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'Active Longitudes' in the Heliomagnetic Reference Frame

V.N. Obridko · V.E. Chertoprud · E.V. Ivanov

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Abstract A new coordinate system – heliomagnetic reference frame – has been proposed in which the great circle passes through the solar pole and the north pole of the magnetic dipole is considered as the central meridian. It is shown that, in the new coordinate system, the active longitudes are defined much more clearly, are more stable in time, and are interlaced every 11 years.

Keywords Solar magnetic field · Solar rotation

1. Introduction

The active longitudes are known since 1897 (Wolfer 1897a, 1897b), but they still remain the object of heated debates. There is a vast literature on the subject, which is partly reviewed in Obridko (2010)[1]. The concentration of sunspot groups is usually studied in the classical, Carrington coordinates. In some cases, the authors use coordinates with a rotation period different from the Carrington period. Here, we propose a coordinate system associated with the global magnetic dipole of the Sun, which we have called "heliomagnetic coordinates".

The idea that active phenomena in the Sun may concentrate at the boundaries associated with the large-scale field was put forward as early as in 1969 by Bumba and Obridko (1969). We can assume the heliospheric equator as such boundary. Bumba and Obridko (1969) analyzed the positions of major "proton complexes" relative to the sector boundaries and Bartels

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[1] Unfortunately, that work contains some citation errors. Benevolenskaya, Kosovichev, and Scherrer (1999) and Bumba, Garcia, and Klvana (2000) considered a short series of data (29 years), which did not allow any conclusions about the 120-year behavior. A consistent 120-year non-axisymmetric pattern is described in the work by Berdyugina (2004), Berdyugina and Usoskin (2003), and Usoskin, Berdyugina, and Poutanen (2005). But in their papers, the length of the "flip-flop" cycle is claimed to be 3.8 and 3.65 years (see Berdyugina, 2004, p. 128). We apologize to the authors and thank the reviewer, who called our attention to this inaccuracy.

V.N. Obridko (✉) · V.E. Chertoprud · E.V. Ivanov
Institute of Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation RAS, Troitsk,
Moscow Region 142190, Russia
e-mail: obridko@izmiran.ru

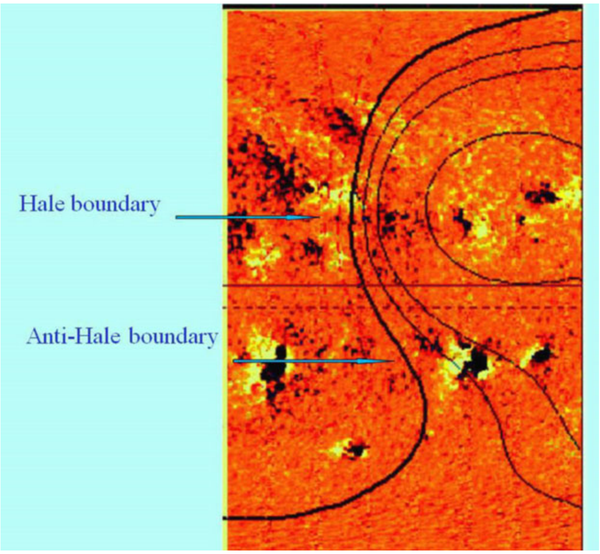

Figure 1 Positions of ARs with respect to the heliospheric equator.

active longitudes. They reached the following conclusions (note that the term “proton complex” was usually applied to a long-lived active region or a group of active regions that produced intensive proton flares):

i) Flare activity and, especially, the proton flares are concentrated in the zones of ‘Bartels’ active longitudes.
ii) Flare activity and, especially, the proton flares are concentrated in the neighborhood closest to the sector boundaries.
iii) 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, being the highest for the proton flares.

The idea that the concentration of flares around active longitudes increases with the power of phenomena has been studied recently for X-ray flares by Zhang *et al.* (2007). They found that there are two active longitudes for X-ray flares, separated by 180°, which have existed for tens of years. X-ray flares occur more often near the two active longitudes than sunspots do. The non-axisymmetry of the longitudinal distribution of X-ray flares increases with the X-ray flare class. Stronger solar activities occur preferentially at certain longitudes.

