Title: Latitudinal structure and dynamic of the photospheric magnetic field
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Abstract

Analysis of the structure and dynamics of the magnetic field of the Sun is fundamental for understanding of the origin of solar activity and variability as well as for the study of solar-terrestrial relations. Observations of the large scale magnetic field in the photosphere taken at the Wilcox Solar Observatory from 1976 up to 2007 have been analyzed to deduce its latitudinal and longitudinal structures, its differential rotation, and their variability in time. This paper is dedicated to the analysis and dynamics of the latitudinal structure of the solar magnetic field over three solar cycles 21, 22, 23. The main results discussed in this paper are the following: the large scale latitudinal structure is antisymmetric and composed of four zones with boundaries located at the equator, -25 and +25 degrees, stable over 10-11 years with a time delay of about 5-6 years in near-equatorial zones. The variability and North-South asymmetry of polarity waves running from the equator to the poles with 2-3-year period was studied in detail.

Keywords: Sun; solar variability; magnetic field; latitudinal structure; solar cycle.

1 Introduction

General panoramas of the solar-terrestrial relationship can be revealed only by comparison of global characteristics of the processes on the Sun with a broad set of parameters of the solar wind and geophysical indexes measured during a long interval of time. For this aim the solar magnetic field is one of the key characteristics involved in all the main processes of solar dynamics.

Different aspects of the magnetic field of the Sun has been studied (see, for example, the reviews of Bumba, 1976; Rabin et al., 1991; Stix, 2004 and references there).

Since the beginning of sunspot magnetic field spectroscopic observations the following characteristics, known as Hale’s law, have been deduced:

1. Each sunspot group (and its associated active region) is permeated by a bipolar magnetic field. The leading (according to solar rotation) and the following opposite polarity regions are generally of the same sign during each 11-year activity cycle.

2. These polarities are opposite in the northern and southern hemispheres.

3. The polarities change from one activity cycle to the next, resulting in a solar magnetic cycle of about 22 years: during odd (even) numbered 11-year cycles the leading polarity is positive (negative) in the northern hemisphere.

According to magnetic field observations made since the introduction of the Babcock magnetograph (Babcock, 1953; Babcock and Babcock, 1955; Babcock,
the polarities of the sub-polar zones are opposite; they change around the maxima of the activity cycles; before the reversion during odd (even) cycles the polarity in the northern sub-polar regions is positive (negative).

The study of topology and dynamics of the solar magnetic field is necessary because its large scale structures strongly influence the coronal field, solar wind propagation and geomagnetic perturbations.

This paper is focused on the study of the latitudinal structure of the large scale photospheric magnetic field (SMF) and their variability through solar activity cycles.

The data used are described in chapter 2. Chapter 3 is dedicated to the analysis of the latitudinal structure, chapter 4 to the North-South asymmetry of the photospheric magnetic field.

The next papers by Gavryuseva E. (2006d, 2006e, 2006f, 2018a, 2018b, 2018c, 2018d) are devoted to the study of the rotation rate SMF (Gavryuseva, 2006d, 2018a), the longitudinal structure (Gavryuseva, 2006e, 2008b, 2018b) and connections of the present findings with solar wind and geomagnetic characteristics (Gavryuseva, 2006f, 2018c, 2018d).

2 Data

The Wilcox Solar Observatory (WSO) data from [http://wso.stanford.edu/](http://wso.stanford.edu/) have been selected as one of the best and longest data sets of the large scale photospheric solar magnetic field (SMF) observations covering the solar activity cycles No 21, No 22, and No 23 (Scherrer et al., 1977).

The line-of-sight component of the photospheric magnetic field is measured by the WSO’s Babcock solar magnetograph using the Zeeman splitting of the 525.02 nm Fe I spectral line. Data is available beginning May 27, 1976 corresponding to the beginning of Carrington Rotation (CR) 1642. The data set analyzed covers the interval up to CR 2061. Daily magnetograms are taken with a three arc minute spatial resolution which corresponds to about 10 heliographic degrees at the center of the solar disc. The rotational grid of the available data is made of 30 equal steps in sine of latitude $\theta$ ($\sin(\theta)$) where $\theta$ is changing from 75.2 North to 75.2 South degrees at the latitudes $\theta$ of $\pm 75.2$, $\pm 64.2$, $\pm 56.4$, $\pm 50.1$, $\pm 44.4$, $\pm 39.3$, $\pm 34.5$, $\pm 30.0$, $\pm 25.7$, $\pm 21.5$, $\pm 17.5$, $\pm 13.5$, $\pm 9.6$, $\pm 5.7$, $\pm 1.9$ degrees, and of 5 degree steps in heliographic longitude. Obviously the spatial resolution is declining with increasing latitude. The regions beyond 75 degrees of latitude are not resolved at all due to the large size of the magnetograph aperture. Each longitudinal value is a weighted average of all the observations made in the longitudinal zone within 55 degrees around central meridian. The noise level of each measurement is less than 10 micro Tesla (Hoeksema, 1984).

