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Some properties of latitude-time evolution of local and background solar magnetic fields

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Abstract

A comparative analysis of evolution of latitude distributions of solar magnetic fields of various scales is presented.

Using the local photospheric magnetic fields (LMF) represented by the magnetic fields of sunspots for cycles 12–23 it is found that the width of the sunspot generating zone is closely related to the magnitude of the total magnetic flux of sunspots. It is demonstrated that latitude-time distributions of the LMF and absolute strengths of the background magnetic field (BMF) in the latitude range $\pm 40^\circ$ are very similar and the time variations of power indices of the BMF and LMF are highly correlated. It is found that power characteristics of the BMF and LMF in cycles 21–23 are in close relation to the size of the low-latitude zone of solar activity.

It is shown that the speed of the polar drift of the BMF of a given polarity tends to increase in epochs of solar cycle maximums.

The obtained regularities can be used as diagnostic criteria for determination of adequate physical models of solar cyclicity.

Keywords: Sunspots; Solar magnetic field; Butterfly diagram; Solar cycle

1. Introduction

Study of latitude-time cyclic evolution of the solar magnetic fields is of essential importance for understanding of nature of the 11-year and longer cycles of solar activity. At present we know many regularities of that evolution for the local photospheric magnetic fields (LMF), which in the range of heliolatitudes $\pm 40^\circ$ are represented by magnetic fields of sunspots (Vitinskij et al., 1986; Hathaway et al., 2003; Li et al., 2003; Miletsky and Ivanov, 2009; Hathaway, 2010; Nagovitsyn et al., 2010; Sokoloff and Khlystova, 2010; Ivanov and Miletsky, 2011; Ivanov et al., 2011; Mordvinov et al., 2012).

One of well-known laws driving the latitude-time evolution of sunspots in the 11-year cycle is the Spörer law, which states that the mean latitude of the sunspot generating zone (SGZ) migrates towards the solar equator. This regularity is usually illustrated by a map of latitude-time distribution of sunspots called “the butterfly diagram”.

Search for relations between a character of the latitude distribution of sunspots and the level of sunspot activity on the Sun is important for understanding of mechanisms of the 11-year cycle of solar activity.

In our previous papers (Miletsky and Ivanov, 2009; Ivanov and Miletsky, 2011) we found that the latitude extension of the SGZ and the current level of solar activity are closely related. It was also shown (Ivanov et al., 2011) that the yearly distribution of sunspot groups can be described, in a first approximation, by the normal law with dispersion that linearly depends on the level of activity. In accordance with the obtained relation both the characteristic width of the SGZ and the maximal latitude density of sunspots grow more slowly than the level of activity.

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Another type of photospheric magnetic field is the background field (BMF) which is much weaker. It is interesting to make a comparison of the latitude-time evolution of the LMF and BMF within the SGZ. Available data make it possible for the three recent 11-year solar activity cycles (Nos. 21–23). The latitude-time distribution of the BMF absolute strength in cycles 21–23 is very similar to the butterfly diagram of sunspots; besides, a fine structure can be found in it (Song, 2007; Andryeyeva and Stepanian, 2008; Minarovjech, 1975). A detailed study of the fine structure of the LNF and BMF latitude-time evolution in cycle 23 is made by Zharkov et al. (2007). In that paper, in particular, a strong positive correlation between the areas of sunspots and the solar magnetic fields is found. It is concluded that such correlation suggests a modulating effect of the symmetric component of the magnetic field on the magnitude of magnetic field in flux tubes emerging as sunspots repeating at the 2–2.5 year time lags after or before the cycle start. Similar correlations of the LMF and BMF is discussed by Mordvinov et al. (2012), where a conclusion is made that the large-scale magnetic field of the Sun is a primary physical factor that determines its local magnetic fields.

A link between these two types of solar magnetic fields is both confirmed by observations and seems obvious from general considerations. However, details of this relationship are still unclear. Various models of generation of the solar magnetic field assume different schemes of such link: the large-scale photospheric magnetic fields can be treated either as a product of diffusion of the sunspot fields (Wilson and Giovannis, 1994; Choudhuri and Dikpati, 1999; Parker, 2009; Baumann et al., 2004), or, on the contrary, as a manifestation of large-scale magnetic fields rooted deeply in the convection zone, which cause sunspots to emerge (Zharkov et al., 2007; Mordvinov et al., 2012).

