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RECONSTRUCTION OF OPEN SOLAR MAGNETIC FLUX AND INTERPLANETARY MAGNETIC FIELD IN THE 20TH CENTURY

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Abstract. We reconstruct mean magnitudes of the open solar magnetic field since 1915 using Hα magnetic synoptic charts of the Sun. The obtained series allows estimation of the interplanetary magnetic field. They also confirm the known conclusion about the secular increase of the solar open magnetic flux in the first half of the 20th century.

1. Introduction

As is well known, there are many different indices that characterize various aspects of solar magnetic activity. The longest and traditional ones, such as the sunspot numbers, are related mostly to sunspot activity, that is with solar magnetic fields of corresponding (small and intermediate) scales. However, fields of global scale are also important for understanding mechanisms of solar activity. Moreover, magnetic fields of this scale modulate parameters of the interplanetary medium and, therefore, play an important role in mechanisms of solar-terrestrial links. Unfortunately, regular direct observations of large-scale solar magnetic fields began as late as in the second half of the 20th century. Therefore, it is of great interest to get information about their behaviour in earlier epoches. In this paper we use indirect data to build reconstructions of solar large-scale magnetic fields since 1915 and, with somewhat less reliability, since 1844.

2. The Average Open Solar Magnetic Field

One of the main characteristics of the solar large-scale magnetic field, which is traditionally referred to as "open magnetic flux", is

$$F_{\mathrm{S}} = \int_S |B_{\mathrm{r}}| dS, \tag{1}$$

where B_{r} is the radial component of magnetic field and S is a shell concentric with the Sun's spherical surface (source surface) with radius R_{S}. One should not confuse this “open magnetic flux” with the commonly understood “magnetic flux,” which is defined by a relation similar to Equation (1), but without modulus, and, of course, is equal to zero for any surface. In order that not to confuse these two terms, below we prefer to use the value

$$B_S = F_S / 4\pi R_S^2 \tag{2}$$

that will be referred to as “average open magnetic field” (AOMF). Usually the AOMF is obtained by extrapolation of measured photospheric magnetic fields to the source surface (Hoeksema and Scherrer, 1986).

Satellite observations demonstrate that the radial component of the heliospheric magnetic field is approximately independent of latitude. Its dependence on the distance from the Sun, r, according to Parker’s spiral theory is $\sim 1/r^2$ and one can use the AOMF to evaluate the interplanetary magnetic field (IMF) on the Earth’s orbit of radius R_E,

$$B_E \sim B_S \, (R_S/R_E)^2. \tag{3}$$

As was demonstrated by Lockwood (2002), the systematic difference between observations and this approximation of IMF is as small as some percents for annual means.

3. The Data Used

For reconstructions of the AOMF we shall use annual means of the following data series: (a) coefficients of multipole expansion of the solar photospheric magnetic field by spherical functions Y_{lm} $(l = 0, \ldots, 9,\ m = -l, \ldots, l)$, obtained from observations at Stanford for 1976–2003 (Hoeksema and Scherrer, 1986); (b) analogous coefficients reconstructed by Hα charts for 1915–1989 (Makarov *et al.*, 2001); (c) series of the geomagnetic activity index *aa* extended by data of the Helsinki observatory (1844–2003) (Nevanlinna and Kataja, 1993); (d) magnitudes of radial component of the IMF the OMNI dataset (1963–2003) (*http://nssdc.gsfc.nasa.gov/omniweb/ow.html*); (e) the traditional sunspot numbers (W) and the sunspot area series (S_{sp}).

