DISTRIBUTED VERSUS TACHOCLINE DYNAMOS

Axel Brandenburg
Nordita, Blegdamsvej 17, DK-2100 Copenhagen Ø, Denmark

ABSTRACT

Arguments are presented in favor of the idea that the solar dynamo may operate not just at the bottom of the convection zone, i.e. in the tachocline, but it may operate in a more distributed fashion in the entire convection zone. The near-surface shear layer is likely to play an important role in this scenario.

Key words: Magnetohydrodynamics (MHD) – turbulence – Sun: magnetic fields.

1. RECENT DEVELOPMENTS

The issue of the location of the solar dynamos has been discussed and reviewed in a number of recent papers. Over the past 25 years a general consensus has been developing to place the solar dynamo at the bottom of the convection zone or even beneath it in the overshoot layer. This location also coincides with the tachocline, where the latitudinal differential rotation in the convection zone turns into rigid rotation in the radiative interior. A number of arguments in favor and against both distributed and overshoot dynamos have been collected in Brandenburg (2005). Which of the two scenarios is more viable cannot yet be decided conclusively until more realistic turbulence simulations of the solar dynamo become available.

From a dynamo-theoretic point of view it appears rather difficult to produce $\sim 100$ kG fields that are required in the standard scenario of an overshoot dynamo (D’Silva & Choudhuri 1993, Schüssler et al. 1994, Caligari, Moreno-Insertis, & Schüssler 1995). Looking at a mixing length model of the solar convection zone, the equipartition field strength at the bottom of the convection zone is less than 1 kG, so the dynamo would need to produce a field in excess of a hundred times the equipartition value; see Table 1 where we have used data from stellar envelope models of Spruit (1974). Also, the idea of flux tubes ascending without disrupting through 20 pressure scale heights all the way from the bottom of the convection zones to the top seems nearly impossible.

By contrast, distributed dynamos operating in the entire convection zone would be expected to have sub-equipartition field strengths of around 300 G for the mean field. An important ingredient is the presence of shear; recent simulations (Brandenburg 2005) indicated that not even helicity is essential for producing large scale fields. Occasionally, such simulations produce what looks like bi-polar regions. So, the typical picture of $\Omega$-shaped loops tied to the bottom of the convection zone (Parker 1979) may not be quite accurate, and the whole sunspot phenomenon may be rather more shallow that suggested by the standard picture. Examples of synthetically produced magnetograms are shown in Fig. 1.

In the present scenario the peak fields that emerge at the surface are thought to be the result of local concentrations. According to work by Kitchatinov & Mazur (2000), sunspots are actually the result of an instability of the mean-field equations of radiation magnetohydrodynamics, possibly assisted by negative turbulent magnetic pressure effects (Kleeroin, Mond, & Rogachevskii 1996). These ideas are in some ways similar to the convective collapse of magnetic fibrils (Zwaan 1978, Spruit & Zweibel 1979).

The usual argument against dynamos working in the convection zone proper is that magnetic buoyancy would bring the field to the surface on too short a time scale (Moreno-Insertis 1983). Indeed, buoyant loss of magnetic fields were anticipated when the first compressible simulations of convective dynamo action came out (Nordlund et al. 1992, Brandenburg et al. 1996). The lack of evidence for buoyant loss of magnetic field was explained by the stronger effect of turbulent downward pumping. This idea has recently been studied in much more detail (Tobias et al. 1998, 2001, Dorch & Nordlund 2001, Ossendrijver et al. 2002, Ziegler & Rüdiger 2003).

A more complete list of arguments both in favor and against distributed dynamos versus tachocline dynamos is given in Table 2. For a more complete discussion of the various points see Brandenburg (2005).

An important aspect that requires some appreciation is simply the fact that mean (toroidally averaged) fields close to equipartition strength can actually be produced.
This is an important result because there is a long history of arguments about the very possibility of producing large scale magnetic fields by the famous $\alpha$ effect, starting with the work of Vainshtein & Cattaneo (1992) and Cattaneo & Hughes (1996). Again, this is not the place to attempt reviewing the vast amount of literature that has emerged over the past few years. An excellent review has been given by Ossendrijver (2003). For yet more recent aspects see the review by Brandenburg & Subramanian (2005a).

At the heart of the problem with the $\alpha$ effect is the fact that this and a few other related effects produce large scale magnetic helicity. On the other hand, the total magnetic helicity obeys a conservation law. However, since the total magnetic helicity is the sum of large scale magnetic helicity and small scale helicity, the production of a similar amount of small scale helicity of the opposite sign is required. It is this small scale helicity of the opposite sign that acts to quench and suppress the original $\alpha$ effect (Pouquet, Frisch, & Léorat 1976). In the absence of magnetic helicity fluxes, this leads to a resistively controlled slow-down toward the final saturation of the dynamo (Brandenburg 2001). This behavior is now well reproduced in the framework of the dynamical quenching model (Field & Blackman 2002, Blackman & Brandenburg 2002, Subramanian 2002).