3 Latitudinal Structure

The magnetic field involved in the active regions has a very high intensity. Because of this the SMF intensity (SMFI) is an index closely related to the solar activity. In Fig. 1 the intensity of the photospheric field is plotted as a function of time $t$ and latitude $\theta$ averaged over 1 CR (upper plot) and over 1
year (bottom plot). Yellow colors indicate high values of SMFI. These plots look very similar to the famous "Butterfly Diagram" of the sunspot distribution over heliographic latitudes through the last three solar cycles. The polarity of the SMF is not taken into account in this case. Any averaging does not change the general shape of the SMFI(θ, t) distribution while it makes difference for a magnetic field mean which considers the sign of the polarity.

To study the SMF structure it is necessary to take into account the intensity and the polarity of the field. Let us call the SMF mean over one or several full rotations of the Sun as the mean latitudinal of the field. Stability of the latitudinal field polarity and its value over several rotations and at the neighboring latitudes should be considered as evidence of the non random character of the latitudinal field. If such field exhibits some clear structure then it is important for the understanding of the origin of the solar activity.

3.1 Zonal Structure Stable over Solar Cycles

The search for long term latitudinal magnetic field structures should be performed by averaging the SMF(θ, t) around the Sun at each latitude θ over one or more rotations. In the upper plot of Fig. 2 the mean over 1 Carrington rotation of the solar magnetic field is plotted as a function of time and latitude θ. In the bottom plot the yearly running mean SMF with 1 CR step is plotted. Yellow and red (blue) colors indicate positive (negative) polarity. In the upper plot the 0-level of magnitude is indicated by a black line, in the bottom plot there are additional levels corresponding to ±50 micro Tesla of the yearly mean SMF. This plot is an immediate result of the temporal averaging of the SMF, and it agrees with the SMF temporal behavior using different observational data (Bumba, 1976; Hoeksema, 1984; Howard et al., 1991), etc. The origin of the solar cycle and the relationship between the large scale solar magnetic field, surface flows and local activities have been widely discussed (Parker, E.N., 1955a, 1955b, 1975, 1988; Bumba and Howard, 1965, 1969; Howard, 1974a, 1974b, 1996; Duvall, 1979; Stix, 1981; Howard and LaBonte, 1980, 1981; DeVore et al., 1984; McIntosh and Wilson, 1985; Sheeley et al., 1985; Sheeley et al., 1987; Bogard, 1987; Snodgrass, 1986, 1987a,b; Rabin et al., 1991; Murray and Wilson, 1993; Benevolenskaja, 1996; Erofeev, 1996, 1999; Obridko and Shelting, 1999; Tikhonov E., 2001; Tikhonov E., Mordvinov V., 2001; Ossendrijver, 2003; Stix, 2004, etc.).

The plots of Fig. 2 clearly show the existence of a global 4–zonal latitudinal structure stable over about 11 years having the following properties.

1. Four zones can be singled out: two pre-equatorial and two sub-polar with latitudinal boundaries θ equal to about +25.0 and −25 degrees.

2. This large scale zonal structure is antisymmetric relative to the equator (the polarities are opposite in the two solar hemispheres).

3. The polarity is stable over about 11 years. The sub-polar zones change their polarity around the maximum of solar activity cycle often with some shift in time between the two hemispheres as seen in Fig. 2. The annual variations of the sub-polar magnetic field seen in the upper plot of Fig. 2 are due to the Earth’s orbital motion.
4. While the boundary of the pre-equatorial zones are relatively stable over 10-11 years the change of the polarity in sub-polar zones starts first at ±25 degrees, later on it is changing at higher latitudes and in 2-3 years (during solar activity maximum) the reversion takes place in poles.

5. The pre-equatorial zones have the same polarity as the leading part of most of the activity regions there; their polarities change from one cycle to the next 5-6 years before the reversion in the sub-polar zones.