This result, applied to sunspot, was verified later by Obridko (2010); it was found that about 70% of the spots with an area >500 MSH proved to be located at a distance of less than 20° in longitude from the neutral line of the large-scale field. We have to remember the important conclusion by Ivanov (2007), who inferred that the longitudinal organization of sunspot groups depends on their area: the larger the area the more pronounced the active longitudes.

One should bear in mind that, with the Hale polarity law taken into account, the concentration of active regions at the sector boundaries must depend on the sign of the sector. Figure 1 illustrates the position of active regions with respect to the heliospheric equator. According to the polarity law, the active regions in the northern hemisphere should appear in the vicinity of the sector boundary. This is the Hale boundary. Correspondingly, at a distance of about 180°, there is the opposite-sign boundary, where the appearance of ARs is less probable. This can be called “anti-Hale” boundary. In the southern hemisphere, the boundaries change places. The boundaries determined in such a way correspond physically to the Hale sector boundaries introduced by Svalgaard and Wilcox (1976). An important difference is that Svalgaard and Wilcox (1976) used data of the interplanetary magnetic field (IMF) sector structure reconstructed from observations of the geomagnetic field variation. They showed that the corona green-line brightness at the Hale boundary was higher than at the anti-Hale boundary. In fact, this is the result we expected to obtain for sunspots. In our work, however, the heliospheric equator is determined directly from observations of the solar magnetic field. The term "anti-Hale boundary" may be not quite adequate. Probably, it would be better to say "inverted Hale boundary". Still we preferred to keep this term in our work, because it was introduced 35 years ago and is used in many publications.

The change of active longitudes is similar to the flip-flop effect. Based on the analysis of data extending from 120 years, Berdyugina and Usoskin (2003) claimed that the length of the flip-flop cycle was 3.8 and 3.65 years. However, according to Usoskin, Berdyugina, and Poutanen (2005), the flip-flop occurred when the main maximum of the longitudinal distribution switched over to secondary minimum. They assumed everywhere bimodal (with two maxima) distributions. Elstner and Korhonen (2005) revealed flip-flop effects with periods from 4 to 17.5 years on 11 stars (see Table 1 in Elstner and Korhonen, 2005). To avoid misunderstanding, we shall use hereinafter the term "11-year switchover effect". This effect is particularly well pronounced in the heliomagnetic reference frame.

2. Heliomagnetic Reference Frame

Based on the results previously obtained, we propose a new coordinate system related to the global magnetic field. Since building up a new coordinate system is not a simple procedure, we shall discuss it in detail. At first sight, it seemed natural to simply rotate the whole coordinate system by an angle equal to that between the solar rotation axis and the dipole axis. In doing so, we changed both the longitudes and latitudes of sunspots. In such a system, the longitude could be measured along the dipole equator. However, it became clear very soon that this results in artifacts and spurious concentration of "sunspots" at the intersections of the dipole and solar equator even in the case of a uniform distribution of sunspots. Therefore, we have changed the definition of the heliomagnetic coordinate system. Now, the usual Carrington system is turned about the solar rotation axis by an angle determined by the longitude of the north pole of the dipole, *i.e.*, we do not move the pole of the heliomagnetic coordinate system from the pole of the Carrington system, but we move the origin in longitude. Then, the zero longitude corresponds to the Carrington longitude of the point in the photosphere at which the north pole of the dipole is localized in the given rotation. Actually, this means turning the Carrington reference frame by a specific angle for every rotation. Therefore, the longitude of a point in the new system is equal to its Carrington longitude minus the instantaneous longitude at the origin of coordinates in the given rotation. The latitude remains unchanged. We have

$$\mathrm{lat}_{\mathrm{new}} = \mathrm{lat}_{\mathrm{Car}};$$

$$\mathrm{long}_{\mathrm{new}} = \mathrm{long}_{\mathrm{Car}} - \mathrm{long}_{\mathrm{dipole}}.$$

In this case, no matter where and for how long we move the origin, the distribution that is uniform in one reference frame will remain as such in another one, independently of the phase of the cycle.

