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Solar dynamo model with nonlocal alpha-effect and diamagnetic pumping

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Abstract. Sunspot data and large-scale solar magnetic field data are used to demonstrate the operation of the Babcock-Leighton mechanism on the Sun. A dynamo model is developed that employs jointly a nonlocal alpha-effect of the Babcock-Leighton type and diamagnetic downward pumping. The pumping concentrates magnetic fields to the base of the convection zone. The magnetic cycle period, equatorial symmetry of the generated fields, their meridional drift, and the polar-to-toroidal field ratio obtained in the model agree with observations.

Keywords. Sun: activity, Sun: dynamo

Does the Babcock–Leighton mechanism operate on the Sun? We believe that the contribution of the Babcock-Leighton mechanism to the global poloidal field for individual activity cycles can be estimated by the parameter,

$$B = \sum_i S_i \ell_i \sin \alpha_i, \tag{1}$$

where summation is over all bipolar active regions of a given cycle, S_i is the area of the largest spot in the region, ℓ_i is the distance between centers of opposite polarities, α_i is the inclination angle, and the parameters are taken at the time of maximum development of a group of sunspots.

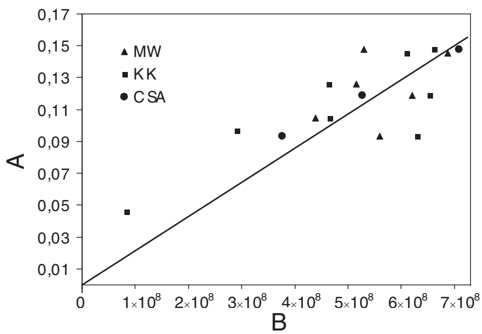

Figure 1. Correlation of the B-parameters (1) of individual solar cycles with A-index of the poloidal field amplitude (Makarov *et al.* 2001) for the subsequent minima of solar activity. The B-parameter was estimated using sunspot data of Mount Wilson (triangles) Kodaikonal (squares) and Pulkovo (circles) observatories.

The B-values (1) were estimated using the partly digitized sunspot data of the Mount Wilson and Kodaikanal observatories (http://www.ngdc.noaa.gov/ngdcinfo/onlineaccess.html) and the CSA catalogue of Pulkovo Observatory (http://www.gao.spb.ru/database/csa/groups_e.html). The high correlation of the B-values with the amplitudes A of the global poloidal field at subsequent activity minima (Fig. 1) encourages us to conclude that the Babcock-Leighton mechanism operates on the Sun. Dasi-Espuig *et al.* (2010) arrived at the same conclusion by analyzing the same data using another method.

Model design. The Babcock-Leighton mechanism is included in our dynamo model via a non-local alpha-effect, which generates the poloidal field near the surface from a deep toroidal field. The model allows for the effect of diamagnetic pumping of the mean magnetic field with an effective velocity $\boldsymbol{V}_{\rm dia} = -\boldsymbol{\nabla}\eta_{\rm T}/2$; $\eta_{\rm T}$ is the turbulent magnetic diffusivity. Meridional flow with the structure of one cell/hemisphere is specified after the global solar circulation model of Kitchatinov & Olemskoy (2011). The dynamo model evolves the mean axisymmetric magnetic field numerically with time in the spherical shell of the convection zone. The model belongs to the distributed type by its numerical design but it realizes an interface dynamo.

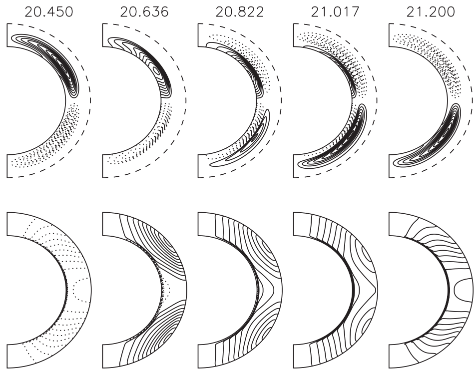

Figure 2. Contours of toroidal field strength (top row) and poloidal field lines (bottom row) for several instances of a modeled magnetic cycle. The pictures of the upper row are rescaled so that the upper (dashed) boundary shows a radius $r = 0.74R_\odot$. The bottom boundary is at $r = 0.7R_\odot$. Time in diffusive units, $R_\odot^2/\eta_{\rm T}$, is shown at the top. Solid (dotted) lines show positive (negative) levels and clockwise (anti-clockwise) circulation.

Model results. The simulated magnetic fields are highly concentrated at the base of the convection zone (Fig. 2) due to the downward diamagnetic pumping. The near-base concentration of the poloidal field allows differential rotation to wind a strong toroidal field over a solar cycle time so that the amplitude of the toroidal field in the model is about one thousand times stronger than the surface polar field.

Magnetic diffusivity near the base of the convection zone is relatively small. As a result, the 11-year period of solar cycles is reproduced with the standard mixing-length value of eddy diffusivity, $\eta_{\rm T} = 10^{13}{\rm cm}^2/{\rm s}$, in the bulk of the convection zone. Concentration of the field in the low-diffusivity region favors the equator-antisymmetric dynamo modes (Chatterjee *et al.* 2004). Accordingly, our model always results in magnetic fields of dipolar parity.

The equatorward meridional flow in the low-diffusivity near-bottom region produces equatorial migration of the deep toroidal field. The effect of the meridional flow in the bulk of the convection zone, where the diffusivity is relatively large, is small. The model avoids high polar concentration of the poloidal field typical of advection-dominated dynamos.

We conclude that a combination of diamagnetic pumping with a nonlocal α-effect in a solar dynamo model helps to improve agreement with observations.

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