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Large-scale patterns and 'active longitudes'

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Abstract. The following aspects of the physics of large-scale solar magnetic fields are discussed: structure of large-scale fields (LSF) and connection with local fields; dynamo and origin of LSF; LSF cycle variation; meridional circulation and LSF; rotation of LSF; fine structure of the field in quiet regions and the concept of the pebble-shaped field; active longitudes, their manifestation in various solar indices, and dependence on the power of solar activity.

Keywords. Sun: magnetic fields, rotation, sunspots

1. Introduction

The majority of up-to-date high-resolution magnetograms (SOHO MDI, SOLIS) display the magnetic field as an aggregate of very fine features. This philamentary structure was foreseen long ago, and its direct observation nowadays is, undoubtedly, a major achievement in the experimental solar physics. The cluster model of sunspots is corroborated by helioseismic data, which has far reaching implications for the theory of magnetic field generation in the Sun.

On the other hand, we have, unexpectedly, lost clear understanding of the large-scale background field. To begin with, its very existence is disputable. There are reasons to believe that the field between the so-called 'kilogauss' tubes is absent. Then, however, the extended regions, obviously, dominated by the fields of one polarity can not be accounted for. High-resolution images only reveal these extended unipolar regions, but if we superimpose a low-resolution map on a high-resolution magnetogram, the polarities will coincide. So, the fine magnetic elements are not randomly distributed over the solar surface, but, rather, form vast regions where one or another polarity is dominating. This is most likely due to the influence of a large-scale (or global) weak magnetic field. Thus, we arrive at the conclusion that a relatively weak global field must exist, which somehow organizes the position of the fine-structure elements.

Both energy and hydrodynamic aspects of this process still remain obscure. We do not know whether background fields are the primary features or are formed as a result of decay of local fields. It is not clear how deep they go down; i.e., are they large-scale all over or only at the surface? Mathematically, the field extrapolation to the upper corona does not make distinction between these cases.

Many properties of the background fields are still vague and even puzzling. Besides, one must discriminate between the notions of background and global fields, which often, is not that simple.

2. Magnetic dipole

The effective magnetic dipole is the base of the large-scale structure. Its magnetic moment and direction are readily calculated from WSO observation data downloaded from (http://quake.stanford.edu/wso/wso.html). The analysis performed by Livshits and Obridko (2006) has shown that the total magnetic moment occasionally decreases significantly, never turning to zero. During one or two years in the declining phase of the activity cycle, the magnetic moments of the vertical (aligned with the solar rotation axis) and horizontal (aligned with the solar equator) dipoles are comparable. This situation is known in astrophysics as the oblique rotator.

During the epoch of the solar minimum, the pole of the dipole executes relatively regular precession motions completing 1–2 circles around the solar rotation axis. This quasi-precession lasts for 1–3 years. Then, the dipole makes a jump to the equatorial zone for 0.7–1.2 years and continues a smooth longitudinal motion for another 1.5–3 years. After that, a new jump occurs, and the 'precession' goes on around the opposite pole of the Sun.

Large-scale fields rotate in anti-correlation with the solar activity indices. The rotation of the global magnetic field decelerates as the activity increases both in the 11-year cycle and in longer term cycles. The maximum rotation periods were recorded in the middle of the XX century, in the extremely powerful cycles 18 and 19 (Obridko and Shelting 2001).

The discrepancy between the rotation of local and global fields may be important in studying the mechanism of dynamo. The Carrington rotation manifests the rotation of the existing sunspots, while the global field may reflect the rotation rate of the sunspot generation region and may affect the distribution of sunspots on the disk.

3. Fine structure of the background field

An interesting feature was revealed lately by the analysis of high-resolution SOHO/MDI observations. It might seem that the background field, which, by definition, lies beyond the local fields, must be quasi-uniform. In fact, it consists of fine elements and looks like a neat pebble beach.