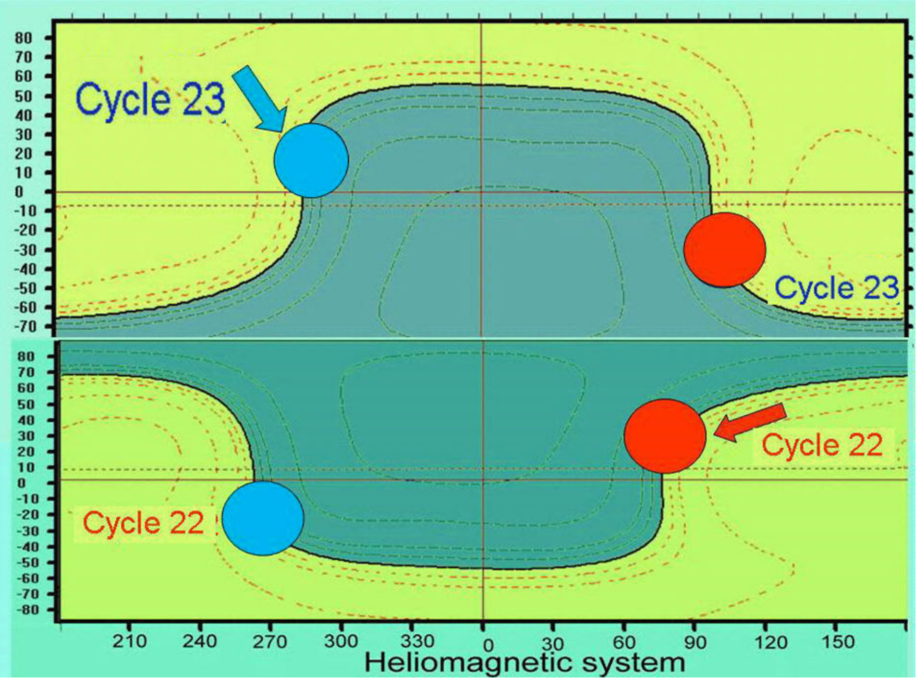

Figure 2 A scheme of the location of sunspot groups relative the heliomagnetic equator in two successive activity cycles.

The fact is that cyclic variations in the direction of the solar dipole comprise both inclination with respect to the heliographic equator and rotation about the solar axis. The dipole rotation about the solar axis is taken as the basis of the heliomagnetic coordinate system. In this system, the inclination only appears in the change of the dipole latitude, while the intersection of the heliomagnetic (or heliospheric) and heliographic equators remains unchanged.

For the central meridian, we take the great circle passing through the solar pole and the north pole of the magnetic dipole. The coordinates of the dipole north pole are directly calculated from the Wilcox Solar Observatory (WSO) data on the solar global magnetic field.

Figure 2 represents the location of sunspots with respect to the heliomagnetic equator. In the heliomagnetic coordinates, all longitudes are fixed, while the latitude of the dipole pole is changing. The heliomagnetic equator is the intersection of the plane perpendicular to the dipole axis, passing through the center of the Sun, with the solar surface. On the latter, the heliomagnetic equator looks as a sine curve, which is plotted as a thick black line in the figure. Accordingly, in the heliomagnetic coordinate system, the heliomagnetic and heliographic equators intersect at two fixed points. By definition, the zero longitude corresponds to the northern polarity (dark blue). The circles show the preferred position of the active regions in accordance with the Hale polarity law (blue and red denote, respectively, the north and south polarity of the main spot). Thus, the Hale longitudes in the heliomagnetic coordinates in Cycle 22 are 90° in the northern hemisphere and 270° in the southern hemisphere. In Cycle 23, the Hale longitudes are reversed. This scheme explains how the solar 11-year switchover effect appears.

