Reconstruction of open solar magnetic flux and interplanetary magnetic field in 19th and 20th centuries

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As is well known, there are a lot of different indices that characterize various aspects of solar magnetic activity. The most long and traditional ones, such as Wolf number and sunspot areas index, are related mostly with sunspot activity, that is, with solar magnetic fields of the corresponding (small and intermediate) scales. However, the fields of global scale, which began to be observed systematically as late as in the second half of the 20th century, are also important for comprehension of solar activity mechanisms. Moreover, the magnetic field of this scale modulates parameters of interplanetary medium and, therefore, plays important role in mechanisms of solar-terrestrial links.

Unfortunately, systematical direct observations of the large-scale solar magnetic fields began as late as in the second half of the 20th century. Therefore, it is of large interest to get information about its behaviour in the earlier epoches.

Average open solar magnetic fields

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

$$F_S = \int_S |B_r| dS \,, \tag{1}$$

where B_r is a radial component of the magnetic field and S is a concentric with the Sun spherical surface of radius R_S. It is implied that the radius of the surface is large enough and all closed lines of the solar magnetic field do not intersect the surface. One should not confuse "open magnetic flux" with commonly understood "magnetic flux", which is determined by relation similar to Eq. 1, but without module, and, of course, is equal to zero for any surface. In order that not to confuse these two terms, below we prefer to use value

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

that will be referred as "average open magnetic field" (AOMF). Usually the AOMF are obtained by extrapolation of measured photospheric magnetic fields to a spherical "source surface" at 2.5 solar radii. For this extrapolation a model is used, in which the corona is current-free under the surface and the magnetic field is radial on it (see, e.g., [1]).

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 spiral theory, is $\sim 1/r^2$. Therefore, one can use the AOMF to evaluate the average magnitude of the magnetic field radial component on the Earth orbit with radius R_E

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

As it was demonstrated by Lockwood [5], the systematic difference between observations and this approximation of the interplanetary magnetic field are as small as some percent for annual means.

Data

In this work we construct and compare two models of AOMF reconstruction. To build the models we use the following data series:

(a) Coefficients of multipole expansion of the solar photospheric magnetic field by spherical functions Y_{lm}, for $l = 0 \dots 9$, $m = -l \dots l$ obtained from observations of Wilcox Solar Observatory at Stanford (1976–2003) [1]. Using the coefficients, we calculate amplitudes of multipoles that corresponds to certain l and m.

(b) The analogous multipole coefficients and multipole amplitudes, reconstructed by Hα-spectroheliograms by Makarov et al. (1915-1989) [2]. Their method, in short, consists in determination borderlines between polarities of the solar global magnetic field by Hα charts and ascribing to the field within the areas some constant magnitude. The reconstruction, therefore, holds information mostly about geometry of the solar magnetic field. Nevertheless, these data can be useful for reconstruction of the solar magnetic field in the epoch before beginning of the direct observations.

(c) The series of the geomagnetic activity index *aa* extended by data of Helsinki magnetic-meteorological observatory (1844-2003) [4].

(d) The magnitude of the radial component of interplanetary magnetic field (IMF) near the Earth's orbit from OMNI dataset of National Space Science Data Center (1963-2003) [3].

For all data sets we use the annual means of the series.

Reconstruction of AOMF

Using method stated in [1], we obtain from the Stanford data (a) the magnetic field on the source surface Following [6], the field magnitudes multiplying them by "correcting factor" $4.5 - 2.5 \sin^2 \lambda$ (where λ is the latitude), thereby taking into account underestimating of the magnetic signal in magnetograph. Then, with use of Eq. 1, we calculate the average open magnetic field for 1976–2003 years. The resulting B_S is plotted on the upper panel of Fig.1. Since the 2^l-pole of the field decrease with radius as $1/r^{2l+1}$, the B_S really determined by the lowest field harmonics [7], and we can reconstruct B_S with use of two indices: the axial dipole strength B_{ADS} (that correspond to the expansion coefficient with $l = 1$, $m = 0$) and the equatorial dipole strength B_{EDS} ($l = 1$, $m = \pm 1$). It proves that the dependence of B_S upon the dipoles strengths, being nonlinear, nevertheless can be approximated well by a linear relation, with coefficients found by the least squares method:

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

with correlation coefficient $r(B_S, B_S^{(DS)}) = 0.96$ (see Fig. 1).

