mathbf{u} \times \mathbf{B}) + \eta \mathbf{J} & (4.3) \\
\mathbf{J} &= \nabla \times \mathbf{B} & (4.4) \\
\frac{\partial (\rho \mathbf{u})}{\partial t} &= -\nabla \cdot (\rho \mathbf{u} \mathbf{u} + \tau) - \nabla P + \mathbf{J} \times \mathbf{B} - g \rho & (4.5) \\
\frac{\partial e}{\partial t} &= -\nabla \cdot (e \mathbf{u}) - P \nabla \cdot \mathbf{u} + Q_{\text{cool}} + Q_{\text{visc}} + Q_{\text{Joule}} & (4.6)
\end{align*}
\]

where $\rho$, $\mathbf{u}$, $\mathbf{B}$, $\eta$, $\mathbf{J}$, $\tau$, $e$, $P$, $Q_{\text{cool}}$, $Q_{\text{visc}}$, $Q_{\text{Joule}}$ are the density, velocity, magnetic field, electric field, magnetic diffusivity, electric current, viscous stress tensor, inter-

[^1]: [http://www.astro.ku.dk/~kg/Papers/MHD_code.ps.gz](http://www.astro.ku.dk/~kg/Papers/MHD_code.ps.gz)
nal energy, acceleration of gravity, gas pressure, cooling term, viscous dissipation and Joule dissipation, respectively. Regularization of the velocity and magnetic field on small scales is implemented with a hyperviscosity and hyperdiffusion scheme already described in Stein & Nordlund (1998) for the non-magnetic case. The viscous stress is:

$$\tau_{ij} = \frac{1}{2}(e_{ij} + e_{ji}),$$

(4.7)

where

$$e_{ij} = \rho[\nu_{j}(q_{j}\partial_{j}u_{i}) + \nu_{j}(2)|\nabla\cdot u|],$$

(4.8)

$$\nu_{j}^{(1)} = \Delta x_{j}(c_{1}c_{f} + c_{2}|u_{j}|),$$

(4.9)

$$\nu_{j}^{(2)} = \Delta x_{j}^{2}c_{3}|\nabla\cdot u|.$$  

(4.10)

The $\partial_{j}^{\ast}$ indicates that the result of the partial derivative is half a grid point above the location of the input value. $\Delta x_{j}$ is the grid spacing. $|\nabla\cdot u|$ means the absolute value of the negative part of the velocity divergence, so where local convergence occurs. The viscosity contribution $\nu_{j}^{(1)}$ consists of two parts, one is proportional to the fast mode wave $c_{f}$ and stabilizes weak waves, while the second part prevents from ringing at sharp edges of changing quantities. $\nu_{j}^{(2)}$ is proportional to the velocity jump and stabilizes shocks. $c_{1},c_{2}$ and $c_{3}$ are dimensionless parameters. The hyperdiffusive operator $d$ is then defined the following way:

$$d_{x}^{\ast}(f) = \frac{\max_{x \pm 1}|\Delta_{3}f|}{\max_{x \pm 1}|\Delta f|} \partial_{x}^{\ast}(f) = q_{x}(\partial_{x}^{\ast}(f))\partial_{x}^{\ast}(f)$$

(4.11)

It is proportional to the first derivative, which guarantees positive energy dissipation, since the proportional factor $q_{x}$ defined as the hyperdiffusive quenching function, is positive. $\max_{x \pm 1}$ is the maximum over three points in the derivative direction, $\Delta_{3}f$ is the third difference and $\Delta f$ is the first difference of the variable. Making $d$ proportional to the third derivative stabilizes waves and advection, while it damps out high wavenumber perturbations. The resistive part of the electric field is treated in the same spirit:

$$E_{x}^{\eta} = \frac{1}{2} [\eta_{y}^{(1)}q_{y}(J_{x}) + \eta_{z}^{(1)}q_{z}(J_{x})] + \frac{1}{2} [\eta_{y}^{(2)} + \eta_{z}^{(2)}]J_{x},$$