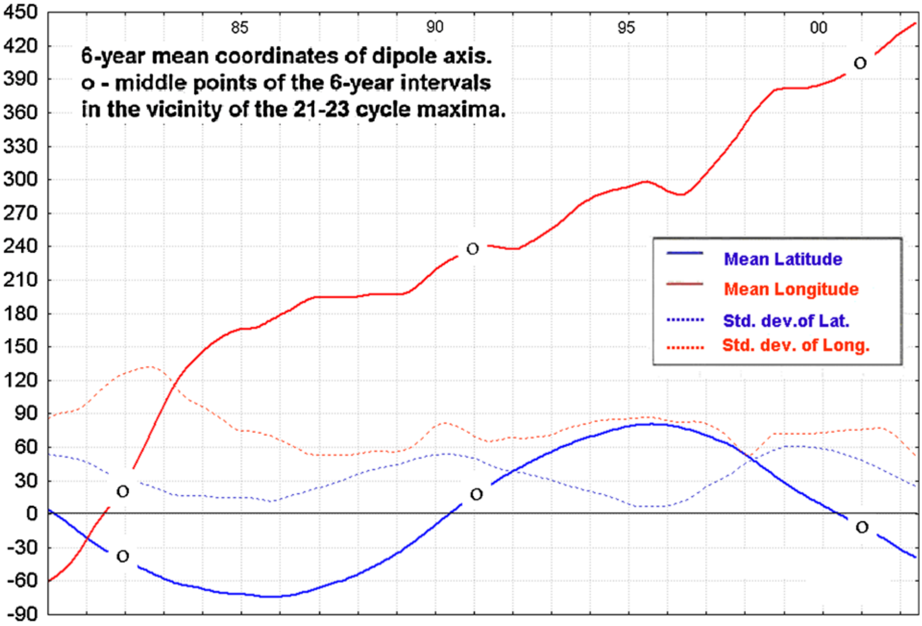

Figure 3 Longitude-latitude diagram of the rotation of the solar dipole.

The determination of heliomagnetic longitudes in the epoch of minimum when the dipole axis and the solar rotation axis coincide does involve certain difficulties. In this period, the scatter of points increases. However, the number of sunspot groups at cycle minimum is small, so that the scatter has little effect on identifying the active longitudes.

Thus, the longitude of the axis of the effective solar dipole (and the longitude of the associated neutral line) changes with time. 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. The longitude of the effective solar dipole shifts by 20.2° per year in average and by 360° for 18 – 20 years. After approximately one Hale cycle, the system of longitudes returns to its initial position. This is seen from the longitude–latitude diagram in Figure 3. Note that in the vicinity of cycle maximum, the Carrington longitude of the dipole pole is close to 0° or 180°. At the maxima of the odd cycles, the zero longitudes in both systems are similar and at the maximum of the even cycle, they differ by 180°. This is important when comparing the distributions in two reference frames.

Note that the 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.

Note that a smooth longitude variation in Figure 3 is a deliberate simplification used to illustrate that the dipole longitude changes significantly over the period of several cycles. The real longitude variation is not uniform and comprises a lot of jumps sometimes as large as 360° (see Figure 7 in Livshits and Obridko, 2006). This raises the question of how the curve could be extended further in the case of 360° jumps. In order to avoid the latter and obtain a smooth variation, we added or subtracted 360° in the vicinity of 0 or 360, respectively. It was not until a relatively smooth variation was obtained that the averaging was performed.

Nevertheless, changes in the sense of rotation of the dipole and its retrograde motions are still possible. They can be seen if the retrograde motions last for no less than a year. The periods of retrograde motion are seen on the diagrams in Livshits and Obridko (2006) and Obridko (2010). Besides the retrograde motion, one can also see a gradual shift of the longitude for the time intervals comparable with an activity cycle. This shift is illustrated in Obridko (2010) and in Figure 3 in the present work.

It must be noted, however, that the procedures of eliminating the 360° uncertainty and averaging do not affect the results of the present work. Here, we are using for the zero longitude the Carrington longitude of the point in the photosphere at which the north pole of the dipole is localized in the given rotation without averaging. In this case, the jump of 360° is insignificant, since the distribution relative to 2° and 362° remains approximately the same.

3. Active Longitudes in the Carrington and Heliomagnetic Coordinates

In the context of our previous discussion, we undertook the task of identifying the active longitudes in the heliomagnetic coordinates and comparing the degree of concentration of sunspot groups in their vicinity in both coordinate systems.

The analysis is based on the following data:

- Total sunspot areas and numbers for 1976 – 2005 provided by the US Air Force and NOAA. Both the numbers and areas of sunspots were used in the analysis.
- WSO observations of the solar large-scale magnetic field for 1976 – 2009.
- Positions of the global magnetic dipole calculated from WSO data for 1976 – 2005.
- SOHO MDI observations of background fields for 1998 – 2003.

