Flux-dominated solar dynamo model with a thin shear layer

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Flux-dominated solar dynamo models have demonstrated to reproduce the main features of the large scale solar magnetic cycle, however the use of a solar like differential rotation profile implies in the the formation of strong toroidal magnetic fields at high latitudes where they are not observed. In this work, we invoke the hypothesis of a thin-width tachocline in order to confine the high-latitude toroidal magnetic fields to a small area below the overshoot layer, thus avoiding its influence on a Babcock-Leighton type dynamo process. Our results favor a dynamo operating inside the convection zone with a tachocline that essentially works as a storage region when it coincides with the overshoot layer.

1 Introduction

Flux-dominated solar dynamo models, which use a solar like velocity field, together with an estimated diffusivity profile and an $\alpha$ effect resembling the Babcock-Leighton mechanism for producing poloidal magnetic fields, have demonstrated to provide solutions that resemble quite well the observations of the large scale solar magnetic cycle (Dikpati et al. 2004, Chatterjee, Nandy & Choudhuri 2004, Guerrero & de Gouveia Dal Pino 2007, hereafter GDP).

In this kind of models, the usually accepted scenario for the dynamo operation can be described as follows: starting with a dipolar field, the $\Omega$ effect takes place both at the convection zone and the tachocline, and a toroidal magnetic field is formed and amplified by the radial and latitudinal components of the differential rotation. Once this field reaches values between $10^3 \cdot 10^5$ G, it becomes buoyant unstable and arises through the convection zone being twisted by the Coriolis force until it emerges at the surface and forms bipolar magnetic regions. This part of the process is known as Babcock - Leighton $\alpha$ effect. At the surface, the leading part of a bipolar region points to the equator, while the rear part is drifted polarward by the meridional circulation. This migration contributes to the formation of big loops in each hemisphere, which later will reconnect in order to form a new poloidal field of opposite polarity to the initial one.

In view of the present status of the observations, the model proposed above presents several problems, as remarked by Brandenburg (2005), the most important of which is related to the location, the sign and the amplitude of the alpha effect. In the scenario discussed above, the $\alpha$ term should reproduce the emergence of magnetic flux tubes of strong toroidal magnetic fields and then the migration of these fields toward the poles. In this way, the most probable location for the dominance of this term would be the upper layers of the convection zone, with a latitudinal distribution peaking around $30^\circ$, which is the latitude at which the strongest magnetic activity is observed. If the solar dynamo is operating at the tachocline, where the shear has positive values, the natural sign of the alpha effect should be negative (positive) in the north (south) hemisphere, and still give the correct migration. Recent works have suggested that the amplitude of the $\alpha$ term could be important in the determination of the parity of the dynamo (Dikpati & Gilman 2001, Bonnaro et al. 2002), this effect is not considered in this work since our domain corresponds to one hemisphere only, but it will be addressed in a forthcoming paper (Guerrero & de Gouveia Dal Pino 2007, in preparation).

Another important question regards the real importance of the tachocline in the dynamo process. As a layer of strong radial shear, the tachocline could be the ideal site for the amplification of the magnetic field, though the maximum amplitude of the shear is located at high latitudes, which suggests an intense activity close to the poles. In this case, meridional circulation could be again an appropriate solution to this problem, since a velocity of about $3 \text{ m s}^{-1}$ could advect down and equatorward the magnetic field across a stable layer until reaching the latitudes where the strong activity is observed (Nandy & Choudhuri 2002, Chatterjee et al. 2004). However, the use of a deep meridional flow in a flux dominated dynamo has been found to be very sensitive to the adopted $\alpha$ effect and the diffusion and velocity profiles (Guerrero & Muñoz 2004) and can also generate...
undesirable abundance variations in the convection zone. In addition, several numerical simulations (Gilman & Miesch 2004, Rüdiger, Kitchatinov & Arlt 2005) have demonstrated the impossibility of penetration of the meridional flow below the tachocline more than a few kilometers. In order to allow some shallower penetration, other possibilities, such as overshooting or turbulent magnetic pumping have been invoked in the literature (Rogers, Glatzmaier & Jones 2006, Ziegler & Rüdiger 2003, respectively), where magnetic flux tubes are drifted to the overshoot layer and can be amplified to the desired magnitudes.

Indeed, if a flow penetrates inside the tachocline, there should be a mechanism that could prevent either the formation of strong toroidal magnetic fields at higher latitudes or the participation of these fields in the cycle which is responsible for the observed phenomena. In recent work (GDP), we have shown that a possible solution to the problem above could be the choice of an appropriate set of physical parameters, since the model is sensitive to the location of the transition between the sub-adiabatic and the super-adiabatic layers, to the diffusivity value at the bulk of the convection zone and to the thickness of the solar tachocline (see Figs. 8a and 8b of GDP). We have also found that the latitudinal shear term is dominant over the radial shear term throughout the cycle, and that the radial shear peaks only in the early years of the cycle and decays afterward to values about two orders of magnitude smaller than the latitudinal component.