Another peculiarity is that the field in these elements is virtually horizontal (see Fig. 1). The center-to-limb variation for the background field as a whole is positive; i.e., the observed values decrease to the limb as they must do in a quasi-radial field. For the weakest fields considered to be small-scale elements of the background field, the variation is negative suggesting that these fields are mainly tangential (Ioshpa *et al.*, 2009). A similar result was obtained in the very first measurements of the full vector outside the active regions, but it was attributed to low sensitivity in measuring transversal fields. At

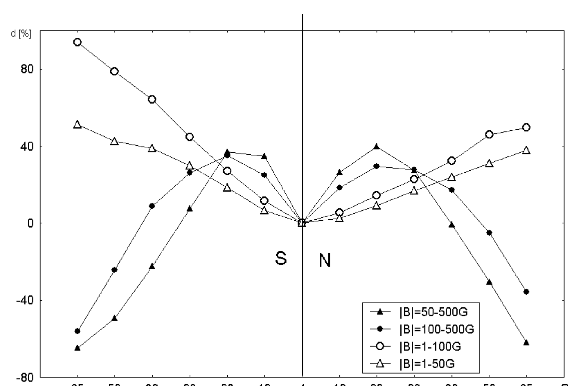

Figure 1. Center-to-limb variation of SOHO/MDI magnetic fields of different scales.

present, it is established for sure that the field in the small-scale elements is tangential. The elements of the background field resemble the windfall of trees in the forest.

The existence of these elements may be due to the fact that some physical processes take place inside a thin double layer located at about 0.995 R, which is called **leptocline** (Lefebvre *et al.* 2007).

4. Meridional motions

Obridko and Shelting (2003) revealed mutually opposite motions of large-scale and local fields, whose rates were not constant. They interpreted these results as follows. Magnetic fields are generated at the base of the convection zone. The wave of generation moves from the mid latitudes to the equator. The rapidly emerging concentrated local fields follow the wave of generation and form a butterfly diagram, being probably, additionally enhanced in the leptocline region. On the other hand, the slowly emerging diffuse large-scale fields loose connection with the wave of generation and are driven to the poles by the meridional drift.

In addition to the mean meridional flow from the equator to the poles, Švanda *et al.* (2007) found extra meridional circulation cells converging towards the activity belts and migrating to the equator as the solar cycle progresses.

The speed of the magnetic flux transport towards the solar poles may differ significantly from the longitudinally averaged speed of the meridional flow. Therefore, the longitudinal structure of these flows should be taken into account.

In the past decades, the study of cyclic variation of solar activity, i.e., regularities that govern the 11-year and 22-year (magnetic) cycles as a whole, is giving place to a detailed study of their internal fine structure. These investigations have revealed a great number of phenomena whose nature is not entirely clear. Besides the cycle variation, all parameters of solar activity experience quasi-periodic oscillations with shorter periods ranging from seconds to years. Of particular interest are oscillations with a period of the order of 1–2 years.

5. Variation of solar indices with a period of 1.3 years

Several studies are devoted to oscillations with a period of 1.3 years revealed at the bottom of the solar convection zone. Komm *et al.* (2002, 2003, 2004) and Howe *et al.* (2000) found out that the 1.3-year periodicity at the base of the convection zone is most pronounced in the solar rotation rate at the equator of the tachocline. The 1.3-year variation of the solar rotation rate in the vicinity of the tachocline was also revealed by Schou (2003). Komm *et al.* (2006) and Kosovichev (2003) did not find evidence of the 11-year cycle near the tachocline, where the 1.3-year oscillations of the solar rotation rate were most noticeable. As shown by Christensen-Dalsgaard (2006), the solar rotation is not stationary: regions of faster and slower rotation alternate in the narrow tachocline region with the mean amplitude increasing towards the solar equator. It is also noted that the amplitudes of variation of the rotation rate and solar activity correlate (see Toomre *et al.*, 2003). A series of work (McDonald *et al.*, 2005; Cadavid *et al.*, 2005) was devoted to the study of quasi-periodicity in fluctuations of the axisymmetric solar magnetic field with the use of the main component and independent component analyses. The oscillation periods of the order of 1.0–1.5 years were considered to be typical of the polar and high-latitude fields and the periods of 1.3 and 1.7 years, to characterize the mid- and low-latitude solar events. The wavelet analysis carried out by Krivova and Solanki (2002) revealed 1.3-year periodicities in the tracers of emerging flux at the solar surface, in particular, sunspots. The power of these variations was observed to vary strongly with time.