6. The latitudinal structure is reconstructed with a periodicity of 20-22 years.

Let us call this SMF topology as 4−zonal 22-year periodical latitudinal structure or, shortly, 4-zonal topology. This 4-zonal topology is qualitatively described by the spherical function \( Y_l^m(\theta, \phi) \), with spherical degree \( l = 3 \) (\( l \) is the total number of nodal lines) and azimuthal order \( m = 0 \) (\( m \) is the number of nodal lines around the equator), modulated by the 22-year periodicity (Gavryuseva and Kroussanova, 2003). A similar model was suggested by Benevolenskaja (1996, 1998), see also (Stenflo, 1974; Stenflo and Vogel, 1986; Stenflo and Gugel, 1988; Erofeev, 2001; Lawrence et al., 2004; Cadavid et al., 2005).

The boundaries of the pre-equatorial zones are unexpectedly stable. They are very slowly approaching to the equator, significantly slower than the drift of the SMFI maximum which shows the "Butterfly" migration visible in Fig. 1. This is illustrated better by Fig. 3 where the zero lines of the polarity inversion are plotted by continuous lines for the comparison with the latitudes weighted with the SMFI between 0 and ±50 degrees shown by points without averaging (upper plot) and by dotted lines for the latitudes weighted with 1 CR mean of the SMFI (bottom plot) in each hemisphere. Additionally in the bottom plot the latitudinal positions of the maxima of the SMFI mean over 1 CR for the each hemisphere are shown.

In the following plots 4, 6, 7, 8 and 10 the latitudes weighted with 1 CR mean of the SMFI are plotted by dotted lines.

While the polarity of the four zonal structure is quasi stable over 11 years, the intensity of the SMF is changing significantly with the 11-year period. The amplitude of the 1 year mean solar line-of-sight magnetic field variability (MSMF) is 135-170 micro Tesla in the sub-polar zones at the latitudes of ±75 degrees. The amplitude in the near-equatorial zones is maximal at 10-15 degrees latitudes and it is equal to 150-200 micro Tesla.

A quasi 20-year periodicity of the auto-correlation of the MSMF distribution for different latitudes as a function of time shift in years is illustrated by Fig. 4. Orange (blue) colors correspond to the positive (negative) coefficients of the MSMF(\( \theta, t \)) auto-correlation. An important characteristic of this auto-correlation is its very low level at the active latitudes, around zonal boundaries where the amplitude of the variability of the SMF intensity is the highest.

The origin of four zonal structure has been studied by Gavryuseva (2008a), and it was concluded that the magnetic field of middle intensity (from 5 to 2000 micro Tesla) is responsible for this structure due to the North-South asymmetry of the positive and negative components of the magnetic field measured in the photosphere.

For geophysical applications the North-South asymmetry of the solar activity is important. This problem can studied by the direct comparison of the magnetic field at the latitudes \( \theta \) and \(-\theta \) in both the hemispheres. In the upper plot of
Fig. 5 the solar magnetic field mean over 1 CR is shown again as a function of time and latitude. Orange (blue) colors indicate positive (negative) polarities. The contours in Fig. 5 correspond to zero level and to ±50 micro Tesla.

The antisymmetrical part is deduced for each $\theta$ as a difference between the SMF rotational means in the opposite hemispheres at each latitude:

$$0.5 \ast (SMF(\theta, t) - SMF(-\theta, t)).$$

These differences are shown in the middle plot. This antisymmetrical to the equator SMF part shows the mean level of the magnetic field of opposite polarity at each latitude in the two hemispheres. It clearly shows the common characteristics of the temporal behavior of the magnetic field of opposite polarity in the northern and in the southern hemispheres and demonstrates the structure of the antisymmetrical field. The middle plot clearly confirms the presence of the 4-zonal structure. Four zones are visible even better on the middle plot than on the upper plot, because the antisymmetric parts which have the same amplitude in both hemispheres give the main contribution to this structure.

The symmetrical part is deduced summarizing the rotational means of the solar magnetic field in both hemispheres at the same latitudes:

$$0.5 \ast (SMF(\theta, t) + SMF(-\theta, t)).$$

By definition this part is symmetrical to the equator: high (low) values correspond to the presence of prevailing (non prevailing) polarities. The North-South symmetrical part of the SMF rotational means is shown in the bottom plot.

The bottom plot shows an interesting feature of the SMF topology: the presence of polarity streams moving from low to high latitudes. This high frequency component was noted in different solar characteristics, for example, such as neutrino flux, radius, $p$–mode frequencies (Gavryuseva and Gavryusev, 1994, 2000; Delache et al., 1993; Gavryusev et al., 1994; Kane, 2005) and a mean-field axisymmetrical bi-components dynamo model was suggested to describe it (Benevolenskaia, 1996, 1998). The multi modal approach was used by Stenflo (1974), Stenflo and Vogel (1986), Stenflo and Gugel (1988), Lawrence et al. (2004), and the relationship between solar activity and the short-term variability of the axisymmetric SMF was investigated by Erofeev (2001).