Figure 4 illustrates the distribution of sunspot areas and numbers over the Carrington longitudes in the northern and southern hemispheres. One can see that no particular dominating longitudes can be isolated in either hemisphere. An increase observed in the vicinity of the longitudes 90° and 270° is statistically unreliable.

Figure 4 (as well as the following Figures 5 and 6) were plotted with the graphical software package Origin 8.1. The smoothing curves were drawn using the standard method by Savitzky and Golay (1964) (*i.e.*, the local polynomial fit using the second polynomial order, two points to the left and two points to the right).

Figure 5 represents the distribution of total sunspot areas in different cycles, separately, for the southern and northern hemispheres in the heliomagnetic reference frame. Repeated observation of the same group on a different day was considered a new measurement. The total number of separate measurements of the area was 11 928. Thus, we had about 2000 measurements for each hemisphere in each cycle. All values in the figure are in relative units. The sum of areas in a given longitude interval is divided by the total sum of areas in a given hemisphere over a given cycle. The mean value on each diagram is 0.0555. The region of deviation from the mean by one r.m.s value is shaded. The smoothing curves are drawn as in Figure 4.

One can see that the longitudes 90° and 270° stand out systematically in all cycles. Particularly, the Hale longitudes are well marked. These are 270° in the odd cycles and 90° in the even Cycle 22 in the northern hemisphere and vice versa in the southern hemisphere (see Figure 2). This regularity is particularly well marked in Cycles 21N and 22N. In other cases, the active longitudes are not seen as clearly, but all points on the smoothed curves, at which the sum of areas differs from the mean value by more than σ, correspond to the Hale heliomagnetic boundaries.

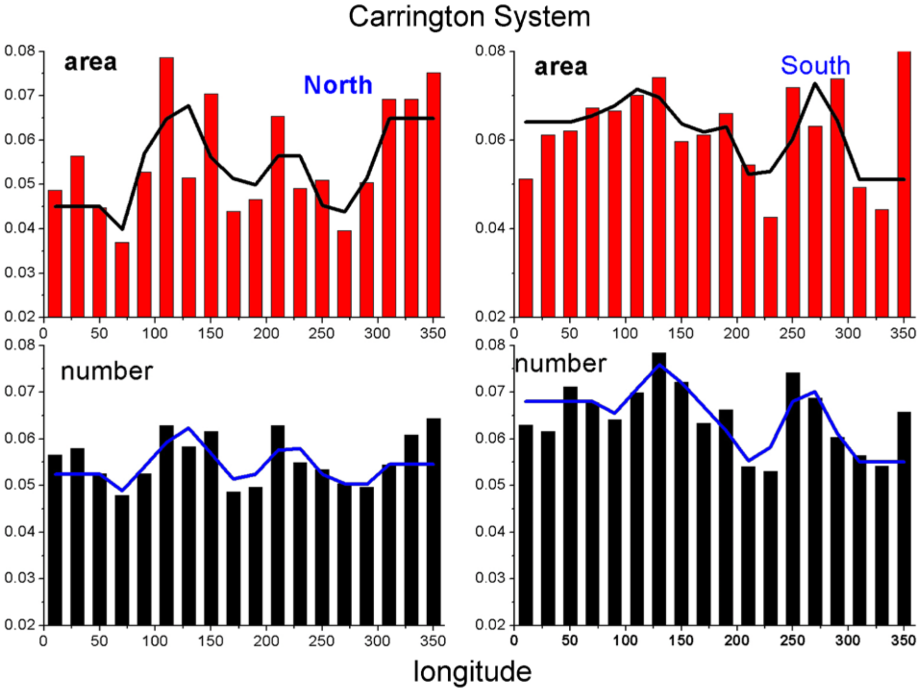

Figure 4 Distribution of sunspot areas and numbers over the Carrington longitudes in the northern and southern hemispheres in the period 1976 – 2005. The continuous black and blue lines are the smoothing curves.

It is true that remapping may result in artifacts, in particular, when the cyclic coordinates are used. Though in our case, the coordinates rotate at an essentially different rate from that of the Carrington system, and the dipole longitude increases continuously, we still verified the reliability of our result.