The target of the next step is reconstruction of the dipole strengths since 1915. The direct dipole strengths and ones calculated with Hα data (b) (we shall refer to the latter as "raw" dipole strengths $\widetilde{B}^{(H\alpha)}$) are compared in Fig. 2. One can see that the ADS from the two data sources are in good agreement and differ in normalization only. Therefore, we can obtain ADS from Hα data with the following relation:

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

The reconstructed ADS is plotted by open circles on the upper panel of Fig. 2.

Unfortunately, the similar approach cannot be naively applied to reconstruction of EDS. As one can see in the bottom panel of Fig. 2, the observed EDS and "raw" H-alpha EDS do not correlate at all. The reason for such a discrepancy is that the large-scale magnetic field with geometry of equatorial dipole exists all over the 11-year cycle, but its magnitude can be essentially different. The method of multipole reconstruction by Hα charts [**?**], however, does not take into account this difference. To make more reliable reconstruction of EDS we must get information about the global field strength. In absence of direct sources of such informations in the investigated period we can search for indirect ones among indices related with magnetic field of smaller scales. In fact, one can see from the behaviour of the observed EDS, that this strength develops

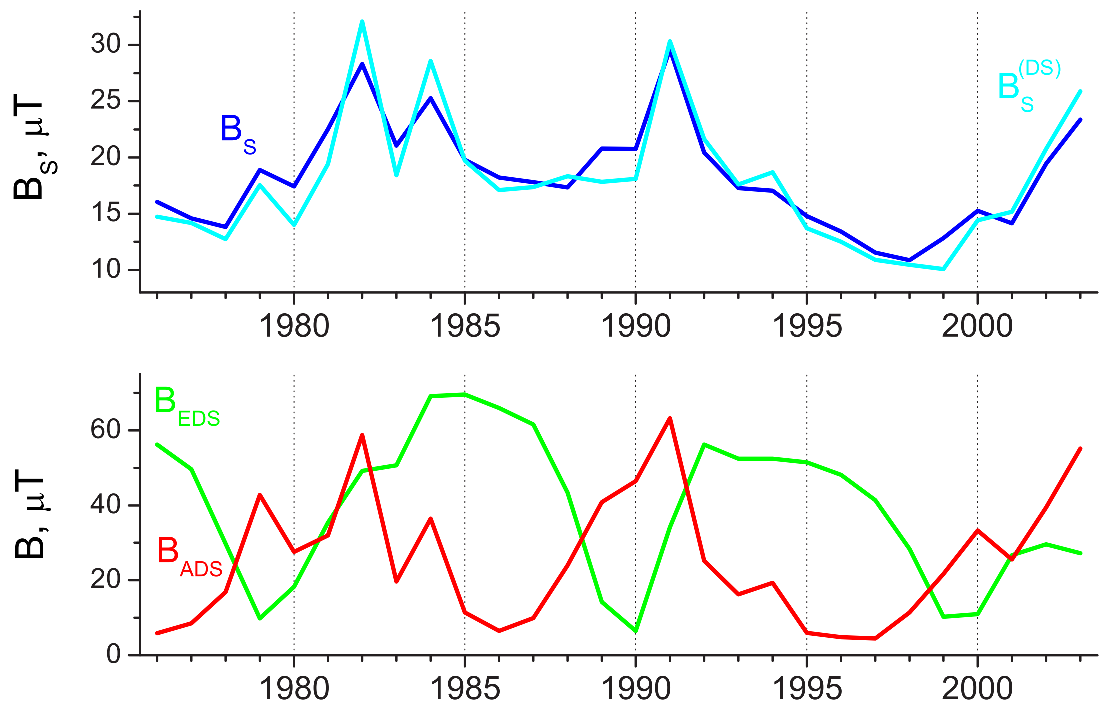

Figure 1: Upper panel: the average open magnetic field by Stanford data B_S and its dipole approximations $B_S^{(DS)}$. Bottom panel: the dipole strengths of solar magnetic field B_{ADS} and B_{EDS} by Stanford data.