Such an interesting phenomenon should be investigated in all the details through several cycles and not only the symmetrical part of these streams. To study the phase relationship between them in both hemispheres it is necessary to use the residuals of the SMF.

3.2 Zonal Structure Running Through Latitudes

The four zonal quasi-stable structure include sub-structures of lower amplitude if they exist. To search them it is necessary to apply a filter to suppress the 4-zonal structure as much as possible. Doing this an additional latitudinal topology of the SMF with the polarity stable over about one year and running through the latitudes to the poles can be easily revealed. First Howard and LaBonte (1981) described discrete poleward streams. Then Stenflo (1994), Benevolenskaja (1996, 1998); Erofeev (2001), Lawrence et al. (2004) studied the axisymmetric variability on the time scale of about 2 years. This structure
could be called a polarity wave running through latitudes with quasi 2-year periodicity or shortly zonal wave topology.

This dynamical structure is clearly visible in Fig. 6 where the deviation of the yearly mean of the SMF from the 2-year SMF mean at each latitude with 1 CR step is plotted. In other words this deviation is a filtered magnetic field (FMF). The FMF looks similar to the symmetrical part of the SMF means (to the North-South SMF means) but it is not necessarily symmetric, and a phase relationship between the FMF(θ, t) and FMF(-θ, t) could be studied (Gavryuseva, 2005, 2006, 2006a,b,c; Gavryuseva & Godoli, 2006).

1. The main difference from the 4-zonal structure stable over 10-11 years discussed in the previous subsection is the running wave character of the polarity which is the same for all longitudes over one year and which is moving through latitudes.

2. The amplitude of the running waves is of the order of 40 micro Tesla but it reaches 90 micro Tesla at the latitudes of 20-25 degrees South. This value is half of that in the 4-zonal topology.

3. These polarity running waves have a period of about 2-3 years, and they need 2.5-3 years to run from the equator to the poles with a velocity of about 40 km/h.

The presence of such polarity waves can explain the "double" maximum of the activity cycle. Actually 11 years include five full 2-year periods, but some of the waves are partly masked by the interference with the polarity waves turning back from the poles. Let us consider for example the wave of negative polarity which appears on the equator in 1980 and the following positive polarity wave in 1981. They move to the southern and northern poles and reach 75-degrees in 1982 and 1983. The estimated time needed to reach the poles is about 2.5 – 3 years (above 75 degrees the waves could be only interpolated because these regions are not resolved).

It is possible to note in Fig. 6 an interesting phenomenon: the presence in 1985 on the middle latitudes in the northern hemisphere of a clearly visible positive polarity and of the following negative one. They smoothly move to the South, cross the equator in 1987.5–1988 and in 1989–1990, reach the southern pole in 1990.5–1991 and in 1992, and then continue the motion, but to the northern pole, which is reached in 1995.5–1996 and in 1997–1998.

The interference of such a pattern with the zonal structure produces a modification of the global 4-zonal topology from cycle to cycle. Some features of the weaker zonal wave topology can be recognized even without the filtering of the 4-zonal topology whose amplitude is at least twice stronger. Indeed in both plots of Fig. 2 streams of positive and negative polarity moving from the equator to higher latitudes can be clearly seen (for the 1 CR and 1 year mean solar magnetic field in the upper and bottom plots). The running wave topology could explain the oscillating character of the polarity inversion in the sub-polar zones.

The periodicity of the drifting latitudinal structure can be studied by the auto-correlation of the FMF data sets as a function of time shift for each latitude. The result of the calculation of the correlation coefficient is plotted in Fig. 7. The 2-year periodicity is clearly visible. The mean correlations over all latitudes...
in each hemisphere are shown at the ±80 degrees levels (multiplied by factor 30). There are maxima at 2, 3, 4, 6, 7.7, 10, etc. years shifts in the southern hemisphere; and at 3, 5, 7, 8.5, 10.5, etc. years shifts in the northern hemisphere, while the high correlation FMF and phase reconstruction over whole Sun takes place 20-21 years later. The FMF zonal wave topology has a quasi 20-year periodicity.

4 North-South Correlation of Solar Magnetic Field Variability

It is interesting to study the phase relation between the variability of the solar magnetic field in the northern and southern hemispheres at the same latitudes. The coefficient of correlation between northern and southern MSMF as a function of time delay for different latitudes is shown in Fig. 8. Orange (blue) colors correspond to the positive (negative) coefficient of the MSMF(θ, t) and MSMF(−θ, t) correlation. Strong anti-correlation at zero delay (less than -0.9) is presented over almost all latitudes in 4 zones (except around the zonal boundaries). A quasi 22-year periodicity is presented in the North-South MSMF correlation. The correlation is the lowest between the MSMF on the zone boundaries of the 4-zonal structure.