Therefore, study of relations between solar magnetic fields of different scales is an important task, and we analyse these relations in this work.

2. Description of data

We use as a source of data on sunspot groups Greenwich catalogue and its USAF/NOAA extension[1] for years 1874–2006. Data on the BMF are extracted from Kitt-Peak observations of the photospheric magnetic field,[2] which has the form of synoptic maps for the Carrington rotations Nos. 1625–2007 (years 1975–2003). Latitude distributions of the magnetic fields are obtained by averaging of the magnetic field strength (either absolute or with sign) over longitudes.

A latitude distribution of solar activity events in a given hemisphere for a given time range can be approximately described by the following parameters: (1) the mean latitude of the events ϕ_0; (2) the characteristic width of the distribution represented by one of the following parameters: (a) the (doubled) standard deviation $\Delta = 2\sigma$, (b) the width of the zone DB (ρ), where the density of events is higher than a given level ρ, (c) the difference D between the highest and lowest latitudes of events. These parameters are described in details in our previous papers (Miletsky and Ivanov, 2009; Ivanov and Miletsky, 2011).

3. Results and discussion

3.1. The latitude size of the sunspot generating zone and the magnetic flux of sunspots

Previously (Miletsky and Ivanov, 2009; Ivanov and Miletsky, 2011) we described solar activity by the sunspot indices W (the sunspot number) and G (the sunspot group number). In the present paper we also use for this purpose the magnetic flux of sunspots (MFX).

It was shown by Nagovitsyn (2005) that the total magnetic flux of sunspots can be expressed via the index of their total area S by the relation

$$\mathrm{MFX}\ [\mathrm{Mx}] = 2.49 \cdot 10^{19} \cdot \mathrm{S}\ [\mathrm{msh}]. \quad (1)$$

Using this relation and 133 yearly averages of the corresponding parameters we obtain a regression equation (see Fig. 1)

$$\mathrm{MFX(D)} = 0.205 + 0.350 \cdot \mathrm{D}, \quad (2)$$

relating the width D of the SGZ and the total magnetic flux with the correlation coefficient R = 0.958 and the confidence level much higher than three standard deviations.

Correlation coefficients between various parameters of the width (D, σ, σ^2, DB, DB^2) and indices G and MFX are listed in Table 1. One can see that the width of the SGZ is closely related both to the level of solar activity (Miletsky and Ivanov, 2009; Ivanov and Miletsky, 2011) and to the total magnetic flux of sunspots. Note that in

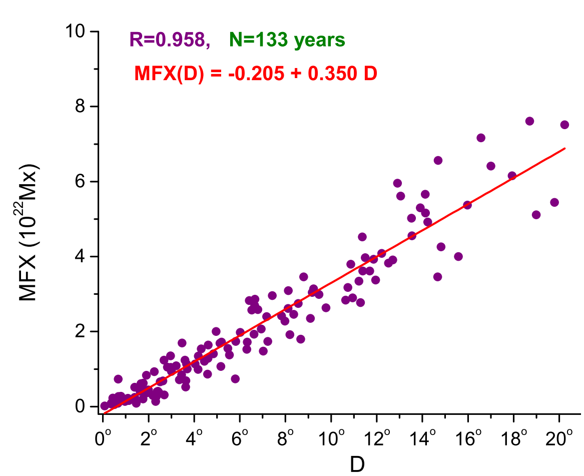

Fig. 1. The relationship between the width of the SGZ (D) and the yearly averages of the sunspot magnetic flux (MFX).

[1] http://solarscience.msfc.nasa.gov/greenwch.shtml.
[2] ftp://nsokp.nso.edu/kpvt/synoptic/mag.

Table 1
Correlations between various measures of the width of the SGZ.

