First Asia-Pacific Solar Physics Meeting
ASI Conference Series, 2011, Vol. 2, pp 143–147
Edited by Arnab Rai Choudhuri & Dipankar Banerjee

Quenching of the alpha effect in the Sun – what observations are telling us

R. H. Cameron*
Max-Planck-Institut für Sonnensystemforschung, Katlenburg-Lindau, Germany

Abstract. The Babcock-Leighton type of dynamo has received recent support in terms of the discovery in the observational records of systematic cycle-to-cycle variations in the tilt angle of sunspot groups. It has been proposed that these variations might be the consequence of the observed inflow into the active region belt. Furthermore simulations have shown that such inflows restrict the creation of net poloidal flux, in effect acting to quench the alpha effect associated with the Coriolis force acting on rising flux tubes. In this paper we expand on these ideas.

Keywords : Sun: dynamo – MHD

1. Introduction

The Babcock-Leighton type of dynamo has received recent support: following the discovery by Dasi-Espuig et al. (2010) of systematic cycle-to-cycle variations in the tilt angle of observed sunspot groups, Cameron et al. (2010) used the Surface Flux Transport Model to show that the polar field at the end of cycle n is correlated with the strength of cycle n+1 for cycles 13-21 (Cameron et al. 2010). This strengthens the result from direct observation of the field which only covered cycles 20-23. The observations thus strongly suggest the solar dynamo is of the Babcock-Leighton type.

The Babcock-Leighton dynamo is essentially linear in its description, and does not comment on what limits the strength of the different cycles. We can easily see that it must involve a modification of the flow field, so the question becomes one of where, and on what scales, does the magnetic field affect the flow. In the traditional alpha quenching of mean-field dynamos the flows are modified on small scales and in the region where there is toroidal field. Kitchatinov & Olemskoy (2011), however, note

*email: cameron@mps.mpg.de

that in Babcock-Leighton dynamos the alpha effect occurs in a different location (in the bulk of the convection zone or near the solar surface) to where the strong toroidal fields are stored (the bottom of the convection zone). They argue that traditional alpha quenching does not apply in this case. The rest of this paper outlines an observationally suggested mechanism for quenching the alpha effect associated with the Coriolis force acting on rising flux tubes.

2. Schematic outline of the Babcock-Leighton dynamo and the non-linear feedback

The basic Babcock-Leighton dynamo mechanism is illustrated by the blue boxes and brown arrows in Fig. 1. From top to bottom, we begin with toroidal flux near the bottom of the convection zone, then an instability (Parker 1966; Spruit & van Ballegooijen 1982), or series of instabilities (e.g., the instability described in Rempel & Schüssler 2001, followed by that in Parker 1966) leads to a flux tube buoyantly rising to the surface. The Coriolis force is thought to tilt the tube during its rise (D'Silva & Choudhuri 1993). As a consequence of the twist, when the flux emerges at the surface in the form of sunspots, the leading spots are slightly closer to the equator than the following spots. Over a period of about a month the spots breaks up into faculae, which is acted on by the systematic meridional flow and differential rotation, as well as the random (on the scale of the magnetic field) granular and supergranular flows. The random flows can be treated as a type of diffusion on the timescales relevant for the solar cycle. Whilst most of the flux is advected towards the nearest pole, some diffuses across the equator. Because the leading polarity flux is slightly closer to the equator than the following polarity, the equator-crossing flux is preferentially of the leading spot polarity in both hemispheres and hence in each cycle there is net flux reaching the pole. The dynamo model relies on this imbalance being sufficient to reverse the polar field. The polar field is then associated with poloidal flux threading the sun which then gets wound up by differential rotation to provide the new toroidal flux (of the opposite sign to that previously present) at the base of the convection zone. This closes the loop (of half a 22-year magnetic cycle).

The surface part of the model is enclosed in the red dashed line in Fig. 1, and it is this part which is also dealt with by the Surface Flux Transport Model (SFTM). The historical record of sunspot emergence and cycle-averaged tilt angles can be fed in as inputs to the SFTM and the surface field therefrom extrapolated outwards using the Current Sheet Source Surface model (Zhao & Hoeksema 2010). The resulting polar field and interplanetary field are then retrieved as outputs. Cameron et al. (2010) used this approach, found that the resulting interplanetary field matches that inferred from measurements of the geomagnetic-*aa* index, and that the polar fields were well correlated with the activity level of the next cycle. Important in the current context is that the polar field is essentially proportional to the activity level of the next cycle, with the linear fit passing close to the origin.