Strong 22-year periodicity of the North-South SMF correlation covers all shorter and weaker variations which we discussed in the previous section. The filtered magnetic field (FMF) should be used for the analysis of the short term North-South SMF correlation at each pair of latitudes: θ and -θ.

Fig. 9 is an illustration of the correlation between subsets of the 2-year long FMF running through 29 years with 1 CR step located at the same latitudes in northern and southern hemispheres: FMF(θ, t_i : t_i+1) and FMF(−θ, t_i : t_i+1). Orange (blue) colors correspond to the positive (negative) correlation between the northern and southern FMF variability. High correlation around the equator is attributed to the fact that SMF observational data on the neighboring latitudes are not completely independent at low latitudes. But the correlation coefficient higher than 0.9 on the latitudes θ above 10 degrees confirms that the FMF variability is synchronized in both hemispheres in the middle and subpolar zones during some intervals of time well visible in Fig. 9 as yellow color regions.

The periodical character of the North-South synchronization of the short term variability of the FMF is demonstrated in Fig. 10 for the correlation between the full FMF data sets related to θ and -θ latitudes as a function of time shift and θ. Orange (blue) colors correspond to the positive (negative) correlation coefficient.

The 2-year period in the FMF North-South correlation is presented through all latitudes. Dashed line at the level of 80 degrees corresponds to the mean correlation coefficient multiplied by 30. The highest correlation takes place with the delay of about 1.8, 9.4, 11.7, 20 and 22 years. The significance of this short term periodicity in the North-South FMF correlation is high because it is calculated for the 29-year long data sets.

Such well synchronized short and long term variability of solar magnetic field in both the hemispheres confirms the reality of the two basic topologies: four
zonal and waves running through latitudes and their periodical character. And even more, this synchronization has a quasi-periodical character (with about 2 and 10-year periodicities) as it can be deduced from Fig. 10.

This structure of the running waves type is mainly due to the magnetic field of middle intensity (from 5 to 2000 micro Tesla as it follows from the recent study of Gavryuseva, (2008a).

5 Summary

1. The latitudinal structure of the solar magnetic field with a polarity period of 22 years has been studied and compared with the SMF intensity behavior. It consists of four zones: two high latitude and two near-equatorial zones with boundaries around +25, 0 and −25 degrees.

2. The presence of polarity waves running from the equator to the poles with quasi 2-year period during the last three cycles has been clearly demonstrated.

3. The North-South asymmetry of the solar magnetic field and its short- and long-term variability in time have been studied and their synchronized character has been shown.

The magnetic field of the Sun has highly-organized latitudinal structure over the solar surface and over time,

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References

[1] Babcock, H.W. (1953), The solar magnetograph, Astrophys.J., 118, 387-396.
[2] Babcock, H.W., and H.D. Babcock (1955), The Sun’s magnetic field, 1952-1954, Astrophys.J., 121, 349-366.
[3] Babcock, H.W. (1959), The Sun’s polar magnetic field, Astrophys.J., 130, 364-365.
[4] Babcock, H.W. (1961), The Topology of the Sun’s magnetic field and the 22-year cycle, Astrophys.J., 133, 572-587.
[5] Benevolenskaya, E.E. (1996), Origin of the polar magnetic field reversals, Solar Phys., 167, 47-55.
[6] Benevolenskaya, E.E. (1998), A model of the double magnetic cycle of the Sun, Astrophys.J., 509, L49-L52.
[7] Bogart, R.S. (1987), Large-scale motions on the Sun: An overview, Solar Phys., 110, 23-24.

[8] Bumba, V. (1976), Large-scale magnetic field of the Sun, in Basic mechanisms of solar activity, edited by V. Bumba and J. Kleczec, D. Reidel Publ. Co., Dordrecht, Holland, p. 47-71.

[9] Bumba, V., and R. Howard (1965), Large-scale distribution of solar magnetic fields, Astrophys. J., 141, 1502-1512.

[10] Bumba, V., and R. Howard (1969), Solar activity and recurrences in magnetic-field distribution, Solar Phys., 7, 28-38.

[11] Cadavid, A.C., J.K. Lawrence, and A. Ruzmaikin (2005), Independent global modes of solar magnetic field fluctuations, Solar Phys., 226, 359-376.

[12] Delache, Ph., V. Gavryusev, E. Gavryuseva, F. Laclare, C. Regulo, and T. Roca Cortes (1993), Time correlation between solar structural parameters: p-mode frequencies, radius and neutrino flux, Astrophys. J., 407, 801-805.