	D	σ	σ^2	DB	DB^2
G	0.989	0.920	0.943	0.936	0.970
MFX	0.958	0.889	0.923	0.898	0.938

addition to the high correlation coefficient the points are distributed uniformly along the regression line (Fig. 1). The found relation (2), expresses a close link between variations of the latitude distribution of sunspots and their total magnetic flux and allows rather accurate calculating of the flux using the information on the width of the SGZ obtained by data on sunspot latitudes.

One can calculate the ratio of the total magnetic flux of sunspots (MFX) to the width of the corresponding zone (D): MFD = MFX/D. This relation determines the flux per unit of latitude or, in other words, its "linear density". In Fig. 2 the dependence of this ratio upon the magnetic flux is shown. With increasing of the magnetic flux, starting from a certain value, the linear growth of MFD slows down and turns to nonlinear one. Further increasing of the flux occurs mostly due to latitude widening of the SGZ.

3.2. Comparison of latitude-time evolution of the LMF and BMF in cycles 21–23

Using the absolute strengths of the BMF (from the sources described in Section 2) for cycles 21–23 and averaging them over longitude we can build a latitude-time distribution of the BMF (Fig. 3, top). The analogues distribution for the density of the latitude distribution of sunspot groups is plotted in the bottom of Fig. 3). The wings of the butterfly diagram are clearly visible on both diagrams.

We assume that the power of BMF in the range of latitudes ±40° can be described by the mean absolute strength of the magnetic field in this range MF (see, e.g., Minarovjech, 1975), and the power by LMF, by the daily sunspot group number G. For quantitative comparing of BMF and LMF variations we average MF and G over years. We also calculate yearly weighted averages of latitudes of the BMG (LatM) and sunspot groups (LatG), using the field strengths as weights in the former case and the sunspot areas, in the latter.

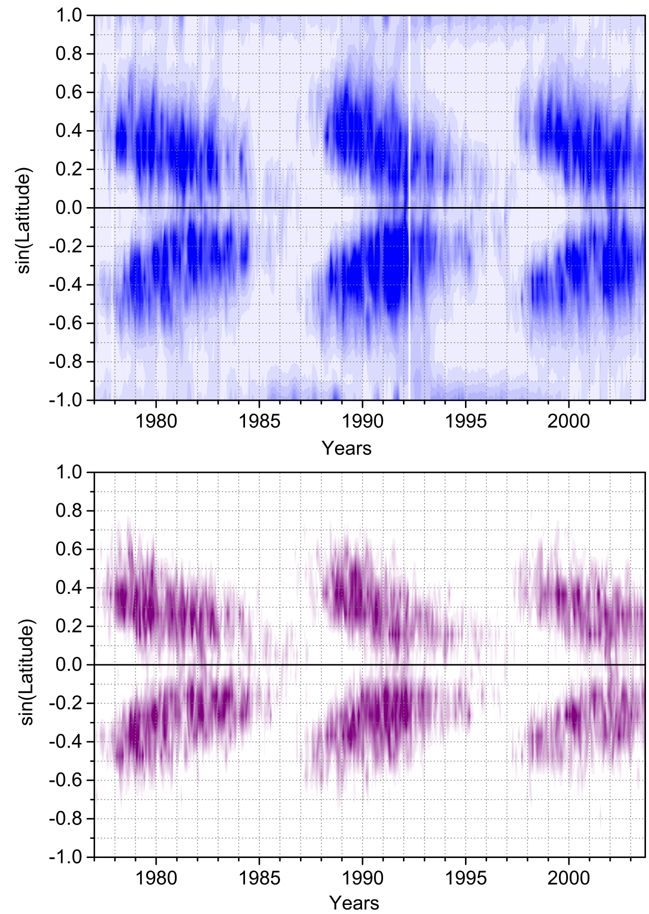

Fig. 3. The latitude-time diagrams for absolute values of the BMF (top) and the density of LMF distribution (bottom) (1975–2003).