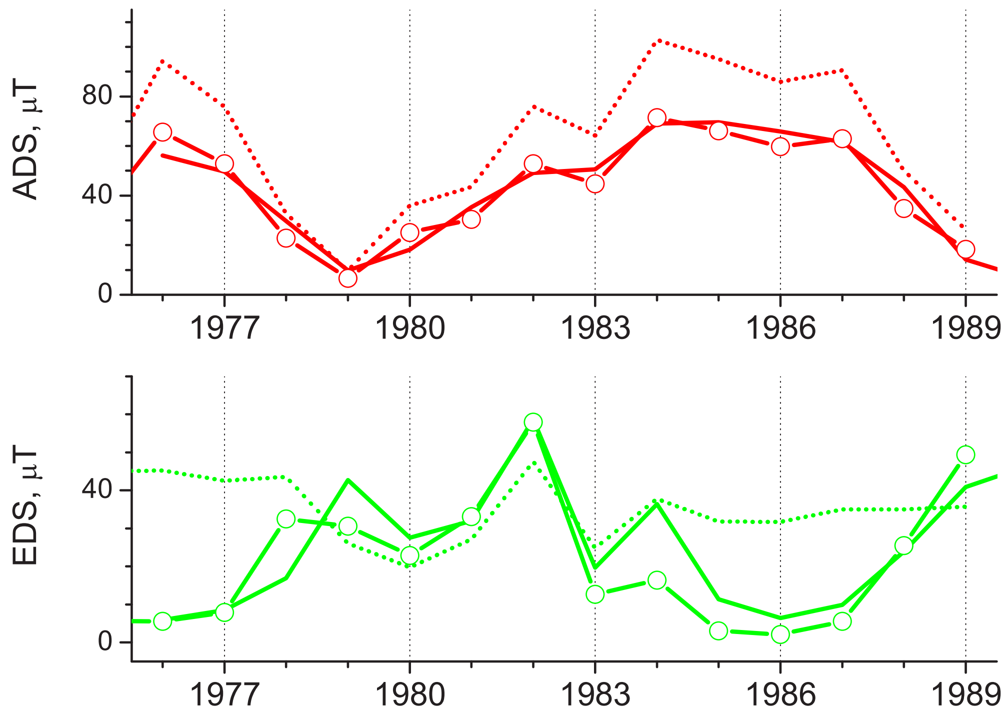

Figure 2: Reconstruction of the dipole strengths. Upper panel: observed ADS B_{ADS} (solid curve), "raw" H-alpha ADS $\widetilde{B}_{ADS}^{(H\alpha)}$ (dotted curve) and corrected H-alpha ADS $B_{ADS}^{(H\alpha)}$ (solid curve+circles). Bottom panel: the same for EDS.

in approximate correlation with sunspot activity. As estimation of this activity we select, after comparing several candidates, the annual total sunspot areas S_{sp} (in millionths of solar disk). Therefore, we approximate the observed EDS by a value

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

with correlation $r(B_{EDS}^{(H\alpha)}, B_{EDS}) = 0.87$ (see Fig. 2).

Hence, we can reconstruct the dipole strengths and, using Eq. 4, AOMF $B_S^{(H\alpha)}$ since 1915 (Fig. 3). The correlation between the observed and reconstructed AOMF on the common part of the time interval 1976–1989 is $r(B_S, B_S^{(H\alpha)}) = 0.76$.

