Does the Babcock–Leighton Mechanism Operate on the Sun?

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Abstract—The contribution of the Babcock–Leighton mechanism to the generation of the Sun’s poloidal magnetic field is estimated from sunspot data for three solar cycles. Comparison of the derived quantities with the A-index of the large-scale magnetic field suggests a positive answer to the question posed in the title of this paper.

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INTRODUCTION

The dynamo theory explains the magnetic activity of the Sun by the action of two main effects: the generation of a toroidal field from a poloidal one by differential rotation (the \(\Omega\)-effect) and the inverse transformation of the toroidal field to the poloidal one by small-scale cyclonic motions (the \(\alpha\)-effect). The magnetic field generation mechanism based on these two effects is called \(\alpha\Omega\)-dynamo (see, e.g., Vainshtein et al. 1980).

The relatively simple \(\Omega\)-effect has been studied extensively and its presence on the Sun is confirmed by observations. The rotation of sunspots (Newton and Nunn 1951) and direct Doppler measurements (Howard and Harvey 1970) determine the latitude dependence of the rotation rate on the solar surface. Using this dependence, helioseismology finds the angular velocity distribution in the solar interior (Wilson et al. 1997; Schou et al. 1998). The differential rotation changes little with time (LaBonte and Howard 1982), contains no small-scale inhomogeneities, and, in this sense, is regular. Therefore, one may expect the toroidal field strength and the related sunspot activity at solar maximum to be determined by the poloidal field strength at the preceding minimum. This circumstance was first pointed out by Schatten et al. (1978). Makarov and Tlatov (2000) and Makarov et al. (2001) found a high correlation between the A-index of the large-scale field at activity minimum proposed by them and the amplitude of the succeeding maximum. For three solar cycles for which direct measurements of the polar field at activity minima are available, the measured field strengths also correlate with the amplitudes of the succeeding maxima (Jiang et al. 2007).

The situation with the \(\alpha\)-effect is completely different. Several causes for the emergence of this effect are known. It can appear due to density inhomogeneity in a turbulent rotating
medium (Parker 1955) and turbulence intensity inhomogeneity (Steenbeck et al. 1966). Magnetostrophic waves at the base of the solar convection zone can give rise to it (Schmitt 1987). Finally, the poloidal magnetic field generation mechanism proposed by Babcock (1961) and Leighton (1969) is also a variety of the $\alpha$-effect. The Babcock–Leighton mechanism deserves special attention for two reasons. First, in contrast to other varieties of the $\alpha$-effect, it is not subject to the so-called catastrophic quenching due to the conservation of magnetic helicity (Kitchatinov and Olemskoy 2011a, 2011b). Therefore, it is quite possible that the Babcock–Leighton mechanism is dominant in the generation of the Sun’s poloidal field. Second, this mechanism is related to the observed characteristics of solar active regions; therefore, its contribution to the magnetic field generation can be estimated from observational data. In this paper, we make such an estimate for three solar cycles.

Sunspots are most likely associated with the emergence of toroidal fields from deep layers of the Sun (see, e.g., Parker 1979). The $\alpha$-effect transforms the toroidal fields into poloidal ones. Therefore, one may expect the poloidal field at solar minimum to correlate with the sunspot activity of the preceding cycle. However, observations reveal no such correlation (Makarov and Tlatov 2000; Makarov et al. 2001). This can be due to random fluctuations of the $\alpha$-effect. Not only the toroidal field strength but also the characteristics of the $\alpha$-effect responsible for the transformation of this field to the poloidal one are important for the poloidal field generation. Random fluctuations of the $\alpha$-effect break the functional relation between the toroidal and poloidal magnetic field components (Jiang et al. 2007; Moss et al. 2008). Nevertheless, the contribution of the Babcock–Leighton mechanism to the poloidal field generation, including the existing fluctuations, can be estimated from sunspot data. In this paper, we make such an estimate.