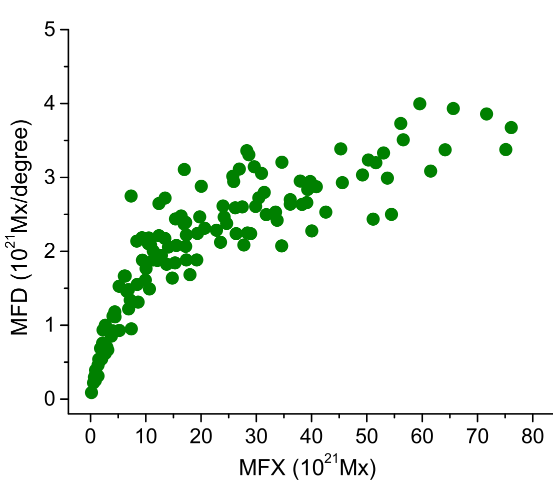

Fig. 2. The relationship between the sunspot magnetic flux MFX and the ratio MFD = MFX/D.

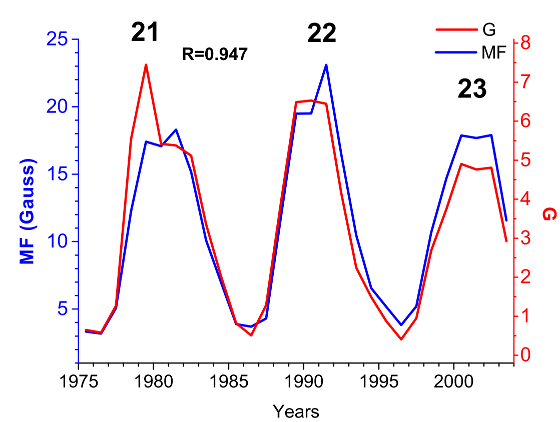

Fig. 4. Time variations of yearly averages of the indices MF (Gs, the blue line and the left Y axis) and G (the red line and right Y axis) as characteristics of the LMF in the latitude range ±40°. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

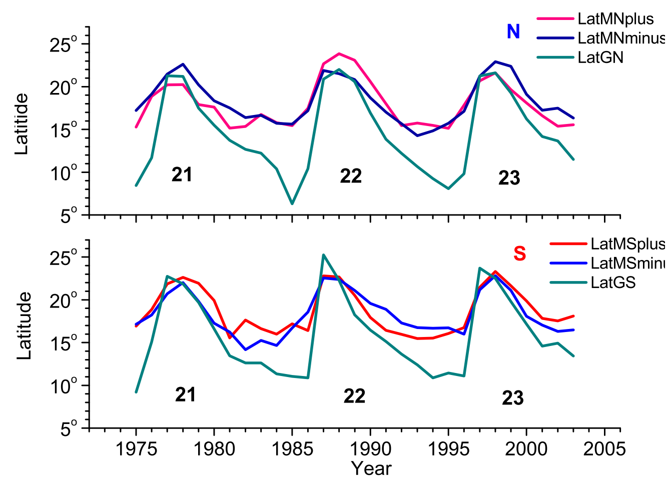

Fig. 5. Time variations of yearly averages of mean latitudes in the latitude range ±40° for N (top) and S (bottom) hemispheres for the strength of the BMF of positive (red) and negative (blue) polarity and for index G (green). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The yearly averages of MF and G in the latitude range ±40° in cycles 21–23 presented in Fig. 4 show a good correlation ($R = 0.947$, $N = 29$). Therefore, time variations of the power indices of BMF and LMF are in good agreement.

As for the average latitudes of the BMF (LatM) and LMF (LatG), one can see (Fig. 5) that their variations agree well only in maximums of the 11-year cycles. Beyond this phase LatM > LatG in both hemispheres. In particular, during the decreasing phase of the 11-year cycle the average latitudes of the BMF are essentially (4°–8°) higher than ones of the LMF.

It is notable that the leading polarity of the BMF (corresponding to the polarity of the leading sunspot in a group) taken separately in a given hemisphere (the case of the northern in each cycle hemisphere is shown in Fig. 6) has a lower average latitude as compared to the trailing one (see the bottom panel of Fig. 6). To the contrast, the amplitude of the BMF of the leading polarity during the maximum of the cycle is higher than the amplitude of the trailing one (the top panel of Fig. 6).