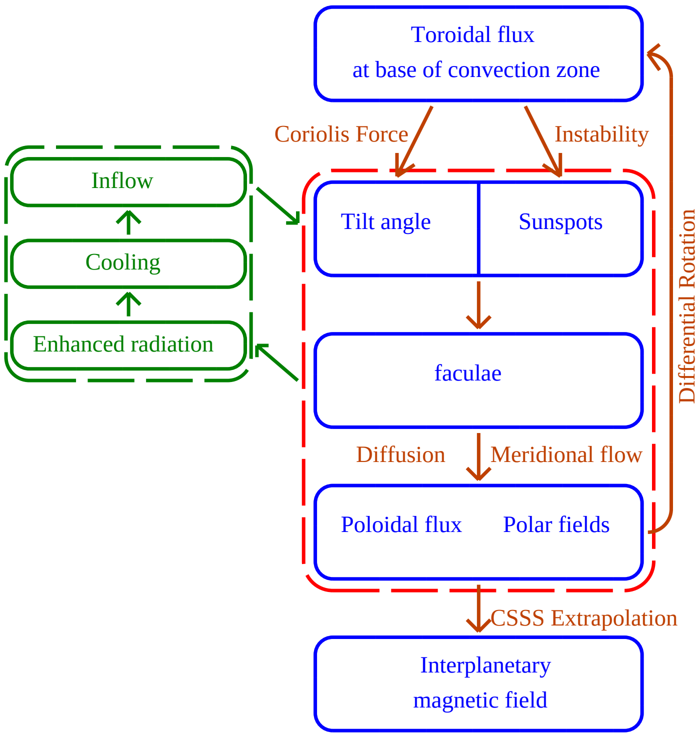

Figure 1. Schematic illustration of how the surface flux transport model (inside the red dashed box) is embedded in the Babcock-Leighton dynamo model (blue boxes) and how the enhanced radiation associated with facular regions can lead to what is essentially alpha quenching.

The fact that the relationship between the polar field and the activity of the next cycle is linear allows us to localize the saturation mechanism in the conceptual illustration. Because the polar field of cycle n is linearly related to the activity of cycle $n + 1$ it follows that the winding up of the poloidal field by differential rotation is, in the Sun, a linear process. Similarly the condition for toroidal flux to erupt from the base of the convection zone cannot vary strongly from cycle to cycle. The nonlinearity responsible for the saturation must therefore be in one or more of: the tilt angles, the granular/supergranular diffusivity or the meridional flow. Since the granular and supergranular properties do not vary much with the cycle (see the review by Rieutord & Rincon 2010) the nonlinearity must be in some combination of the tilt angle and meridional flow.

The required types of changes are observed in both the near-surface velocity field (Haber et al. 2002) and in the tilt angles of sunspot groups (Dasi-Espuig et al. 2010). In fact, the two types of observations are not independent. As suggested by Dasi-Espuig et al. (2010), the observed changes in the tilt angles could be produced by the observed local changes of the meridional flow. The change in the meridional flow has itself been explained by the observed difference in radiance between bright facular regions and undisturbed quiet-Sun regions. We can then reconstruct a likely logic chain for the reduction of the tilt angle. It is sketched in the green boxes in Figure 1. The bright faculae is associated with an enhanced emission, which cools the plasma in the facular regions slightly more efficiently then in the surrounding quiet-Sun. This produces a small temperature difference which drives the observed inflow into the activity belt. The scenario here was proposed by Spruit (2003) and was simulated and compared to the helioseismic results by Gizon & Rempel (2008). The inflow, in turn, reduces the latitudinal separation of the opposite polarities of sunspot groups (observed tilt angle reduction). Idealized calculations by Jiang et al. (2010) show that the effect of the inflows on the poloidal flux is significant.