4. Reconstruction of the AOMF

From the Stanford data (a) we obtain the magnetic field on the source surface, correct the field to account for underestimation of the signal in magnetograph, following Wang and Sheeley (2002) and calculate the AOMF for 1976–2003 years (Figure 1). As was shown in Lean, Wang, and Sheeley (2002), we can reconstruct B_S with use of the two lowest multipoles: the axial dipole strength B_{ADS} ($l = 1$,

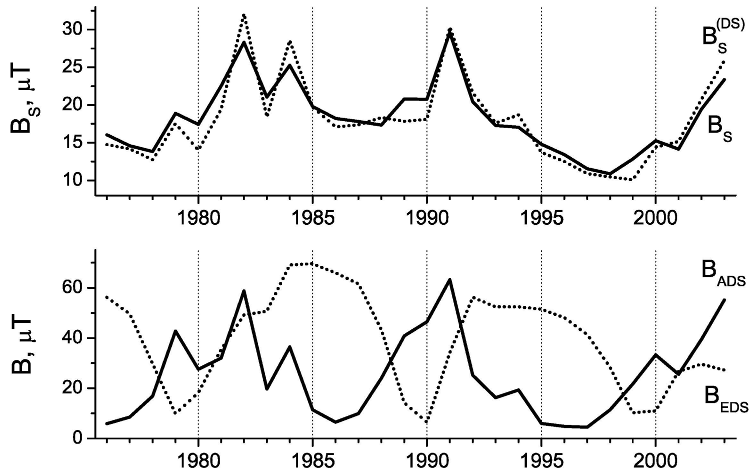

Figure 1. Upper panel: the AOMF from the Stanford data B_S (*solid curve*) and its dipole approximations $B_S^{(DS)}$ (*dotted curve*). *Bottom panel:* the dipole strengths of the solar magnetic field B_{ADS} (*solid curve*) and B_{EDS} (*dotted curve*) from the Stanford data.

$m = 0$) and the equatorial one B_{EDS} ($l = 1, m = \pm 1$). The dependence of B_S upon the dipole strengths is nonlinear, but can be approximated by a linear regression

$$B_S \approx B_S^{(DS)} = 0.224\, B_{ADS} + 0.359\, B_{EDS}, \tag{4}$$

with correlation $r(B_S, B_S^{(DS)}) = 0.96$ (Figure 1). The direct dipole strengths and ones reconstructed from Hα data (b) (we shall refer to the latter as "raw" strengths $\tilde{B}^{(H\alpha)}$) are compared in Figure 2. One can see that the values of the ADS from these two data sources are in a good agreement and we can obtain the ADS from the Hα data using a simple rescaling:

$$B_{ADS}^{(H\alpha)} = 0.696\, \widetilde{B}_{ADS}^{(H\alpha)}. \tag{5}$$

A similar approach cannot be naively applied to reconstruction of the EDS, since the observed EDS and the "raw" Hα EDS do not correlate at all. The reason for such a discrepancy is that the equatorial dipole exists during the whole 11-year cycle, but its magnitude can vary considerably. However, the method of multi-pole reconstruction by Hα charts (Makarov *et al.*, 2001) yields information mostly about geometry of solar magnetic fields, rather than their strength. In the absence of direct sources of data about strengths of the solar global magnetic field in the investigated period, we can search for indirect ones among indices related to fields of smaller scales. Indeed, one can see from behaviour of the observed EDS that its magnitude develops in approximate correlation with sunspot activity. As an estimation of this activity we selected, after comparing several candidates, the annual total sunspot areas S_{sp} (in millionths of solar disk). Therefore, we approximate the observed EDS