Using Mt.Wilson magnetographic data for 1986–1994, in particular, rotation velocity measurements, Javaraiah (2003) found that the 1.3-year periodicity was dominant in the solar surface rotation rate. Özgüç *et al.* (2003) used the Fourier and wavelet transforms to show that variations with a period of 1.3 years were present in the daily flare index. It turned out that the amplitude of short-term oscillations varied strongly with time. Rybák and Karlovský (2003) arrived at a similar conclusion. They isolated a few unstable periodicities in the Wolf number variation for 1850–2002, including the period of 1.3 years. Ikhsanov and Ivanov (2004) revealed the same periodicity in the large-scale solar magnetic field from Stanford (1976–2004) and Kitt Peak (1970–1984) magnetic data. The spherical harmonic coefficients of radial magnetic field for the axisymmetric and non-axisymmetric modes were calculated in (Knaack *et al.*, 2005; Knaack and Stenflo, 2005; Knaack, 2005) from Mt.Wilson and Kitt Peak daily magnetograms, and a few modes were isolated in the variation of the photospheric magnetic field. It was shown that these modes differ in different activity cycles; e.g., the 1.3-year periodicity is better pronounced in the even cycles (20, 22) than in the odd ones (21, 23).

Mendoza *et al.* (2006) studied the periodicities in various types of the solar magnetic flux (total, closed, open, low- and high-latitude open fluxes). All fluxes fluctuate with a period of 1.7 years. The medium-term, one-year fluctuation is significantly present in the total and closed fluxes, but it is less important in the open fluxes. Due to the uncertainties involved in estimating the exact period of the quasi-annual peak, the authors could not differentiate it from the 1.3-year periodicity. In their opinion, this high-frequency component is in phase with the 11-year solar cycle. Wang and Sheeley suggested that 1.3-year oscillations could occur as a result of stochastic interaction of local fields and meridional flows (Wang, 2004; Wang and Sheeley, 2003).

It should be noted that the studies using the data on large-scale magnetic field are necessarily based on relatively short observation series covering 2–3 solar cycles. Direct helioseismic observations are even shorter. An exception is the work by Makarov *et al.* (2002) where the authors calculated the photospheric magnetic field by an original method using a long series of observations of H-alpha filaments and prominences from 1915 to 2000. The revealed 1.3-year periodicity in latitudinal oscillations of the zonal boundaries of the large-scale magnetic field (neutral lines) was associated with oscillations of the solar rotation rate in the tachocline region. It was shown that this latitudinal oscillation was weak in the period 1950–1970 in the northern hemisphere, but was clearly pronounced in 1960 in the southern hemisphere. The authors did not find significant correlation of this periodicity with the 11-year cycle.

Gulyaev (2006) has demonstrated that these oscillations coincide with oscillations of the heliospheric current sheet. This result was corroborated by Obridko and Shelting (2007).

Livshits and Obridko (2006) analyzed the periodic components of the rotation of the effective solar dipole. They found out that the solar dipole can be resolved into the 'vertical' (co-axial) and horizontal components. Only two frequencies can be identified in the variation spectrum of the magnetic moments of these dipoles. The quasi-11-year cycle is absolutely similar for the magnetic moments of the horizontal and vertical dipoles. The situation is quite different if we consider oscillations with a period of 1.3–2.5 years, so called QBO. These periods are only present in the magnetic moment of the horizontal dipole and are absolutely absent in the case of the vertical dipole.

In the recent years, the oscillation periods of 1.3 years are not as clearly identified in helioseismic measurements as they were earlier (Howe, 2009). This raises the question of how reliable they are and how often they occur in the variation spectrum of different solar parameters. Obridko and Shelting (2007) have shown that oscillations with a period of 1.3 years usually vanish in the declining phase of the 11-year cycle. Below, in Section 9, these oscillations are treated as a short-term acceleration of the global field.