[13] DeVore, C.R., N.R. Sheeley, and J.P. Boris (1984), The concentration of the large-scale solar magnetic field by a meridional surface flow, Solar Phys., 91, 1-14.

[14] Duvall, T.L. 1979, Large-scale solar velocity fields, Solar Phys., 63, 3-15.

[15] Erofeev, D.V. (1996), Rigidly rotating modes of the solar magnetic field, Solar Phys., 167, 25-45.

[16] Erofeev, D.V. (1999), Large-scale structure of the sunspot activity and the background magnetic field formation, Solar Phys., 186, 431-447.

[17] Erofeev, D.V. (2001), The relationship between solar activity and large-scale axisymmetric magnetic field, Solar Phys., 198, 31-50.

[18] Gavryuseva, E., and V. Gavryusev (1994), Time variations of the $^{37}$Ar production rate in chlorine solar neutrino experiment, Astron. Astrophys., 283, 978-984.

[19] Gavryuseva, E., and V. Gavryusev (2000), Solar variability and its prediction, Long and short term variability in Sun’s history and global change, ed. W. Schroder, Science Edition, Bremen, Germany, p. 89-115.

[20] Gavryuseva, E. (2005), Latitudinal streams of solar magnetic field, Proc. of 11 Int. Scientific Conf. Solar-Terrestrial Influences, Nov. 2005, BAS, 229-233.

[21] Gavryuseva, E. (2006), Topology and dynamics of the magnetic field of the Sun, News of the Academy of Sciences, Izv. TAN, Ser. Physics, 70, No.1, 102-108.

[22] Gavryuseva, E. 2006a, Latitudinal structure of the photospheric magnetic field, Proc. IAU, Vol. 2, Symposium S233, March 2006, 124.

[23] Gavryuseva, E. 2006b, North-South asymmetry of the photospheric magnetic field, Proc. IAU, Vol. 2, Symposium S233, March 2006, 63.
[24] Gavryuseva, E. 2006c, Basic topology and dynamics of magnetic field leading activity the Sun Proc. IAU, Vol.2, Symposium S233, March 2006, 67.

[25] Gavryuseva, E. 2006d, Variability of the differential rotation of the photospheric magnetic field Proc. IAU, Vol.2, Symposium S233, March 2006, 65.

[26] Gavryuseva, E. 2006e, Longitudinal structure of the photospheric magnetic field, Proc. IAU, Vol2, Symposium S233, March 2006, 61.

[27] Gavryuseva, E. (2006f), Relationships between photospheric magnetic field, solar wind and geomagnetic perturbations over last 30 years Solar Activity and its Magnetic Origin, Proc. of the 233rd Symposium of the IAU, Cairo, Egypt, March 31 - April 4, 2006, Ed. V. Bothmer; A. A. Hady. Cambridge: Cambridge University Press, 291.

[28] Gavryuseva, E. (2008a), In search of the origin of the latitudinal structure of the photospheric magnetic field, ASP Conf. Ser., 383, Proc. of ”Subsurface and atmospheric influence on solar activity”, held at NSO, Sacramento Peak, Sunspot, New Mexico, USA 16-20 April 2007, Ed. R. Howe, R. W. Komm, K. S. Balasubramaniam & G. J. D. Petrie, 99-106.

[29] Gavryuseva, E. (2008b), Longitudinal structure originated in the tachocline zone of the Sun, ASP Conf. Ser., 383, Proc. of ”Subsurface and atmospheric influence on solar activity”, held at NSO, Sacramento Peak, Sunspot, New Mexico, USA 16-20 April 2007, Ed. R. Howe, R. W. Komm, K. S. Balasubramaniam & G. J. D. Petrie, 381-388.

[30] Gavryuseva, E. (2018a), Rotation of the photospheric magnetic field through solar cycles 21, 22, 23, arXiv:1802.02461.

[31] Gavryuseva, E. (2018b), Longitudinal structure of the photospheric magnetic field in Carrington system, arXiv:1802.02692.

[32] Gavryuseva, E. (2018c), Relations between variability of solar and interplanetary characteristics, arXiv:1802.03133.

[33] Gavryuseva, E. (2018d), To the connection between intensity of the solar and geomagnetic perturbations, arXiv:1802.04548.

[34] Gavryusev, V., E. Gavryuseva, Ph. Delache, and F. Laclare (1994), Periodicities in solar radius measurements, Astron. Astrophys, 286, 305-308.