An alternative approach to reconstruction of AOMF is using relation between the coronal and interplanetary magnetic fields. For example, such a method was used by Lockwood at al. [8], who exploited relation between AOMF and geomagnetic index aa. As we showed in [9], IMF can be approximated by a simple linear relation that includes aa and W indices. Therefore, taking into account the link between AOMF and IMF, we can search for dependance of AOMF upon these indices. The least squares method results in a following model (referred below as "aaW-model")

$$B_S^{(aaW)} = 0.71 \, aa + 0.014 \, W \, , \qquad (7)$$

which yields correlation with the observed AOMF $r(B_S^{(aaW)}, B_S) = 0.76$ (for the period 1976–2003). This reconstruction is very close to one derived from geomagnetic aa data by Lockwood et al. [8] (correlation between them for 1868–1996 is higher than 0.9).

Fig. 4 shows two obtained alternative reconstructions, which prove to be rather similar, with correlation $r(B_S^{(H\alpha)}, B_S^{(aaW)}) = 0.77$ for 1915–1989. One can see that Hα-model gives, as a rule, higher maxima and lower minima in AOMF variations, but behavior of the low-frequency component of both reconstructions are rater similar (see Fig. 7). In particular, both curves manifest evident increase in the first half of the 20th century. This increasing is caused not only by AOMF growth in maxima of 11-year cycles, but also by growth of the magnetic field strengths in minima of the cycles. It is important to underline that these two reconstructions are based upon independent information. To build the first model we exploit information about large scale solar magnetic field, while the second one is based upon data of sunspot and geomagnetic activity. Therefore, the obtained reconstructions of the solar open magnetic field seems to be sufficiently reliable and aaW-model, based upon an extended data set (c) of aa index [4], provides us with estimation of AOMF since 1844.