We generated 10 random longitudes for every cycle and each hemisphere (*i.e.* about 60 000 randomly determined "longitudes") and substituted them for the directly measured ones, leaving the areas and latitudes of sunspots without change. Then, we calculated the distribution diagrams in heliomagnetic coordinates similar to the diagrams represented in Figure 5. Applying the χ^2 analysis, we found that, for these diagrams, the hypothesis of uniform distribution could be rejected only with a probability less than 30%. Besides, the points on some diagrams departing from the mean value by more than σ are located chaotically and have nothing to do with the Hale heliomagnetic boundaries.

According to the concept of switchover effect, the longitudinal distribution of sunspot areas must display pair-to-pair correlation. The distributions in the northern hemisphere in the odd cycles must correlate positively between themselves and with the distributions in the southern hemisphere in the even cycles and negatively with the distributions in the northern hemisphere in the even cycles and in the southern hemisphere in the odd cycles. The calculated correlation of Cycle 21N with Cycles 21S and 22N is negative (−0.40 and −0.59, respectively), and with Cycles 22S and 23N is positive (0.25 and 0.61). These values agree with the expected ones. However, the correlation between Cycles 21N and 23S turned out to be positive (0.63). On the other hand, the correlation between Cycles 23N and 23S is negative (−0.33) as expected.