[35] Gavryuseva, E., & G. Godoli (2006), Structure and rotation of the large scale solar magnetic field observed at the Wilcox Solar Observatory, Physics and Chemistry of the Earth, Elsevier, 31, 68.

[36] Gavryuseva, E., and N. Kroussanova, (2003), Topology and dynamic of solar magnetic field, Proc. of the Tenth International Solar Wind Conference, AIP Conf. Proc., 679, 242-245.

[37] Hoeksema, J.T. (1984), Structure and evolution of the large scale solar and heliospheric magnetic fields, Ph.D. Thesis, Stanford University.

[38] Howard, R.A. (1974a), Studies of solar magnetic fields. I. The average field strengths, Solar Phys., 38, 238-299.
[39] Howard, R.A. (1974b), Studies of solar magnetic fields. II. The magnetic fluxes, Solar Phys., 38, 59-67.

[40] Howard, R.A. (1996), Solar active regions as diagnostics of subsurface conditions, Annual Rev. Astron. Astrophys., 34, 75-109.

[41] Howard, R.A., and J. Harvey (1970), Spectroscopic determinations of the solar rotation, Solar Phys., 12, 23-51.

[42] Howard, R.A., and B.J. LaBonte (1980), The Sun is observed to be a torsional oscillator with a period of 11 years, Astrophys.J., 239, L33-L36.

[43] Howard, R.A., and B.J. LaBonte (1981), Surface magnetic fields during the solar activity cycle, Solar Phys., 74, 131-145.

[44] Howard, R.F., L.L. Kitchatinov, R.S. Bogart, and E.Ribes (1991), Large scale velocity fields, Solar Interior and atmosphere, ed. Cox A.N., Livingston W.C., Matthews M.S., Arizona university press, 748-778.

[45] Kane, R.P. (2005), Short-term periodicities in solar indexes, Solar Phys., 227, 155-175.

[46] Lawrence, J.K., A.C. Cadavid, and A. Ruzmaikin (2004), Principal component analysis of the solar magnetic field I; The axisymmetric field at the photosphere, Solar Phys., 225, 1-19.

[47] McIntosh, P.S., and P.R Wilson (1985), A new model for flux emergence and the evolution of sunspots and the large-scale fields, Solar Phys., 97, 59-79.

[48] Murray, N., and P.R. Wilson (1993), The reversal of the solar polar magnetic fields, Solar Phys., 142, 221-232.

[49] Obridko, V.N., and B.D. Shelting (1999), Structure and cyclic variations of open magnetic fields in the Sun, Solar Phys., 187, 185-205.

[50] Ossendrijver, M. (2003), The solar dynamo, The Astron. Astrophys. Rev., 11, 287-367.

[51] Parker, E.N. (1955a), The formation of sunspots from the solar toroidal field. Astrophys. J., 121, 491-507.

[52] Parker, E.N. (1955b), Hydromagnetic dynamo models, Astrophys. J., 122, 293-314.

[53] Parker, E.N. (1975), The generation of magnetic fields in astrophysical bodies. X. A solar dynamo based on horizontal shear, Astrophys. J., 198, 205-209.

[54] Parker, E.N. (1988), The dynamo dilemma, Solar. Phys., 110, 11-21.

[55] Rabin, D.M., C.R. DeVore, N.R Sheeley Jr., K.L. Harvey and J.T. Hoeksema (1991), The solar activity cycle, in Solar Interior and atmosphere, edited by A.N. Cox., W.C. Livingston, M.S. Matthews, Arizona university press, 781-843.
[56] Scherrer, P.H., J.M. Wilcox, L.Svalgaard, T.L. Duvall, Ph.H. Dittmer and E.K. Gustafson (1977), The mean magnetic field of the Sun: observations at Stanford. Solar Phys., 54, p.353-361.

[57] Sheeley, N.R., C.R. DeVore and J.P Boris (1985), Simulations of the mean solar magnetic field during sunspot cycle 21, Solar Phys., 98, 219-239.

[58] Sheeley, N.R., A.G.Nash and Y.-M. Wang (1987), The origin of rigidly rotating magnetic field patterns on the Sun, Astrophys.J.,, 319, 481-502.

[59] Snodgrass, H.B. (1986), Spectroscopic evidence for a moving pattern of azimuthal convective rolls on the Sun, Astrophys.J.,, 316, L13-L39.

[60] Snodgrass, H.B. (1987a), Spectroscopic evidence for a moving pattern of azimuthal rolls on the Sun, Astrophys.J.,, 316, L91-L94.

[61] Snodgrass, H.B. (1987b), Torsional oscillations and the solar cycle, Solar Phys.,, 110, 35.