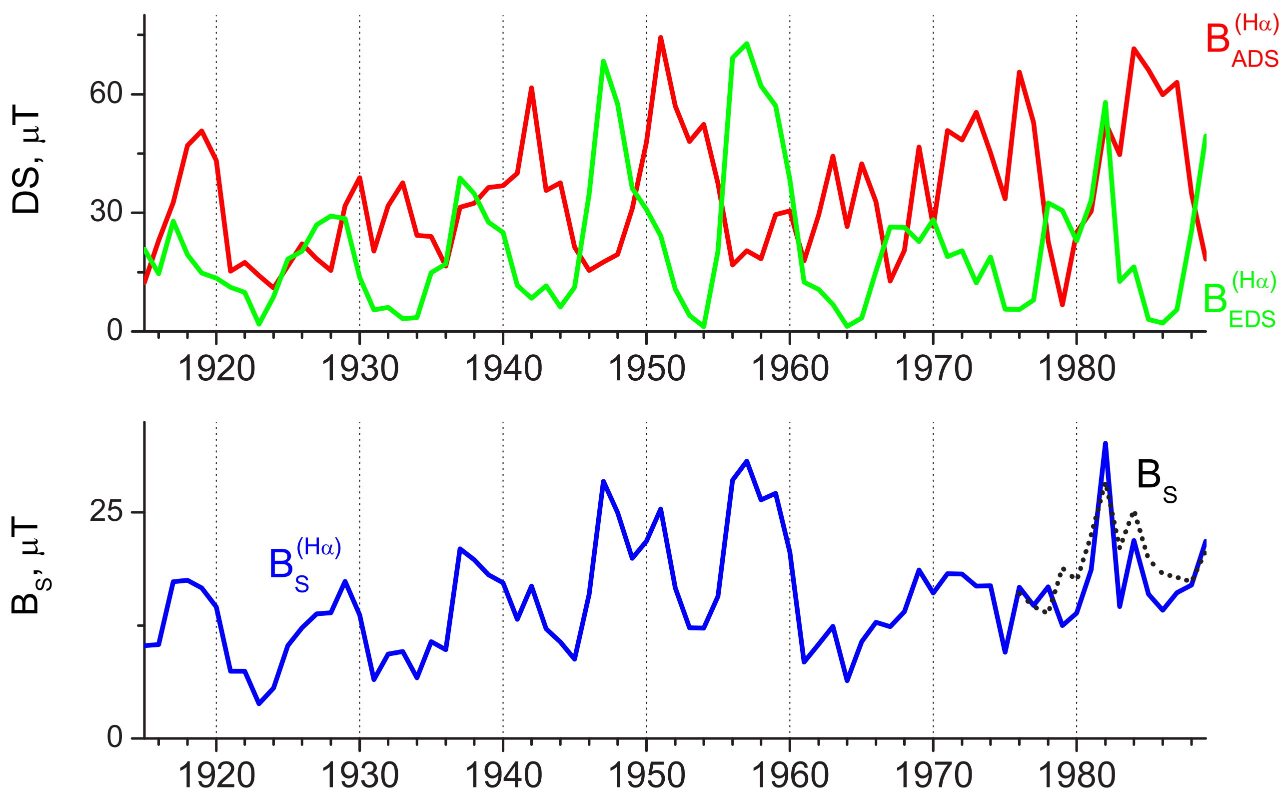

Figure 3: Upper panel: reconstructed dipoles strengths $B_{ADS}^{(H\alpha)}$ and $B_{EDS}^{(H\alpha)}$. Bottom panel: reconstructed AOMF $B_S^{(H\alpha)}$ and AOMF by Stanford data B_S.

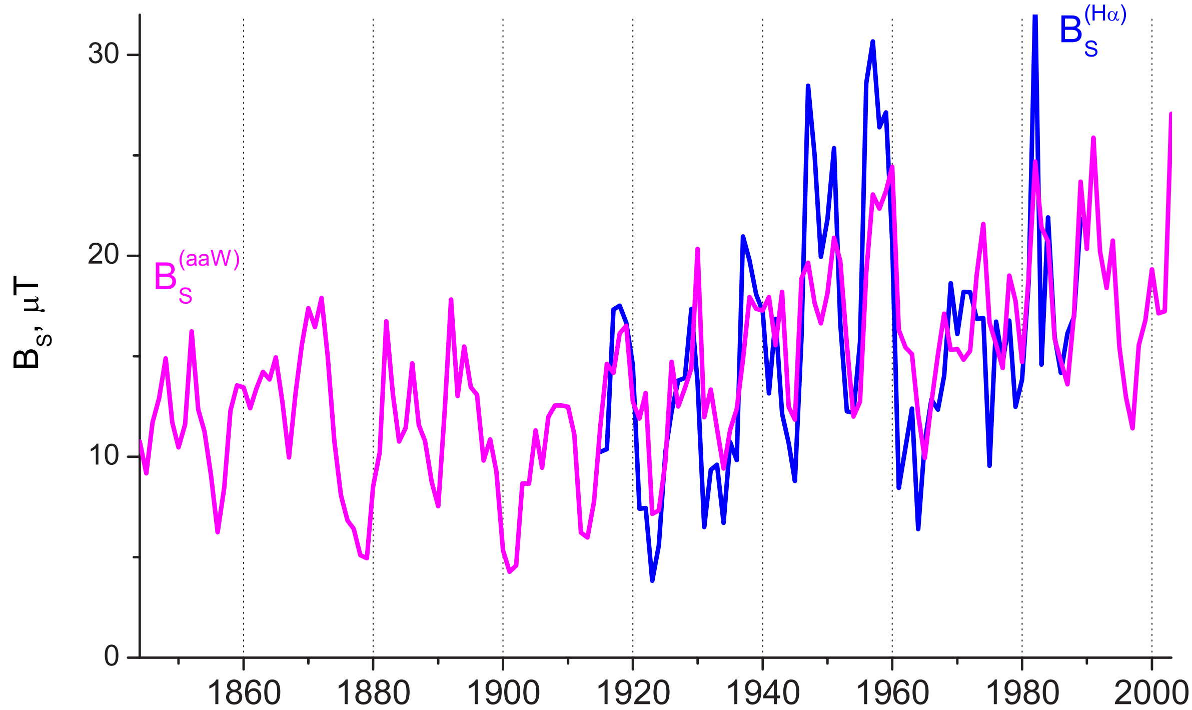

Figure 4: Comparing of two AOMF reconstructions: $B_S^{(H\alpha)}$ and $B_S^{(aaW)}$.