3.3. Comparison of latitude widths of LMF and BMF zones

In Fig. 7 we present "the butterfly diagrams" of Fig. 3 using isolines of equal density. To characterise widths of these latitude distributions in a uniform manner it is useful to introduce the width of the zone DB (ρ_0) where the value of the sunspot density (for sunspots) or strength (for the magnetic field) is higher than a certain threshold ρ_0. We selected the following thresholds: $\rho_0(G) = 0.0024$ groups/year/msh for sunspots and $\rho_0(MF) = 8$ Gs for BMF. Widths DB (ρ_0) in a certain moment are shown in Fig. 7 by arrows.

Using the yearly means of indices for cycles 21–23 (1975–2003) we obtain equations that relate indices G and MF to squares of widths of the corresponding zones $DB^2(G)$ (for G) and $DB^2(MF)$ (for the BMF). It turns out (see Fig. 8) that a close dependence between strengths of magnetic field and the widths of the low-latitude activity zones exists both for the LMF

$$DB^2(G) = -49.9 + 136.9 \cdot G, \quad (R = 0.980) \tag{3}$$

and for the BMF

$$DB^2(MF) = -379 + 83.4 \cdot MF, \quad (R = 0.988). \tag{4}$$

Previously (Miletsky and Ivanov, 2009; Ivanov and Miletsky, 2011) a similar dependence was found for sunspots, with the width of the SGZ being determined as the difference between the highest and lowest latitudes of sunspot groups.

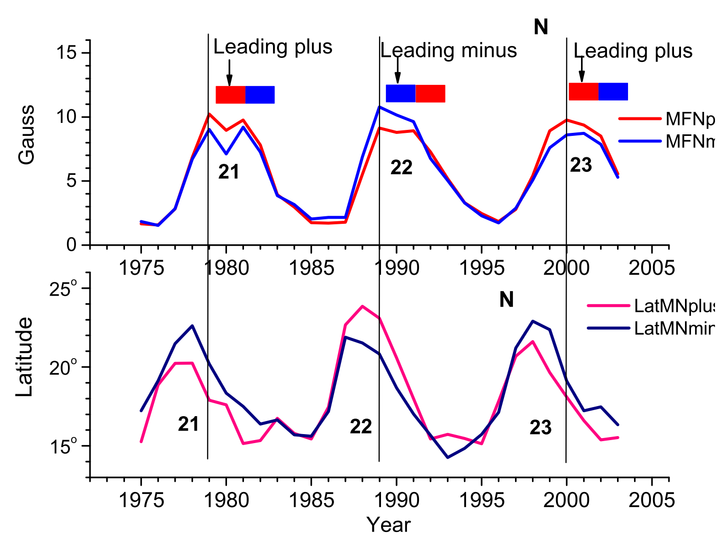

Fig. 6. Time variations of yearly averages of the strengths of the BMF (top) and mean latitudes (bottom) of positive (red) and negative (blue) polarity in the latitude range 0°–+40° (N-hemisphere). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

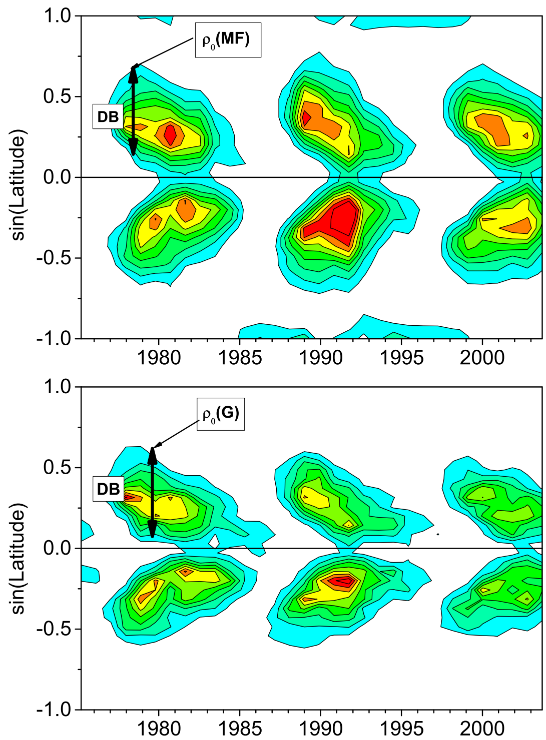

Fig. 7. Isolines of latitude-time distributions of absolute strengths of the BMF (top) and the density of the LMF distribution (bottom) (1975–2003). The width of activity zone DB (ρ_0) for a certain threshold ρ_0 is shown by arrows.