6. Tentative conclusions. What we do not know?

We do not fully understand the nature and evolution of large-scale field but it is sure enough that this is not a mere result of low-resolution observations.

It is not clear how the weak large-scale fields can control the organization of stronger local fields.

We do not know whether the fields of different scales are generated at the same or at different depths.

Some physical processes take place inside a thin double layer, located near the photosphere

7. Active longitudes

The active longitudes were first discovered by Wolfer in 1897, but they still remain the object of heated debates. It should be noted that the term 'active longitudes' without the particular index specified is quite indefinite. Obviously, the active longitudes for sunspots are not the same as the active longitudes for coronal holes. In this work, we shall deal mainly with the active longitudes for sunspots.

Below, we shall mention only some publications on active longitudes to illustrate the main contradictions. The tendency of the solar cycle to manifest itself at some preferred longitudes was found by Benevolenskaya *et al.* (1999) and Bumba *et al.* (2000). The data on the occurrence of sunspots confirm the existence of two preferred longitudes separated by 180°, which migrate in a fixed rotation frame but are persistent throughout 120 years. Their differential rotation differs significantly from that of individual spots. This implies that the depth at which sunspots are formed (and affected by the non-axisymmetric component of the field) is not the same as the anchoring depth of developed sunspots (I. G. Usoskin, S. V. Berdyugina and J. Poutanen (2005).

The lifetime of the sunspot formation zones exceeds significantly the lifetimes of individual spots and may reach 15–20 rotations. The stability of the active longitudes is larger for the larger spots (Ivanov, 2007). This is superimposed by a more intricate system of longitudes that rotate at different velocities.

The system of active longitudes with the rotation period $P \sim$ 27 days prevails in the most intensive 11-year activity cycles. The system of active longitudes with $P \sim 28$ days is best pronounced at the minimum of the secular cycle. The most stable magnetic structures at a quasi-source surface in the solar corona are separated by $\sim 180°$ in heliographic longitude and are similar to dipolar structures. The nature and behavior of these large-scale magnetic patterns are interpreted as a superposition of cyclic dynamo modes and the nonaxially symmetric relic field of the Sun (Mordvinov and Kitchatinov, 2004; Kitchatinov and Olemskoi, 2005).

This result is in contradiction with the aforementioned deceleration of the global magnetic field in cycles 18–19 (Obridko and Shelting, 2001). However, the rotation periods of global and local fields may depend on activity in different way.

The occurrence of the active longitudes is considered in a number of theoretical papers. Bigazzi and Ruzmaikin (2003) explain the Suns preferred longitudes as a coupling of the magnetic dynamo modes. Elstner and Korhonen (2005) believe that, 'to explain

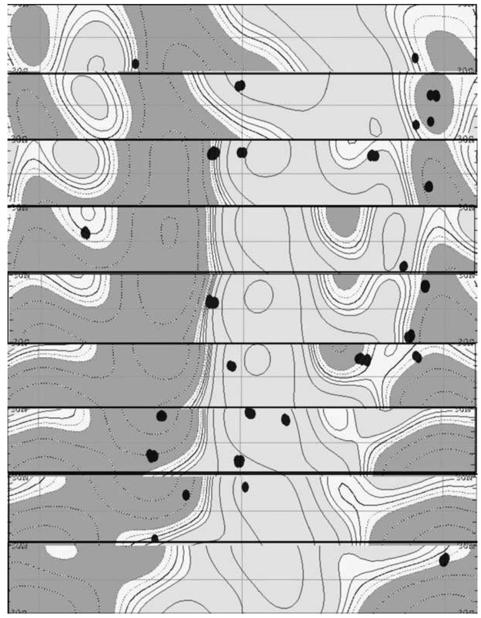

Figure 2. Synoptic maps of large-scale magnetic field (Carrington rotations 1676–1684) with the positions of major active regions marked.

this phenomenon, a non-axisymmetric dynamo mode, giving rise to two permanent active longitudes at opposite stellar hemispheres, is needed together with an oscillating axisymmetric magnetic field'. Axel Brandenburg and Petri J. Käpylä (2005) solve a two-dimensional mean field dynamo model where magnetic helicity conservation is fully included. The model develops longitudinal variability with activity patches traveling in longitude. These patches may be associated with active longitudes.