Reconstruction of interplanetary magnetic filed

The rescaled AOMF B_E, according to Eq. 3, can serve as an approximation of the interplanetary magnetic field. To illustrate it, we plot in Fig. 5 B_E values, calculated by direct AOMF data and absolute values of the interplanetary magnetic field radial component $|B_x|$ from OMNI dataset (d). One can see that the curves are in a fair agreement, with $r(B_E, |B_x|) = 0.88$ (1976–2003). The obtained reconstructions of AOMF also correlates with IMF, although the correlations is lower, being 0.65 for $B_E^{(H\alpha)}$ (1976–1989) and 0.87 for $B_E^{(aaW)}$ (1963-2003). The second model is a better approximation of IMF magnitude, while the first one in some years underestimates the values of the radial IMF component. Probably, the disagreement between B_E and the $|B_x|$ is caused by some transient processes, that cannot be described by conception of rather "quiet" expansion of solar global magnetic fields to the heliosphere.

Nevertheless, we can regard the reconstructed AOMF as an approximation of IMF strength. We also can apply an alternative approach and build two direct linear regressive model of $|B_x|$, rather than to rescale AOMF data. The best linear approximations are:

$$|B_x^{(H\alpha)}| \;=\; 0.0389 \cdot B_{ADS}^{(H\alpha)} + 0.0535 \cdot B_{EDS}^{(H\alpha)}\,, \qquad (8)$$