In this paper, we present a detailed description on how the suppression of the magnetic fields at high latitudes is obtained. We also present the results when two different prescriptions for the meridional circulation profile are employed. They seem to be insensitive to these variations.

Table 1 Parameters employed in the present model compared to those of GDP. \( U_0 \) is the maximum amplitude of the meridional circulation at the surface, \( R_p \) is the penetration depth of the flow, \( \beta_1 \) and \( \beta_2 \) fit the latitudinal profile of the meridional circulation to the helioseismology results, \( \eta_c \) and \( \eta_s \) are the values of the magnetic diffusivity at the convection zone and at the surface, respectively.

| Parameter | Value in GDP | Present value |
|-----------|--------------|--------------|
| \( U_0 \) | 25 m s\(^{-1}\) | 10 m s\(^{-1}\) |
| \( R_p \) | 0.69 \( R_\odot \) | 0.70 \( R_\odot \) |
| \( \beta_1 \) | 6.06 \( \times \) 10\(^{-9}\) cm\(^{-1}\) | 3.47 \( \times \) 10\(^{-10}\) cm\(^{-1}\) |
| \( \beta_2 \) | 4.6 \( \times \) 10\(^{-9}\) cm\(^{-1}\) | 1.39 \( \times \) 10\(^{-10}\) cm\(^{-1}\) |
| \( \eta_c \) | 5 \( \times \) 10\(^{-9}\) cm\(^2\) s\(^{-1}\) | 3 \( \times \) 10\(^{-11}\) cm\(^2\) s\(^{-1}\) |
| \( \eta_s \) | 1 \( \times \) 10\(^{-12}\) cm\(^2\) s\(^{-1}\) | 3 \( \times \) 10\(^{-12}\) cm\(^2\) s\(^{-1}\) |

of the parameters, as indicated in Table 1. We note that, as in GDP (see Fig. 3 of that work) we have considered two different profiles for the magnetic diffusivity in the convective zone. In a thin layer near the top, we have assumed a supergranular diffusivity, while in the inner region of the convective zone we have adopted a lower value. Indeed, there is no physical reason why this value should be smaller than that near the top. However, if we take the same large value (10\(^{12}\) cm\(^2\) s\(^{-1}\)) for the entire convection zone, the dynamo will enter in the diffusion dominated regime. Another important alteration is the location of the eruption of the magnetic flux tubes. In GDP, the toroidal magnetic fields are transported from the top of the tachocline, i.e. \( r_c \propto B_\phi(R_c + \Delta_1/2) \) (where \( B_\phi \) is the azimuthal component of the magnetic field, and \( R_c \) is the location of the center of the tachocline of thickness \( \Delta_1 \)), while in the present work the eruption point is placed in the middle of the overshoot layer (\( r_c = 0.715 R_\odot \)), see the dashed line in the snapshots of Fig. 1). Besides being more realistic, this assumption allows us to make direct comparisons with the stability analysis of magnetic flux tubes in the overshoot layer (see Fig. 1 of Ferriz-Mas & Schüssler 1994).\(^2\)

Fig. 1 displays four snapshots of the evolution of the toroidal magnetic field (in color-scale) and poloidal field (lines) for four different stages of a half (11-year) cycle. The top, middle and bottom panels correspond to a thin, intermediate and a thick tachocline, respectively. As it can be seen, at the beginning of each new cycle, toroidal magnetic fields start to be formed at two different places: one part inside of the convective layer, around 70 degrees, where the poloidal shear term has its maximum value; and another one at the tachocline, very close to the poles where the radial shear reaches its maximum amplitude.

When a thin tachocline is considered (top of Fig. 1), the toroidal field generated at the poles remains confined below the center of the overshoot layer. At the place where we consider the eruption of the magnetic flux tubes, this high latitude toroidal field does not reach the necessary values

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1. For sake of simplicity we have not included in our induction equation a diamagnetic diffusion term which could be important when gradients of turbulent diffusivity are present (see e.g., Kitchatinov & Rüdiger, 1992)

2. We note that this scheme is slightly different from the one assumed by Dikpati et. al. (2004), who take the average value for the toroidal magnetic field along the overshoot layer.
Fig. 1  Snapshots of the positive (negative) toroidal field contours are shown in blue (red) scale together with the field lines of the positive (negative) poloidal field in continuous (dashed) lines, for four different times (T/8, T/4, 3T/8 and T/2) along a half 11-year cycle. The upper (a), middle (b) and bottom (c) panels present the same snapshots for models with a thin (0.02R☉), intermediate (0.06R☉) and thick (0.1R☉) tachocline.