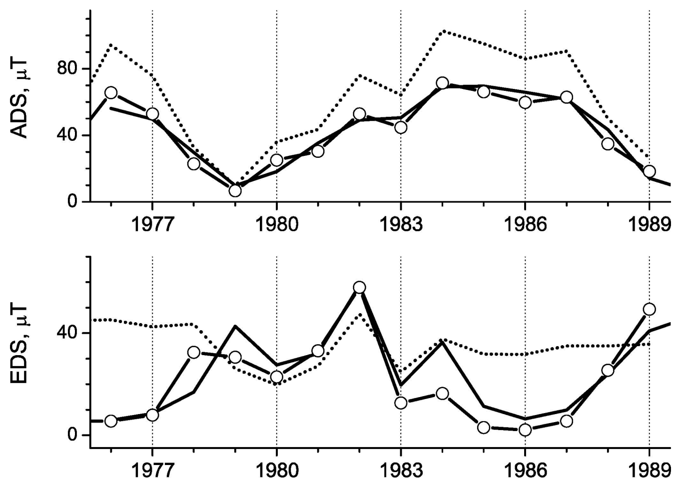

Figure 2. Reconstruction of the dipole strengths. *Upper panel:* the observed ADS B_{ADS} (*solid curve*), the "raw" Hα ADS $\widetilde{B}^{(H\alpha)}_{\mathrm{ADS}}$ (*dashed curve*) and the corrected Hα ADS $B^{(H\alpha)}_{\mathrm{ADS}}$ (*solid curve with circles*). *Bottom panel:* the same for the EDS.

by a value

$$B_{\mathrm{EDS}} \approx B^{(H\alpha)}_{\mathrm{EDS}} = 5.4 \times 10^{-3}\, \widetilde{B}^{(H\alpha)}_{\mathrm{EDS}} S_{sp}, \tag{6}$$

with correlation $r(B^{(H\alpha)}_{\mathrm{EDS}}, B_{\mathrm{EDS}}) = 0.87$. Hence, we can reconstruct the dipole strengths and the AOMF $B^{(H\alpha)}_{\mathrm{S}}$ since 1915 (Figure 3). The correlation between the observed and reconstructed AOMF over the common part of the time interval 1976–1989 is $r(B_{\mathrm{S}}, B^{(H\alpha)}_{\mathrm{S}}) = 0.76$.

An alternative approach to reconstruction of the AOMF is using a relation between the coronal field and the IMF. As we showed in Miletsky and Ivanov (2003), the IMF can be approximated by a linear regression that includes *aa* and *W* indices, so we can search for a dependence of the AOMF on these indices. The least-squares method results in a following model ("aaW model"):

$$B^{(aaW)}_{\mathrm{S}} = 0.71\, aa + 0.014\, W, \tag{7}$$

with correlation $r(B^{(aaW)}_{\mathrm{S}}, B_{\mathrm{S}}) = 0.76$ for 1976–2003.

Figure 4 shows two obtained alternative reconstructions. One can see that the Hα model gives, as a rule, higher maxima and lower minima of the AOMF variations, but behaviour of the low-frequency components of both reconstructions are rather similar (Figure 7). In particular, both curves manifest an evident increase in the first half of the 20th century.

It is important to underline that these two reconstructions are based upon independent information. To build the first model we exploited information of the large scale solar magnetic field, while the second one is based upon data of the sunspot and geomagnetic activities. Therefore, the obtained reconstructions of the AOMF are sufficiently reliable, and we can use the aaW model and the extended data set

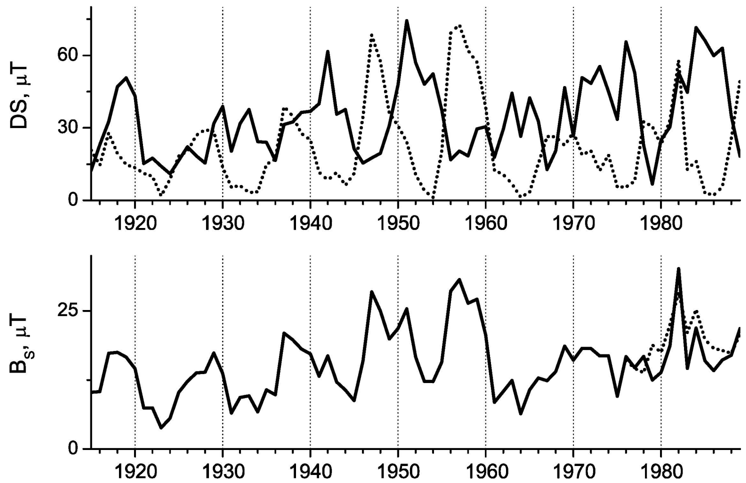

Figure 3. Upper panel: the reconstructed dipole strengths $B_{\mathrm{ADS}}^{(H\alpha)}$ (*solid curve*) and $B_{\mathrm{EDS}}^{(H\alpha)}$ (*dotted curve*). *Bottom panel:* the reconstructed AOMF $B_{\mathrm{S}}^{(H\alpha)}$ (*solid curve*) and the observed AOMF from the Stanford data B_{S} (*dotted curve*).