(4.12)
and by cyclic permutation for the other two E-field components. Here

\[
\eta^{(1)}_j = \frac{\Delta x_j}{Pm}(c_1 c_f + c_2 |u_j|),
\]

(4.13)

\[
\eta^{(2)}_j = \frac{\Delta x_j^2}{Pm} c_3 |\nabla \cdot u|_\perp.
\]

(4.14)

\[
\eta^{(3)}_j = \frac{\Delta x_j^3}{Pm} c_4 |\nabla \times u|_\perp.
\]

(4.15)

In this way, the treatment of numerical stabilization and hyperdiffusivity is closely analogous for the flow field and the magnetic field. The parameter \(Pm\) is then a numerical equivalent of the magnetic Prandtl number. Its exact quantitative level cannot be identified directly with a real Prandtl number, however.

### 4.4 Results

A set of simulations was made to investigate the dependence of magnetic field amplification on the numerical magnetic Prandtl parameter \(Pm\). Dependence on numerical resolution, as a proxy for dependence on Reynolds number, was investigated with an additional set of three runs.

Fig. 4.1 shows the dependence on \(Pm\) found. The boundary between presence and absence of dynamo action appears to be close to \(Pm = 2\). In the case \(Pm = 5\) the amplitude of the field increases exponentially with a growth time of \(\sim 200\) min saturating at \(\langle B^2 \rangle^{1/2} \approx 115\) G.

Fig 4.3 shows simulation runs for an initial state of 10 mG and a numerical Prandtl parameter \(Pm = 1\) for different numerical resolutions. The code uses a uniform resolution in the two horizontal coordinates (\(\Delta x\) in Fig. 4.3); the vertical resolution is non-uniform. It is chosen highest near the photosphere where cooling by radiation drives the flows (grid spacing at the photosphere is denoted by \(\Delta z_0\) in the Figure). As the Figure shows, the decay time increases with increasing resolution, from about 50 minutes at \(\delta x = 14\) km to 70 min at 7 km. At the (expensive) resolution of 3.5 km the limited time coverage of the run indicates decay at an even slower rate. Extrapolation to even higher resolution is uncertain from these data, however.

Since the dissipation built into the code decreases with decreasing grid spacing, the inverse of resolution is a numerical analog of a Reynolds number. Since the nature of the numerical dissipation is rather different from physical dissipation and depends strongly on the order of the spatial discretization used, however, it is not possible to translate the grid spacing in our simulations meaningfully into ‘effective’ magnetic Reynolds numbers. The uncertainty is less in the case of the magnetic Prandtl number,
Figure 4.1: Evolution of $\langle B^2 \rangle^{1/2}$ as a function of the numerical magnetic Prandtl parameter $Pm$ for a numerical resolution of $\Delta x = 7$ km and $\Delta z_0 = 6$ km. Solid: initial field strength 10 mG, dashed 1 mG.

since it measures the ratio of two quantities which, though both artificial, are based on the same algorithm.

4.5 Discussion and Conclusions

The results show the same trends as found in the shearing box simulations discussed in the Introduction: the growth rate of dynamo action increases with magnetic Prandtl number, and no dynamo action is detected below a critical value $Pm \approx 1$. As Fig. 4.3 shows, the growth rate appears to increase with numerical resolution, however, and the corresponding critical $Pm$ may increase as well. The combination of high resolution and low $Pm$ required to study this is numerically challenging.

The growth rate we find for the case $Pm = 5$ is comparable with that reported by Pietarila Graham et al. (2010) for their $P_{M,\text{eff}} \approx 2$. Since the numerical Prandtl parameter is not identical with the physical Prandtl number, but depends on the implementation of energy dissipation at small scales in the code, a dependence of the effective Prandtl number scale on code used was to be expected.