Because the inflows are caused by activity, their strength should increase with activity, and indeed Cameron & Schüssler (2010) showed how the observed time dependence of the inflow can be modeled as the integral of local inflows assumed to be proportional to the local field strength. The calculations of Jiang et al. (2010) show that the amount of net flux escaping to the poles decreases with increasing strength of the inflows. The activity-related inflows therefore act to quench the alpha effect associated with rising flux tubes: strong cycles have a large amount of surface field, which drives strong inflows and reduces the latitudinal separation between the opposite polarities in sunspot groups. It is worth emphasising that the inflow is the integral of the flows produced by individual active regions. The weak integrated inflow of a weak cycle is less able to affect the tilt angles of sunspot groups than the strong integrated inflow of a strong cycle. This is so even though the sizes and strengths of individual active regions of strong and weak cycles are drawn from the same distribution (Jiang et al. 2011). In this way it differs from some of the other mechanisms which affect the tilt angle of active regions, such as those studied by D'Silva & Choudhuri (1993) and Nandy, D. (2002), in that it explicitly links the change in the tilt angles to the properties of the cycle during which they emerge. The inflows thus act as a non-local (in the sense that the inflows are driven by other active regions and plage) alpha quenching mechanism.

In passing we also comment that there is still some debate (Švanda & Zhao 2008) over whether the meridional inflow has a component which is delocalized with respect to the magnetic activity. However since newly emerging regions do not avoid existing active regions (rather they appear to preferentially emerge in them, Harvey & Zwaan 1993) this does not greatly affect the argument.

3. Conclusion

Solar dynamo theorists appear to be fortunate: observations suggest that an important mechanism for quenching the alpha effect associated with rising tubes is present at the solar surface, where it can be observed. Furthermore, the flows involved are large scale, and have been mapped below the surface. Our good fortune is based on the fact that, on the Sun, faculae are substantially brighter than the quiet-Sun; energetically, the power associated with the radiance variations integrated over a cycle has been estimated to be similar to that of the magnetic field (Schüssler 1996) and is in phase with the magnetic activity. This need not be the case for other stars (Beeck, Schüssler & Reiners 2011), and if the net brightness enhancement due to activity becomes too weak (or becomes a brightness deficit) than the quenching mechanism we have identified here will not apply. In such cases the expectation is that the cylces would have larger amplitudes and some other non-linearity would be responsible for the saturate. There are indications that stars where the brightness fluctuations are anticorrelated with the cyclic activity have stronger field strengths Radick et al. (1998), however such stars differ in other systematic ways and other causes of the stronger activity are possible. Future work will see if testable predictions for a range of other types of stars can be made for future asteroseismology missions such as PLATO.

References

Beeck B., Schüssler M., Reiners A., 2011, ArXiv e-prints

Cameron R. H., Jiang J., Schmitt D., Schüssler M., 2010, ApJ, 719, 264

Cameron R. H., Schüssler M., 2010, ApJ, 720, 1030

Dasi-Espuig M., Solanki S. K., Krivova N. A., Cameron R., Peñuela T., 2010, A&A, 518, A7+

D'Silva S., Choudhuri A. R., 1993, A&A, 272, 621

Gizon L., Rempel M., 2008, Sol. Phys., 251, 241

Haber D. A., Hindman B. W., Toomre J., et al. 2002, ApJ, 570, 855

Harvey K. L., Zwaan C., 1993, Sol. Phys., 148, 85

Jiang J., Cameron R. H., Schmitt D., Schüssler M., 2011, A&A, 528, A82

Jiang J., Işik E., Cameron R. H., Schmitt D., Schüssler M., 2010, ApJ, 717, 597

Kitchatinov L. L., Olemskoy S. V., 2011, Astr. Lett., 37, 286

Nandy D., 2002, Ap&SS, 282, 209

Parker E. N., 1966, ApJ, 145, 811

Radick R. R., Lockwood G. W., Skiff B. A., Baliunas S. L., 1998, ApJS, 118, 239

Rempel M., Schüssler M., 2001, ApJ, 552, L171

Rieutord M., Rincon F., 2010, Living Reviews in Solar Phys., 7, 2

Schüssler M., 1996, in Solar and Astrophysical Magnetohydrodynamic Flows, ed. K. C. Tsinganos and A. Ferrari, 17–37

Spruit H. C., 2003, Sol. Phys., 213, 1

Spruit H. C., van Ballegooijen A., 1982, A&A, 106, 58

Švanda M., Kosovichev A. G., Zhao J., 2008, ApJ, 680, L161

Zhao X., Hoeksema J. T., 1995, Space Sci. Rev.189-192