to become buoyant. This effect can be seen also in the upper panel of Fig. 2, where a time-latitude butterfly diagram for the contours of both, the toroidal magnetic field at r_c (lines) and the radial magnetic field (grey scale background) at the surface are shown. The contours for the toroidal field are equally log-spaced for amplitudes above 5 × 10^4 G, which is the value at which the buoyancy begins to develop. Along with the confinement, we can note that the high latitude toroidal field diffuses very efficiently since its generation stops, as quickly as, the radial shear component decreases. On the other hand, the field which is developed inside the convection zone is advected down and equatorward by the meridional flow, subtly penetrating the tachocline and reaching values above 5 × 10^4 G. The snapshots show that when the toroidal fields are going downward, the toroidal magnetic field for the new cycle begins to be formed. The appearance of this new field seems to dislocate the older one and cause an additional push downward.

The middle (b) and bottom (c) panels of Fig. 1 show the same stages of the cycle for models with an intermediate and a thicker tachocline. These diagrams show that the radial shear, in spite of having a smaller amplitude than in the previous case, is distributed along a larger area, so that a larger portion of magnetic field is amplified leading to a strong solar activity at high latitudes which is incompatible with the observations. Note that this result differs from the one previously obtained in GDP due to the distinct location of the domain of influence of the α effect. When the buoyancy point is placed in the center of the overshoot layer, as in the present case, only a thin tachocline is able to lead to solar like results (top panel of Fig. 2).

We have also tested the validity of this mechanism to avoid the formation of high latitude toroidal fields with another meridional circulation profile. The bottom panel of Fig. 2 shows the butterfly diagram obtained with the analytical profile used by Dikpati & Charbonneau (1999). We
Fig. 2  Time-latitude butterfly diagram for the model of Table 1 and top of Fig. 1 with a thin tachocline (top panel), and for the meridional circulation profile used by Dikpati & Charbonneau 1999 (bottom panel). The continuous (dashed) lines represent the positive (negative) strength of the toroidal field at the center of the overshoot layer \( (r_c=0.715 R_\odot) \). The lines are log-spaced and cover the interval between \( 5 \times 10^4 - 10^5 \, \text{G} \). The background gray scale represents the positive (dark) and negative (clear) radial field at the surface.

note that it reproduces quite well the observations, with the butterfly wings of the toroidal field only below \( \sim 45 \) degrees and with a half cycle period of 15 years.

Finally, we have also performed simulations similar to those of Fig. 2, but (artificially) turning off the radial shear term (i.e. \( \partial \Omega / \partial r = 0 \)) in the induction equation (see, e.g. equations 1 and 2 of GDP) and found that the latitudinal distribution of the toroidal magnetic fields remains unaltered in the butterfly diagrams. This result indicates that the fields generated in the tachocline do not significantly contribute to the observed activity, suggesting that in a flux dominated solar dynamo process with a Babcock-Leighton \( \alpha \) effect the real role of the tachocline is to be, essentially, a storage region, provided that it coincides with the overshoot layer. This is in agreement with the conclusions of Dikpati, Gilman & MacGregor (2005).

4 Conclusions

We have described a physical scenario in which a simple flux-dominated solar dynamo model with an appropriate set of parameters produces results which are in good agreement with the observations. The main assumptions and results are summarized below:

1. Since an analysis of the evolution of the maximum of the shear terms along the cycle shows that the latitudinal shear is always dominant over the radial one (which attains appreciable values only during the first years and quickly decays afterward), a possible mechanism to prevent the formation of toroidal magnetic fields by the radial shear at high latitudes could be the consideration of a thin tachocline. In this case, we find that the dynamo will form a thin layer of toroidal field below the overshoot layer with insufficient amplitude to produce buoyant flux tubes. Several numerical tests have demonstrated the robustness of this assumption in order to avoid the appearance of sunspots near the poles.

2. The bulk of the toroidal magnetic field is formed at the interior of the convection zone thanks to the latitudinal shear and is drifted by convection and/or magnetic pumping towards the sub-adiabatic overshoot layer where we assume that it undergoes magnetic buoyancy and rises to the surface at values above of \( 5 \times 10^4 \, \text{G} \). Note that the turbulent diamagnetism (which was mentioned in the section 2) may also play an important role in order to pile-up the toroidal magnetic field in the overshoot layer, since it behaves like a downward velocity term in the induction equation, as demonstrated by Kitchatinov & Rüdiger (1992). The importance of this term has not yet been studied in detail, but will be considered in forthcoming studies.

3. The above mentioned results suggest that the dynamo which is responsible for the observed activity does not operate at the tachocline, as usually assumed, but inside the convection zone and is due to the strong latitudinal shear. In this sense, the real role of the tachocline, if it coincides with the overshoot layer, is to store the magnetic flux tubes until they reach the necessary amplification to become buoyantly unstable.

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