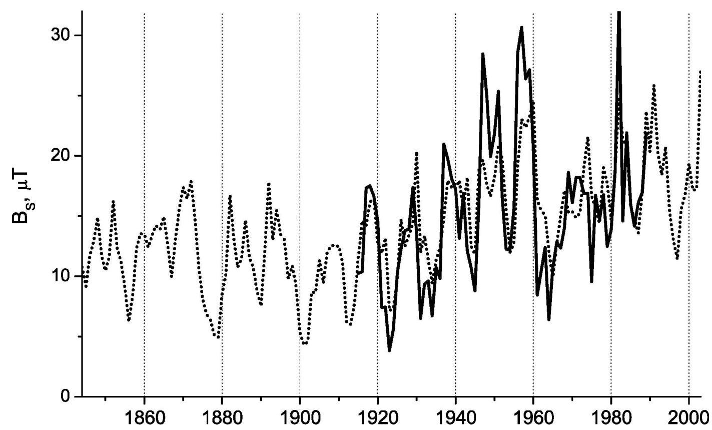

Figure 4. Comparing of the AOMF reconstructions: the Hα reconstruction $B_{\mathrm{S}}^{(H\alpha)}$ (*solid curve*) and the aaW reconstruction $B_{\mathrm{S}}^{(aaW)}$ (*dotted curve*).

(c) of *aa* index (Nevanlinna and Kataja, 1993) for estimation of the AOMF since 1844 (Figure 4).

5. Reconstruction of the Interplanetary Magnetic Field

The rescaled AOMF B_{E} can serve as an approximation of the IMF (see Equation (3)). To illustrate it, we plot in Figure 5 B_{E} values calculated by the direct AOMF data and

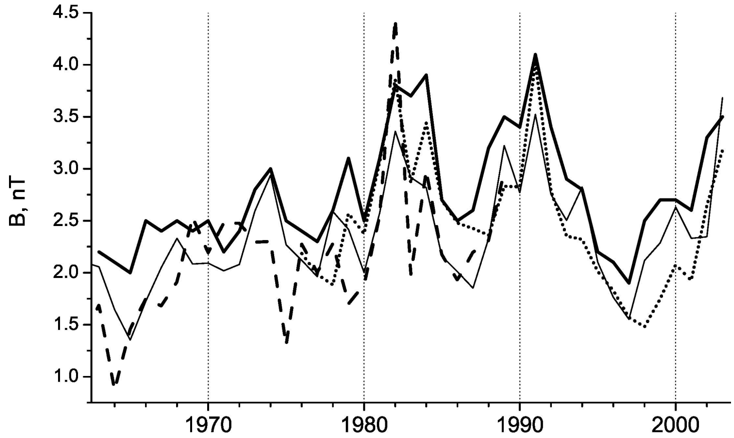

Figure 5. The mean absolute radial component of the IMF $|B_x|$ (*thick solid curve*) compared with the rescaled AOMF from direct observations B_{E} (*dotted curve*), from Hα reconstruction $B_{\mathrm{E}}^{(H\alpha)}$ (*dashed curve*) and from the aaW model $B_{\mathrm{E}}^{(aaW)}$ (thin *solid curve*).