On the other hand, the existence of two active longitudes was questioned by various authors or was denied altogether, at least, over long time intervals. Losh (1938) found that there is one maximum and one minimum per rotation, and that the phase of the maximum is stable over a solar cycle. Balthasar and Schüssler (1984) investigated sunspot numbers and showed that the phase of the maximum remains more or less the same for two solar cycles and then, it changes by about 180°. Balthasar (2007) revealed only one maximum in the Fourier spectrum, i.e., one active longitude. Knaack & Stenflo (2005) and Knaack *et al.* (2005) used Mt.Wilson and Kitt Peak magnetograms and found that the dominant rotation periods were different for cycles 21, 22 and 23. Bouwer (1992) investigated various indicators of solar activity and found that precise periods between 27 and 28 days persist only for a short time, sometimes only for a few solar rotations. Pelt *et al.* (2006) claim that strong and well substantiated evidence for an essential and century-scale persistent nonaxisymmetry in the sunspot distribution does not exist. Henney and Durney (2007) found a surprisingly non-negligible likelihood, approximately 1 in 3, that observed periodicities from integrated full-disk solar parameters are a chance occurrence for time series of the order of 20 years in duration.

8. Active longitudes and structure of the large-scale field

The success in detecting the active longitudes depends on many factors, in particular, on the intensity of events and on the shift of the large-scale field boundaries. As the latter, we can assume the heliospheric equator. Such a study was performed by Bumba and Obridko (1969). They analyzed the positions of major proton complexes relative to the sector boundaries (Bartels active longitudes) and arrived at the following conclusions:

1. The flare activity and especially the proton flare activity is concentrated in the zones of 'Bartels' active longitudes.

2. The flare activity and especially the proton flare activity is concentrated in the neighborhood closest to the sector boundaries.

3. It seems that the concentration of flare activity around the 'active longitudes' as well as around the sector boundaries increases with the importance of the event. The highest degree of concentration may be seen for the proton-flare regions.

Later, these conclusions were verified more than once and were corroborated on the whole, particularly, when major groups were involved.

Figure 2 shows the position of the heliospheric equator and some major active regions. About 70% of spots with the area > 500 m.p.h are located at a distance less than 20° in longitude from the neutral line of the large-scale field.

However, the longitude of the axis of the effective solar dipole (and the longitude of the associated neutral line) changes with the course of time.

Now, let us consider how the Carrington longitude of the north pole of the effective magnetic dipole changes over a long time interval. Figure 3 illustrates the time variation of this coordinate for 29 years from 1977 to 2005.

One can see that the Carrington longitude of the north pole of the effective magnetic dipole increases gradually by about 1.5° for one Carrington rotation and by 1.5° for a year. This means that the rotation period of the global magnetic field is 27.1621 days, i.e., is by 0.1132 day smaller than the Carrington rotation rate. After approximately one Hale cycle, the system of longitudes returns to its initial position.

This is seen from the longitude-latitude diagram in Fig. 4.

The dotted curve represents the motion of the north pole of the effective solar dipole in the Carrington reference frame. The cycle minima are marked. The black solid curve is approximation by the 5-order polynomial. Note that transition from one hemisphere to another occurs at approximately the same longitudes.

Thus, the magnetic dipole restores both its magnitude and position every 22 years after having passed through all Carrington longitudes and latitudes. The associated reference frame executes a similar periodic motion.