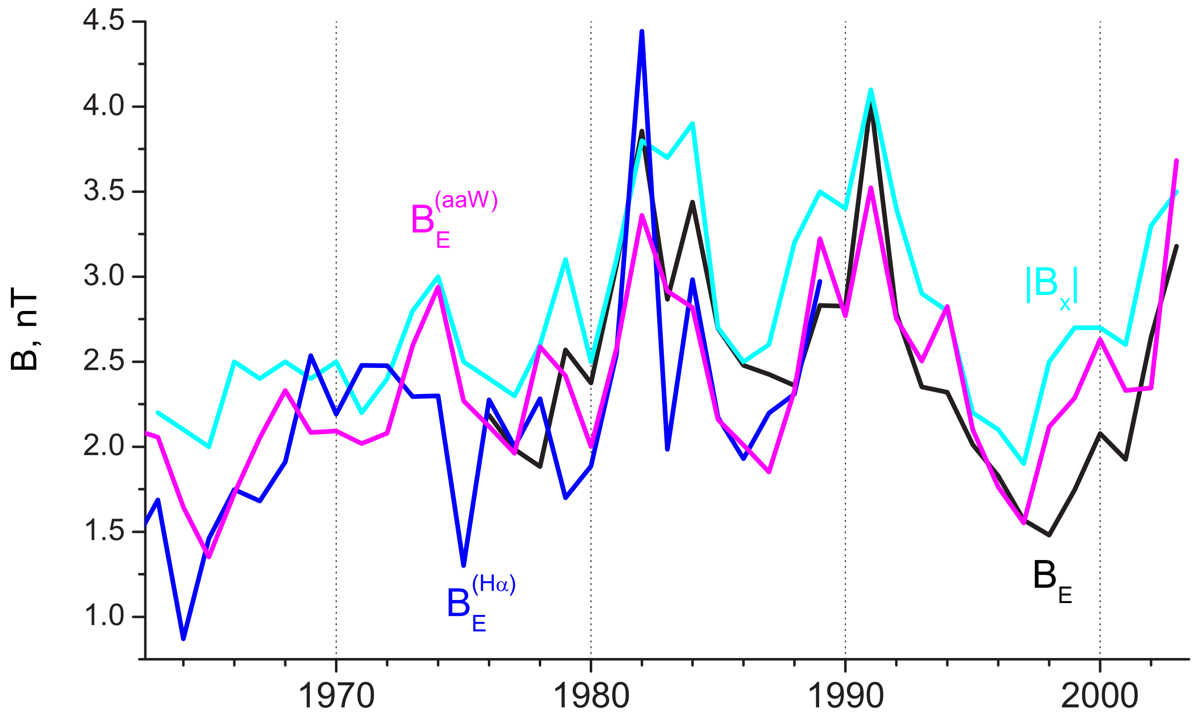

Figure 5: Mean absolute radial component of the IMF $|B_x|$ compared with rescaled AOMF from direct observations B_E (black), from H-alpha reconstruction $B_E^{(H\alpha)}$ and from aaW-model $B_E^{(aaW)}$.

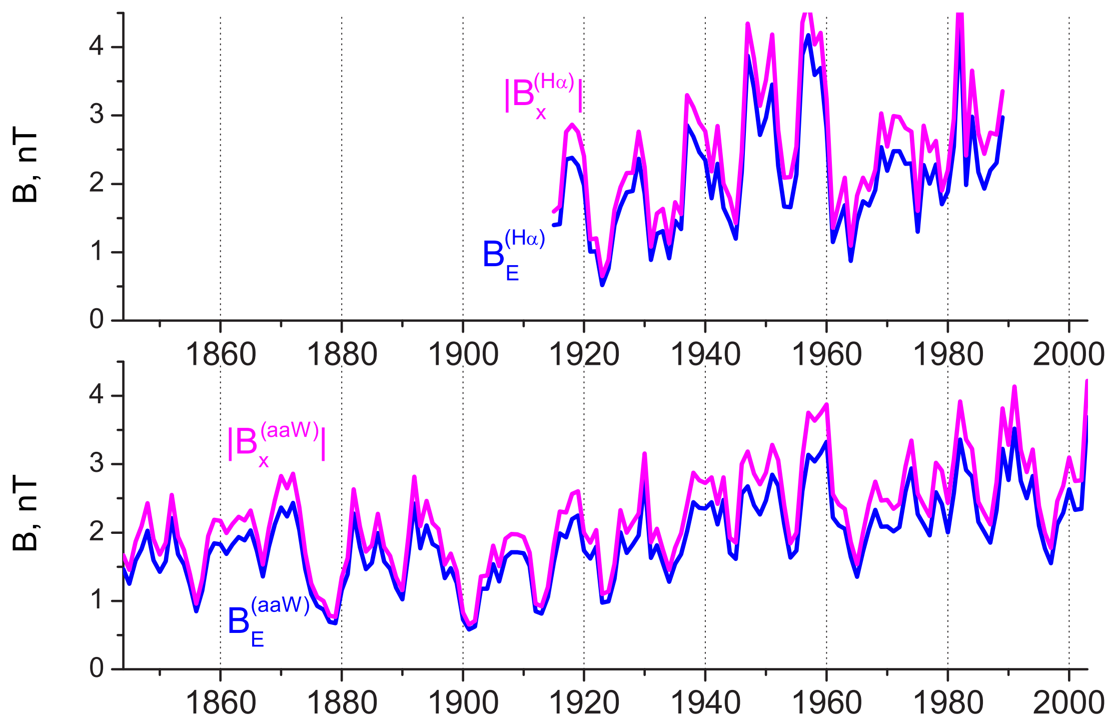

Figure 6: Upper panel: results of direct IMF reconstruction $|B_x^{(H\alpha)}|$ by H-alpha charts compared with rescaled AOMF reconstruction $B_E^{(H\alpha)}$. Bottom panel: the same for linear aaW models $|B_x^{(aaW)}|$ and $B_E^{(aaW)}$.