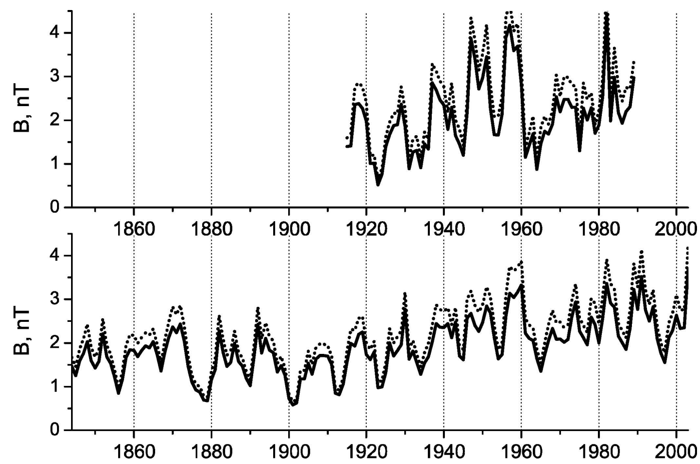

Figure 6. *Upper panel:* results of the direct reconstruction of IMF from Hα charts $|B_x^{(H\alpha)}|$ (*dotted curve*) compared with the rescaled AOMF reconstruction $B_{\mathrm{E}}^{(H\alpha)}$ (*solid curve*). *Bottom panel:* the same for the linear aaW models $|B_x^{(aaW)}|$ and $B_{\mathrm{E}}^{(aaW)}$.

the absolute values of the IMF radial component $|B_x|$ from the OMNI dataset (d). One can see that the curves are in fair agreement, with $r(B_{\mathrm{E}}, |B_x|) = 0.88$ (1976–2003). The reconstructions of AOMF also correlates with the IMF, although the correlation is lower, being 0.65 for $B_{\mathrm{E}}^{(H\alpha)}$ (1976–1989) and 0.87 for $B_{\mathrm{E}}^{(aaW)}$ (1963–2003).

Nevertheless, we can regard the reconstructed and rescaled AOMF as an approximation of the IMF. We can also use another approach and build two direct

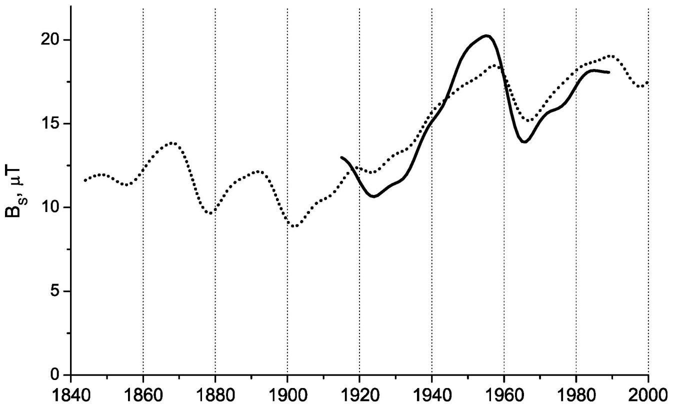

Figure 7. The trend components of the two AOMF reconstructions: $B_S^{(H\alpha)}$ (*solid curve*) and $B_S^{(aaW)}$ (*dotted curve*).

linear regressive models of $|B_x|$, using aa and W as input data. The least-squares method yields for these models

$$\left|B_x^{(H\alpha)}\right| = 0.0389 B_{\text{ADS}}^{(H\alpha)} + 0.0535 B_{EDS}^{(H\alpha)}, \tag{8}$$

$$\left|B_x^{(aaW)}\right| = 0.109 aa + 0.003 W. \tag{9}$$

The reconstructions obtained by these two approaches are compared in Figure 6 and quite similar.

To emphasize secular variations, we smoothed the reconstructed series of the AOMF (Figure 7). We can see that both models exhibit an increase of the AOMF approximately by a factor of two in the first half of the 20th century.

6. Conclusions

We presented two independent models of reconstruction of the AOMF. The first one (Hα model) is based upon photospheric observations, the second one (aaW model) mainly uses geomagnetic data. Both models confirm the known conclusion about increasing of the AOMF in the first part of the 20th century (see, e.g., Wang and Sheeley, 2002; Lockwood, Stamper, and Wild, 1999; Cliver and Ling, 2002). The second reconstruction of the AOMF and IMF, based upon the aa-index, can be extended to the second part of the 19th century. The similarity of results independently obtained by two methods in the 20th century gives us grounds to regard this extension to the 19th century as reliable. The obtained reconstructions also can be used to estimate the IMF in the epoch under study.

Acknowledgements

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