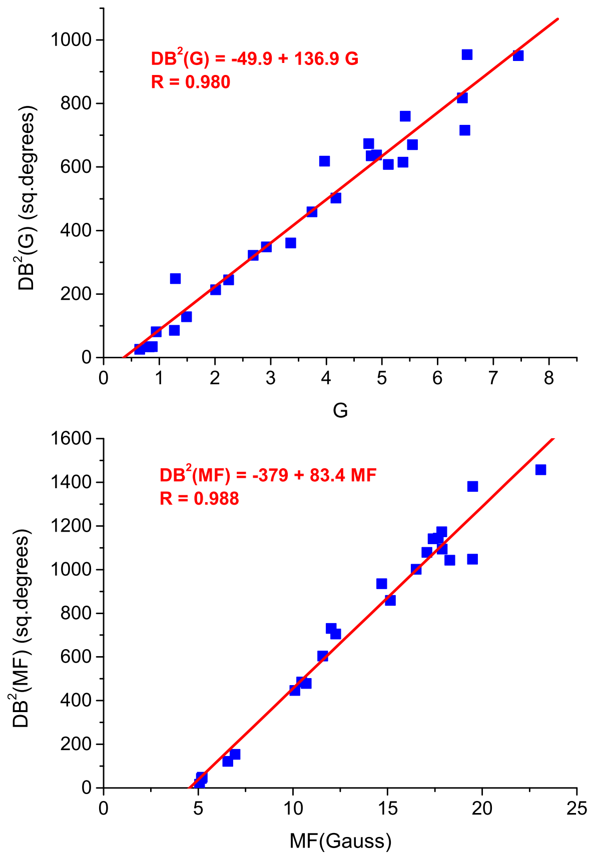

Fig. 8. Links of the yearly average of index G and the strength MF to squares of widths of the corresponding zones $DB^2(G)$ (top) and $DB^2(MF)$ (bottom).

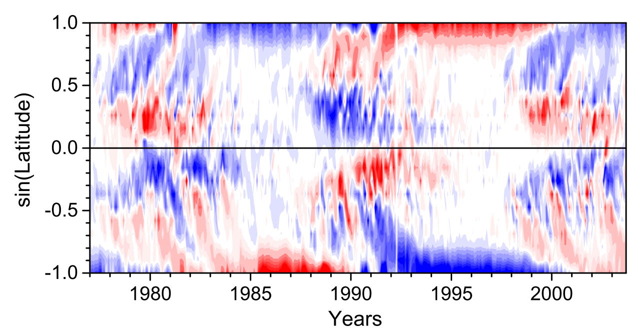

Fig. 9. The latitude-time distribution of the BMF strength (1975–2003). The red and blue colours correspond to positive and negative polarities of the field. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.4. Latitude-time evolution of the signed BMF in cycles 21–23

Another type of latitude-time distribution can be obtained by averaging the BMF over longitude with taking into account its polarity. Note that the value obtained by such a averaging corresponds, in fact, to an excess of the magnetic field of a certain polarity. These values, generally speaking, do not depend on the absolute strength of the field and, in particular, may be zeros. It is known that the pattern of latitude-time evolution obtained by such averaging reflects many important features of the 11-year cyclicity. The view of the corresponding diagram (Fig. 9) is well known (see, e.g., Hathaway, 2010).

Fig. 9 differs significantly from the diagram obtained for the absolute strengths of the field. These differences are especially evident for latitudes higher than ±40°, where "strips" of the BMF drifting to the poles are clearly visible.

For more detailed study of properties of this polar drift we make a filtration of the diagram by a band-pass FFT filter that removes oscillations with periods out of the range 8–39 solar rotations (Fig. 10). We use the latitude range of this diagram marked by the green lines (23°–53°) for determination of speeds of the pole drift of the BMF. In Fig. 11 these speeds determined for most long and powerful structures of the magnetic field in each hemispheres are plotted. The blue squares correspond to the speeds in the northern hemisphere of the Sun, and the red circles, in the southern one. One can see a tendency to decreasing of the speed in epochs of maximums of the 11-year cycle as compared to epochs of minimums. That agrees with results recently obtained by Hathaway and Rightmire (2010) for cycle 23.