The failure in identifying the active longitudes is often due to the fact that the latter are rather associated with the rotation of the large-scale field than with Carrington

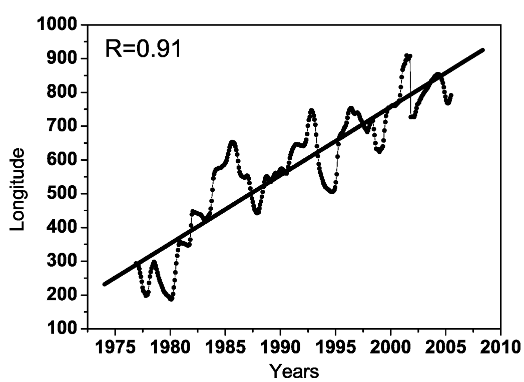

Figure 3. Time variation of the longitude of the north pole of the effective solar dipole

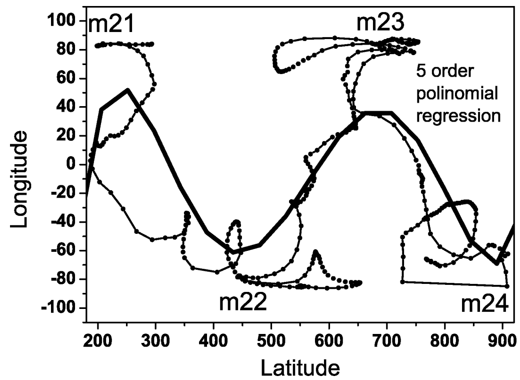

Figure 4. Longitude-latitude diagram of the rotation of the solar dipole

coordinates. Over a few years, the active longitudes in Carrington coordinates become unstable and are restored again in the following cycle.

9. Rotation of the solar effective dipole

Knowing the longitude shift of the pole, we can calculate the time dependence of the dipole rotation rate (Fig. 5). It is seen from the figure that, though the mean rotation rate of the dipole is only by 0.4% larger than the Carrington rotation rate, the dipole is occasionally accelerated to reach the velocity of 14.7°/day, which exceeds the Carrington rotation rate by 13.6% and corresponds to the syndic rotation period of 24 days. The solid curve shows approximation by the 4-order polynomial. As is readily seen, it is precisely these short-term accelerations that make the mean velocity in the relatively low cycles 21 and 23 exceed the mean velocity in the higher cycle 22 in agreement with (Obridko and Shelting, 2001).

It is interesting to note that the accelerations have a periodic character. Figure 6 represents the Fourier power spectrum of the rotation rate of the effective magnetic dipole. One can see that the acceleration occurs with a typical period of 1.4 years. In the declining phase of cycle 23, however, the acceleration is absent in agreement with the result by Howe (2009).

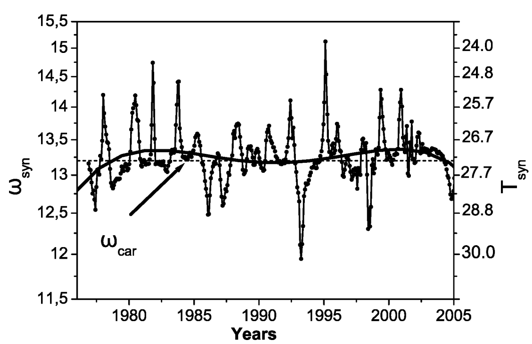

Figure 5. Time dependence of the synodic angular rotation rate of the solar effective dipole (ω_{syn}) and synodic period (T_{syn}). The dotted line shows the angular rate of Carrington rotation (ω_{car}).

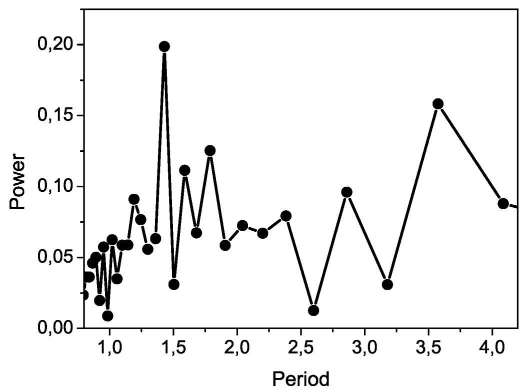

Figure 6. Fourier spectrum of the rotation rate of the solar dipole

10. General conclusions

All active events in the Sun are the result of interaction of the global (possibly poloidal) and axisymmetric (quadrupole-like) fields.

The term 'active longitudes' is not quite correct, since they are not constant either in time or space and are closely related to the structure of the large-scale field.

The active longitudes are connected with the large-scale field and are best pronounced in the most powerful events and major sunspot groups.

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