A possible way out of this was suggested first by Blackman & Field (2000a,b) who proposed that small scale magnetic helicity could leave the sun through the surface so as to allow the dynamo to saturate unimpededly; see also Kleeroin et al. (2000, 2002, 2003) for similar work on the galactic dynamo. However, this does not happen just automatically; what is required is an active driving of magnetic helicity flux within the domain toward the boundaries. One such flux was identified by Vishniac & Cho (2001). Their flux works only in the presence of shear; see Subramanian & Brandenburg (2004, 2005), and Brandenburg & Subramanian (2005b). Another important flux would be due to simple advection; see Shukurov et al. (2005). The way the sun could dispose of its excess small scale magnetic helicity might be through coronal mass ejections (Blackman & Brandenburg 2003). Figure 2 shows the dramatic difference between simulations with and without open boundaries. This simulation does have strong shear, which is important for driving the Vishniac & Cho (2001) flux.

### Table 1. Solar mixing length model of Spruit (1974). The equipartition field strength obeys $B_{eq}^2/4\pi = \rho u_{rms}^2$.

| $z$ [Mm] | $H_p$ [Mm] | $u_{rms}$ [m/s] | $\tau$ [d] | $\nu$ [cm$^2$/s] | $2\Omega_0\tau$ | $B_{eq}$ [G] |
|----------|------------|----------------|-----------|----------------|----------------|-------------|
| 24       | 8          | 70             | 1.3       | $1.5 \times 10^{12}$ | 0.6            | 1600        |
| 39       | 13         | 56             | 2.8       | $2.0 \times 10^{12}$ | 1.3            | 2000        |
| 155      | 48         | 25             | 22        | $3.2 \times 10^{12}$ | 10             | 3100        |
| 198      | 56         | 4              | 157       | $0.6 \times 10^{12}$ | 70             | 650         |

### Table 2. Summary of arguments for and against tachocline and distributed dynamos, some of which are discussed in the text. [Adapted from Brandenburg (2005).]

| arguments | tachocline dynamos | distributed/near-surface dynamos |
|-----------|---------------------|----------------------------------|
| in favor  | flux storage        | negative surface shear yields equatorward migration |
|           | turbulent distortions weak | correct phase relation |
|           | correct butterfly diagram with mer. circ. | strong surface shear at latitudes where the spots are |
|           | size of active regions naturally explained | max($\Omega$)/$2\pi = 473$ nHz agrees with $\Omega$(youngest spots) |
| against   | 100 kG field hard to explain | active zones move with $\Omega$(0.95) |
|           | flux tube integrity during ascent | 11 yr variation of $\Omega$ seen in the outer 70 Mm |
|           | too many flux belts in latitude | even fully convective stars have dynamos |
|           | maximum radial shear at the poles | |
|           | no radial shear where sunspots emerge | |
|           | quadrupolar parity preferred | |
|           | wrong phase relation | |
|           | 1.3 yr variation of $\Omega$ at base of CZ | |
|           | coherent mer. circ. pattern required | possible anisotropies in supergranulation |

2. CONCLUDING REMARKS

In this short paper we have summarized just a few of the aspects that appear crucial in determining the location of the solar dynamo. As we have said in the beginning, a full account of these ideas is given in Brandenburg (2005), and have been reviewed in Brandenburg...
The main reason is that a distributed dynamo appears quite plausible, i.e. previous problems have largely been ruled out. Furthermore, from a dynamo-theoretic viewpoint, dynamos operating only in a narrow shell at the bottom of the convection zone appear rather implausible. As far as observational evidence is concerned, one can say that the distributed dynamo scenario is at least not in conflict with observations. Moreover, as expected, the magnetic field drives cyclic variations of the toroidal flow speed (so-called torsional oscillations) with the 11 year cycle period (Howe et al. 2000a, Vorontsov et al. 2002). The amplitude of these flow variations decreases with depth, which is mainly due to the larger mass to be swung around at greater depth. However, if the dynamo really produced 100 kG fields in the overshoot layer, one would eventually expect corresponding flow variations at that depth. Such variations may currently still be below the detection limit, but what is seen are variations with a typical period of around 1.3 year at the base of the convection zone (Howe et al. 2000b).

Another aspect concerns the proper motion of sunspots: young sunspots are known to rotate faster than older ones (Tuominen 1962). This suggests that sunspots may be anchored in the layer where the angular velocity is maximum (Tuominen & Virtanen 1988, Balthasar, Schüssler, & Wöhl 1982, Nesme-Ribes, Ferreira, & Mein 1993, Pulkkinen & Tuominen 1998). The rotational velocity of very young sunspots (age less than 1.5 days) is 14.7°/day at low latitudes (Pulkkinen & Tuominen 1998), corresponding to 473 nHz, which is about the largest angular velocity measured with helioseismology anywhere in the sun. This corresponds to the helioseismologically determined angular velocity at a radius \( r/R = 0.95 \), which is 35 Mm below the surface. Similar conclusions can be drawn from the apparent angular velocity of old and new magnetic flux at different latitudes (Benevolenskaya et al. 1999).

There is still a problem in understanding why the cycle period is 22 years, and not 3 years, which would be the natural frequency for distributed dynamos (Köhler 1973). This is in principle also a problem for overshoot dynamos and it is traditionally “solved” by postulating an overall decrease of the electromotive force. This is obviously not satisfactory. A plausible “excuse” for such an overall decrease of the electromotive force might be a partial alleviation of catastrophic quenching due to magnetic helicity fluxes, mediated by coronal mass ejections. However, at the moment there is no dynamo model taking seriously into account the magnetic helicity losses due to coronal mass ejections. However, this would be a major goal for future work.
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