[62] Snodgrass, H.B. and R.K.Ulrich (1990), Rotation of Doppler features in the solar photosphere, Astrophys.J.,, 351, 309-316.

[63] Stenflo, J.O. (1974), Differential rotation and sector structure of solar magnetic fields, Solar Phys., 36, 495-515.

[64] Stenflo, J.O. (1977), Solar-cycle variations in the differential rotation of solar magnetic fields, Astron.Astrophys., 61, 797-804.

[65] Stenflo, J.O., M. Vogel (1986), Global resonances in evolution of solar magnetic fields, Nature, 319, 285-290.

[66] Stenflo, J.O., M. Gudel (1988), Evolution of solar magnetic fields: Modal structure, Astron.Astrophys.,, 191, 137-148.

[67] Stenflo, J.O. (1994), in R.J.Rutten and C.J.Schrijver (eds.), Solar Surface Magnetism, Kluwer Academic Publishers, 365.

[68] Stix, M. (1981), Theory of solar cycle, Solar Phys., 74, 79-101.

[69] Stix, M. (2004), The Sun. An Introduction, Second Edition, Springer-Verlag, Berlin.

[70] Tikhomolov, E. (2001), Hydrodynamic source of the 11-year solar variations, Solar Phys., 199: 165-186.

[71] E. Tikhomolov E., Mordvinov V. (2001), Long-term evolution of the magnetic field generated by an ensemble of Rossby vortices, Astron. Nachr.,, 322, 3, 189-195.
Figure 1: Distribution of the magnetic field intensity in latitude and in time averaged over 1 CR (upper plot) and over one year (bottom plot) with 1 CR step. Yellow colors indicate high intensity values. In the upper plot, the contours correspond to the 100 and 300 micro Tesla levels, while in the bottom plot, there is an additional level corresponding to 50 micro Tesla of the yearly mean SMFI.
Figure 2: Distribution of the magnetic field in latitude and in time averaged over 1 CR (upper plot) and over one year (bottom plot) with 1 CR step. Yellow and red (blue) colors indicate positive (negative) polarities. In the upper plot the contours correspond to the levels of 0, ±50, 100, 300 micro Tesla, in the bottom plot there are additional levels corresponding to ±50 micro Tesla of the yearly mean SMF. In the upper plot 0-level is indicated by a black line. In the bottom plot the contours correspond to the levels of -50, 0, 50 micro Tesla.
Figure 3: The polarity inversions are plotted by continuous lines. The latitudes weighted with the SMFI between 0 and ±50 latitude degrees are shown by points without averaging (upper plot) and by dotted lines for the latitudes weighted with 1 CR mean of the SMFI (bottom plot). In the bottom plot the positions of the maxima of the SMFI mean over 1 CR in both hemispheres are shown by dashed line.
Figure 4: The auto-correlation of the 1-year mean SMF distribution as a function of time for different latitudes. Orange (blue) colors correspond to the positive (negative) coefficient of the MSMF(θ, t) auto-correlation.
Figure 5: The mean solar magnetic field over 1 CR as a function of time and latitude (upper plot). The difference or antisymmetrical part of the SMF 1 CR running means is shown in the middle plot. The North-South symmetrical part of the 1 CR means of the SMF is shown in the bottom plot. Yellow and red (blue) colors indicate positive (negative) polarities. The contours correspond to zero level and to the ±50 micro Tesla.
Figure 6: The deviation of the yearly mean of the SMF from the 2-year mean of the SMF for each latitude with 1 CR step. Orange (blue) colors correspond to the positive (negative) correlation coefficients.
Figure 7: The coefficient of the auto-correlation of the filtered magnetic field data sets as a function of time shift for each latitude. Orange (blue) colors correspond to the positive (negative) correlation coefficients.
Figure 8: The coefficient of correlation of the full data sets at $\theta$ and $-\theta$ latitudes as a function of time shift and $\theta$. Orange (blue) colors correspond to the positive (negative) correlation coefficients. Dashed line at the level of 80 degrees corresponds to the mean correlation coefficient multiplied by 30.
Figure 9: The coefficient of correlation of the subsets of the FMF 2-year long running through 29 years with 1 CR step located at the same latitudes in northern and southern hemispheres: $\text{FMF}(\theta, t_i : t_{i+1})$ and $\text{FMF}(-\theta, t_i : t_{i+1})$. Yellow and orange (blue) colors correspond to the positive (negative) correlation coefficients.
Figure 10: The coefficient of correlation between the northern and southern FMF as a function of time delay for different latitudes. Orange (blue) colors correspond to the positive (negative) coefficient of the $\text{FMF}(\theta, t)$ and $\text{FMF}(-\theta, t)$ correlation.