THE METHOD

The Babcock–Leighton mechanism is associated with the so-called Joy’s law for active regions on the Sun. The law asserts that the preceding (leading in the rotational motion) sunspots of bipolar groups are, on average, closer to the equator than the following ones. Thus, on average, there is a (positive) tilt of the line connecting the centers of opposite polarities to the solar parallels (Fig. 1). The average tilt angle $\alpha$ increases with latitude, suggesting that Joy’s law is related to the effect of the Coriolis force on the rising magnetic loops (Wang and Sheeley 1989).

Since the tilt angle $\alpha$ is finite, the magnetic field of active regions contains a poloidal component. During the decay of active regions and subsequent turbulent diffusion over the solar surface, this component will contribute to the Sun’s global poloidal field. We believe that the total contribution of active regions in an individual solar cycle to the poloidal field is proportional to

$$B = \sum_i S_i \ell_i \sin \alpha_i,$$

(1)
where the summation is over all active regions and the summable quantities are taken during the maximum development of the sunspot group. The quantities on the right-hand side of the formula are explained in Fig. 1: $S_i$ is the area of the largest sunspot in the group, $\ell_i$ is the separation between the centers of opposite polarities, and $\alpha_i$ is the tilt angle.

Let us explain Eq. (1). The contribution to the poloidal field is assumed to be proportional to the magnetic flux from an active region. Since the magnetic field strength in developed sunspots varies within a moderately wide range, approximately from 2.5 to 3.5 kG (Obridko 1985), the magnetic flux may be considered to be proportional to the area of the largest spot. The characteristic separation between group sunspots is small compared to the solar radius. Therefore, after the group decay, turbulent diffusion will lead to the "cancellation" of opposite polarities. Only a small part of the magnetic flux from an active region will contribute to the global poloidal field. Babcock (1961) estimated this contribution to be about 1%. One may expect this contribution to increase with $\ell$. Since $\ell$ is small (compared to $R_\odot$), the dependence on this quantity in Eq. (1) is assumed to be linear. Finally, the poloidal field component in an active region is proportional to $\sin \alpha$.

Equation (1) includes the minimal set of parameters to estimate the Babcock–Leighton mechanism. Nevertheless, we managed to find only one long series of (digitalized) sunspot data suitable for such an estimation. The Catalog of Solar Activity (CSA) of the Pulkovo Astronomical Observatory (http://www.gao.spb.ru/database/csa/groups_r.html; Nagovitsyn et al. 2008) provides this possibility. The data of this catalog allow $B(1)$ to be calculated for three solar cycles.

**RESULTS**

Figure 2 shows the values of $B$ of Eq. (1) for solar cycles 19–21 and the $A$-index of the large-scale field (Makarov and Tlatov 2000) for the solar minima following these cycles. Also shown here are the positions of these three cycles in coordinates of $A$ and the so-called solar cycle amplitude $W$ ($W$ is the maximum value of the yearly mean Wolf numbers).

It has been repeatedly pointed out, and we confirm this conclusion, that the quantities
A and W do not correlate with each other (Makarov and Tlatov 2000; Makarov et al. 2001; Jiang et al. 2007). In terms of the dynamo theory, this implies that there is no functional relationship between the toroidal field at the cycle maximum and the poloidal field at the succeeding minimum. This relationship is believed to be realized by the $\alpha$-effect and its ambiguity is due to random fluctuations inherent in this effect.

Fig. 2. Left: positions of individual solar cycles in coordinates of $B$ calculated from Eq. (1) and $A$-index at the succeeding activity minimum. Right: the same for the amplitude $W$ of Wolf numbers and the $A$-index.

However, this does not rule out the possibility of estimating the contribution of the $\alpha$-effect with all the existing fluctuations to the poloidal field generation. Equation (1) gives such an estimate for a special variety of the $\alpha$-effect that is commonly called the Babcock–Leighton mechanism. The values of $B$ obtained from this estimate closely correlate with the $A$-index (Fig. 2). The line in the left part of the figure represents the relation

$$A = 4.1 \times 10^{-11} B,$$

where in calculating $B$ from Eq. (1), we expressed $S_i$ in millionths of the solar hemisphere and $\ell_i$ in kilometers. Of course, the calculations for only three solar cycles do not allow us to judge the reliability of the relation found with full confidence. Nevertheless, the results of Fig. 2 indicate that the Babcock–Leighton mechanism actually operates on the Sun.

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