Assuming a difference of a factor $\approx 2$ between the scales, the lowest $P_{M,\text{eff}} \approx 1$ reported in Pietarila Graham et al. (2010) would correspond to $Pm \approx 2$ in our simu-
Figure 4.2: $|B_z|$ in kG at the photosphere for $Pm = 5$ after $t=231$ min for a numerical resolution of $\Delta x = 7$ km and $\Delta z_0 = 6$ km. The image scale is exponential ($val^{0.25}$) to amplify small structures and still be able to clearly identify large values.

lations, which we find to be above the threshold for dynamo action. The fact that all results reported by Pietarila Graham et al. show dynamo action is thus consistent with our results.

Taken together, these results make clear that the question of small scale dynamo action in the surface layers of the Sun is still unresolved. As in the case of the fluctuating dynamo model discussed in the Introduction, the limit of a high magnetic Reynolds number (or numerical resolution) combined with low Prandtl number cannot be reliably extrapolated from currently available results.

4.5.1 Relation between intrinsically weak and strong surface fields

Given that the small scale dynamo acts and produces the weak field component, could (some fraction of) the intrinsically strong component originate from it as well? From the results obtained with our simulations this seems unlikely. Our simulation with $Pm = 5$ converged to an average absolute vertical magnetic field strength of about 30 G
at the photosphere (after 230 min simulation time) and small scale magnetic structures of surface fields up to 930 G evolved (see Fig. 4.2), nevertheless no magnetic bright points can be found in bolometric intensity maps, which has as well been reported by Vögler & Schüssler (2007). The reason for this behavior might be that in this mixed-polarity simulations magnetic features of high vertical field strength usually are surrounded by the opposite polarity field and along with the ongoing magnetic field compression process, part of the magnetic flux cancels out. This means that magnetic structures of high field strength remain too small and short lived to be seen as bright features. Contrary to that, in unipolar simulations of the same kind with the same average magnetic field strength, strong magnetic elements were detected after about 10min of simulation time, starting from a homogenous background field (Thaler & Spruit 2014a). Therefore it seems likely that a small scale surface dynamo process, even if actually takes place on the Sun, is not responsible for much of the intrinsically strong field component.

4.5.2 Role of an imposed weak net flux

If the experience with the shearing boxes studied in accretion physics are an indication, the presence of even a relatively weak mean flux density in the simulation may have

---

**Figure 4.3:** Evolution of $\langle B^2 \rangle^{1/2}$ as a function of numerical resolution, for $Pm = 1$ and initial field strength 10 mG.
a significant effect on a dynamo process. In the case of the Sun, remnants of active regions spreading across the surface might have a similar effect, lowering the threshold for dynamo action. The behavior in the limit of low $P_m$ and high $R_m$ at zero mean flux would then be somewhat academic for the solar case. Simulations to address small scale dynamo action in the presence of a dispersed strong field component might then be more relevant. In this case, the issue of the ‘supertransient’ behavior discussed in section 4.2.1 might also be relevant, according to the following speculative scenario.

If it were the case that for solar conditions ($R_m \sim 10^7$, $Pr_m \sim 10^{-5}$) dynamo behavior does not occur in the absence of a mean field, the presence of a weak average field supplied by detritus from active regions could keep a small scale dynamo going. Depending on where this ‘catalytic’ field component is present, this might result in small scale dynamo action to be intermittent, with dynamo action switching off from time to time in supertransients. This would show itself in the form of patchy activity, rather than being present around each and every granule on the surface as a local convective dynamo action would predict.

References

Batchelor, G. K., 1950, Royal Society of London Proceedings Series A, 201, 405-416
Balbus, S. A., & Hawley, J. F. 1998, Reviews of Modern Physics, 70, 1
Finn, J. M. & Ott, E., 1988, Physical Review Letters , 60, 760-763
Kolmogorov, A., 1941, Akademiia Nauk SSSR Doklady, 30, 301
Livingston, W. & Harvey, J., 1971, IAU Symposium, 43, 51,
Thaler, I. & Spruit 2014b, submitted for publication in A&A
Zirin, H., 1985, Australian Journal of Physics, 38, 961-969