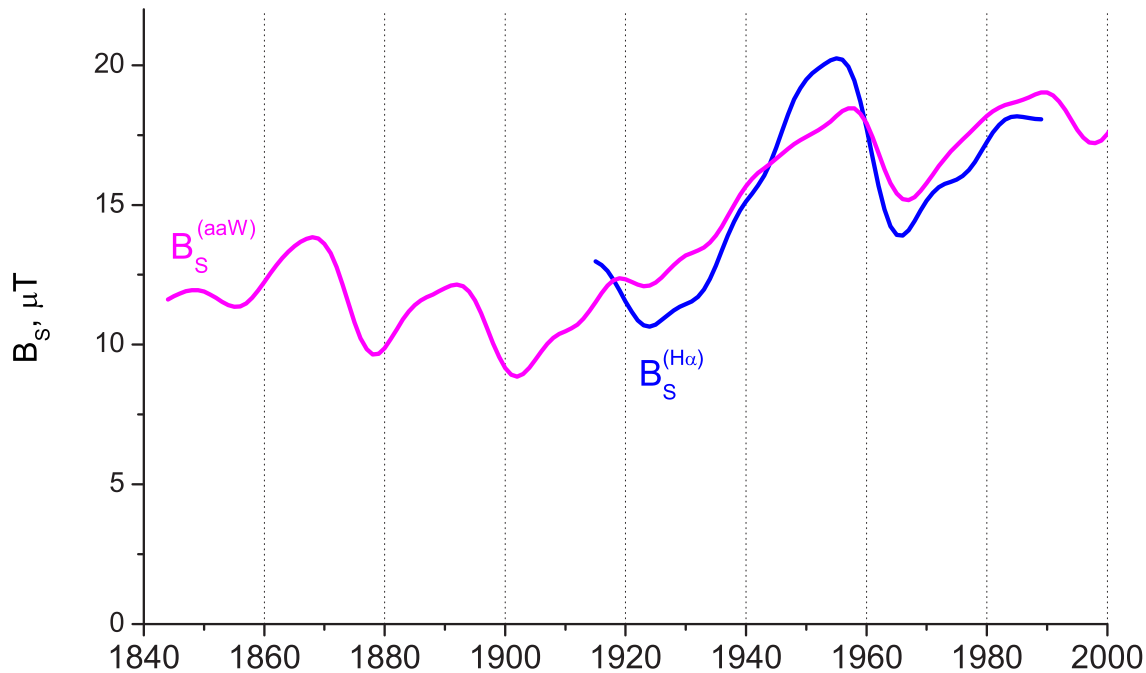

Figure 7: Trend components of $B_S^{(H\alpha)}$ and $B_S^{(aaW)}$ AOMF reconstructions.

$$|B_x^{(aaW)}| \;=\; 0.109 \cdot aa + 0.003 \cdot W \,. \tag{9}$$

The results of these two approaches are compared in Fig. 6. One can see that the direct reconstructions of $|B_x|$ and model that use the rescaled AOMF yield very similar results.

To emphasize secular variations, we smoothed the reconstructed series of AOMF (Fig. 7), using gaussian weights with $\sigma = 4$ yr. We can see that both models exhibit increase of AOMF approximately by a factor of two in the first half of 20th century. Magnitude of this increase is somewhat greater in case of H-alpha model, nevertheless both reconstructions are in qualitative agreement.

Conclusions

- Independent reconstructions of the AOMF by H-alpha data and by indices aa and W are in wholly satisfactory agreement, especially in their low-frequency part;
- Both reconstructions demonstrate approximately two times increasing of AOMF in the first part of 20th century;
- The reconstructions of AOMF can be used for estimation of the radial component of the interplanetary magnetic field;
- Reconstructions of AOMF and IMF that based on geomagnetic aa-index can be expanded into the second part of the 19th century.

Acknowledgements

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