4. Conclusions

In this work we present results of comparative analysis of the time-latitude evolution of solar magnetic fields of different scale.

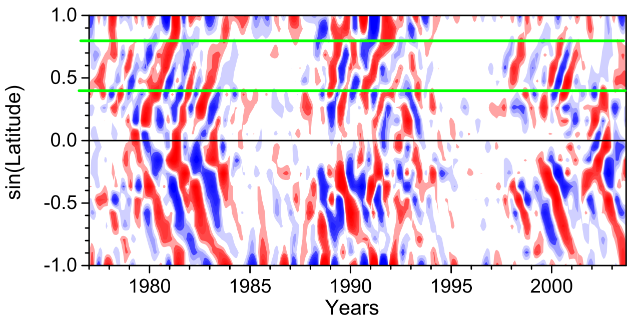

Fig. 10. The diagram of Fig. 9 after filtration by a band-pass FFT filter keeping variation in the range of periods 8–39 solar rotations.

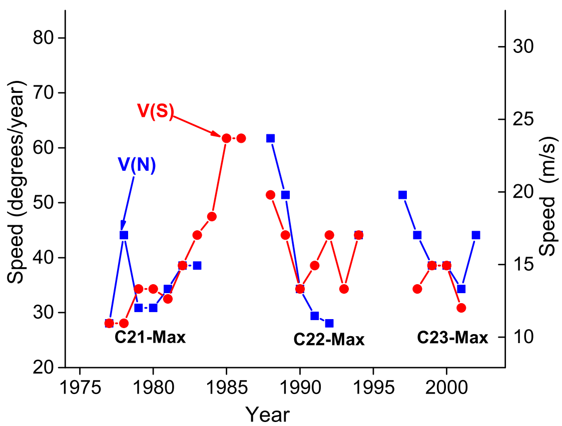

Fig. 11. Time variations of the speed of BMF drift to the poles in the northern (blue) and southern (red) hemispheres. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

For the local photospheric magnetic field (LMF) represented by the fields of sunspot for cycles 21–23 it is found that the width of the zone that generates the LMFs is closely related to the magnitude of the total magnetic flux of sunspots (previously a similar relation was found for the level of solar activity, see Miletsky and Ivanov (2009), Ivanov and Miletsky (2011)). The growth of the magnetic flux, as well as of sunspot activity, is accompanied by extension of the sunspot generating zone. The found regularity reveals a close relation between variations of latitude distribution of sunspots and the magnitude of their magnetic flux.

Comparison of main features of latitude-time evolution of the LMF (the index of sunspot group numbers G) and absolute strengths of the background photospheric magnetic field of the Sun (1975–2003) in the range of latitudes $\pm 40^\circ$ shows that the latitude-time distributions of the LMF ("the butterfly diagrams") and BMF are very similar. One can see also that the time variations of power indices of the LMF and BMF are in good correlation. It is consistent with analogues conclusions made by other authors (Zharkov et al., 2007; Andryeyeva and Stepanian, 2008; Minarovjech, 1975; Mordvinov et al., 2012).

It turns out that the average latitudes of BMF in the 11-year cycles is, as a rule, higher that ones of LMF. This difference is especially prominent in the decreasing phase of the cycle.

It is found that power characteristics of the BMF and LMF in cycles 21–23 are in close relation to the size of the low-latitude zone of solar activity.

It is also found that the speed of the pole drift of the magnetic field of a selected polarity tends to decrease in epochs of maximums of the 11-year cycle as compared to epochs of minimums.

The obtained regularities can be used as diagnostic criteria for determination of adequate models of solar cyclicity. In particular, in such models growth of magnetic flux must be accompanied by widening of the zone of generation of the flux.

The found links also give possibilities to reconstruct the latitude-time evolution of the LMF and BMF on the base of information on the level of solar activity.

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