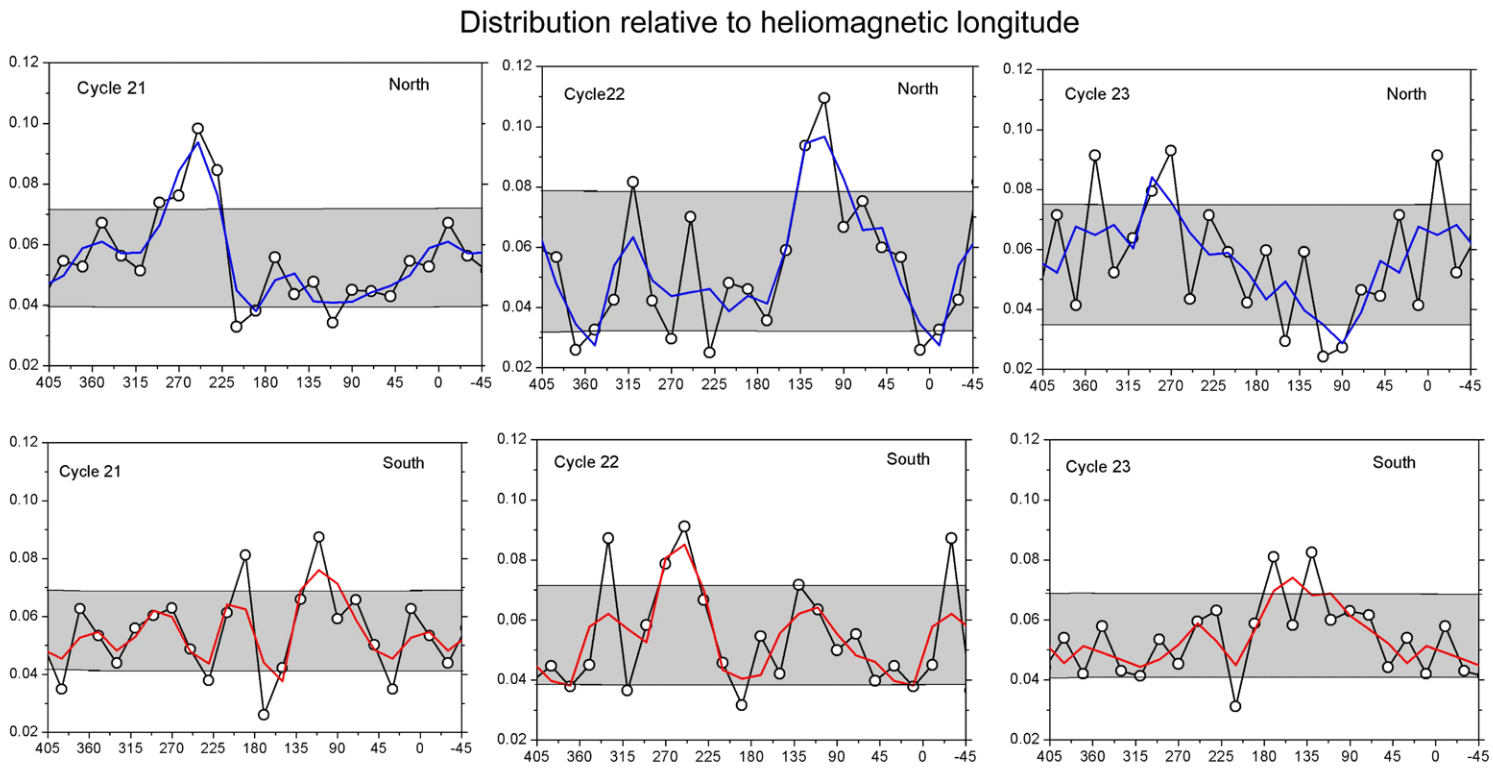

Figure 5 Distribution of total sunspot areas in different cycles in the heliomagnetic reference frame. The blue and red lines are the smoothing curves.

The switchover effect can be verified as follows. Since the Hale boundary in Cycles 21N, 22S, and 23N is known to be at the heliomagnetic longitude of 270° and in Cycles 21S, 22N, 23S, correspondingly, at the longitude of 90°, we can plot integral distributions with respect to these longitudes. The same procedure was also applied to random distributions. For this purpose, the sets of data for all cycles of both groups mentioned above were fully revised. The data were normalized to the sum of areas in each group of cycles. For the sake of comparison, the longitudes in the cycles were reduced to zero; *i.e.*, in the final distributions, we subtracted 270 from all longitudes of the first group and 90 from the longitudes of the second group. Thus, contrary to Figure 5, all longitudes are given with respect to the Hale boundary in the particular cycle and in the particular hemisphere.

Figures 6(a, b, c) illustrate the results of the comparison for each group of cycles and for the totality of cycles under consideration. Figures 6(d, e, f) show the results of the comparison for a random distribution. One can see a noticeable concentration at the Hale boundary for real sunspots and its absence for the random distribution.

The last check involved an independent analysis based on magnetic data. A similar comparison was carried out for control in the heliomagnetic reference frame using the SOHO/MDI magnetic data. We calculated the normalized annual mean values of the squared intensity of the magnetic field for the period 1998 – 2003. This period corresponds to the maximum of Cycle 23. In the other phases of the cycle, the strong fields were too scarce. The calculations were performed for two conditions: for all pixels with $|B| > 100$ G and with $|B| > 500$ G. The distribution of sunspot areas for the same period (maximum of Cycle 23) is shown in the same figure for comparison (Figure 7). The data were smoothed over three points. It is readily seen that the curves in each hemisphere roughly coincide. One can also see a pronounced concentration at the Hale longitudes in both hemispheres and the 11-year switchover effect.

4. General Conclusions

The distribution of sunspot groups and their areas in Cycles 21 – 23 and the distribution of strong magnetic fields in Cycle 23 have been analyzed. It was shown that the term ‘active longitudes’ is not quite correct, since they are not constant either in time or in space. Over a few years, the active longitudes in Carrington coordinates become unstable and are restored again in the following cycle.

On the other hand, many authors consider that the Carrington reference frame may not be the best one. However, none of the time-invariant coordinate systems improves the situation. Then, we may consider a time-variable system related to some real location on the Sun.

It was shown that the local activity in the Sun is governed by the global magnetic field. In agreement with this fact, the active regions tend to appear in the vicinity of the sector boundaries, *i.e.* the heliomagnetic equator. So, we introduce a new coordinate system and we relate it to the global magnetic dipole rotating about the Carrington coordinates. In doing so, we found that the active longitudes became much more clearly defined, were more stable in time, and were interlaced every 11 years. Naturally, the rotation of the active longitudes differed from that of individual sunspots, as was claimed in Benevolenskaya, Kosovichev, and Scherrer (1999), Bumba, Garcia, and Klvana (2000), Usoskin, Berdyugina, and Poutanen (2005). It is relevant to the present work that the rotation rate of the sector structure does not coincide with the Carrington rotation rate as was demonstrated by various authors (Mikhailutsa and Makarova, 1999; Kuklin and Obridko 1988a, 1988b, 1988c; Kuklin, Obridko, and Vitinsky, 1990; Obridko and Kuklin, 1994). The rotation periods of the

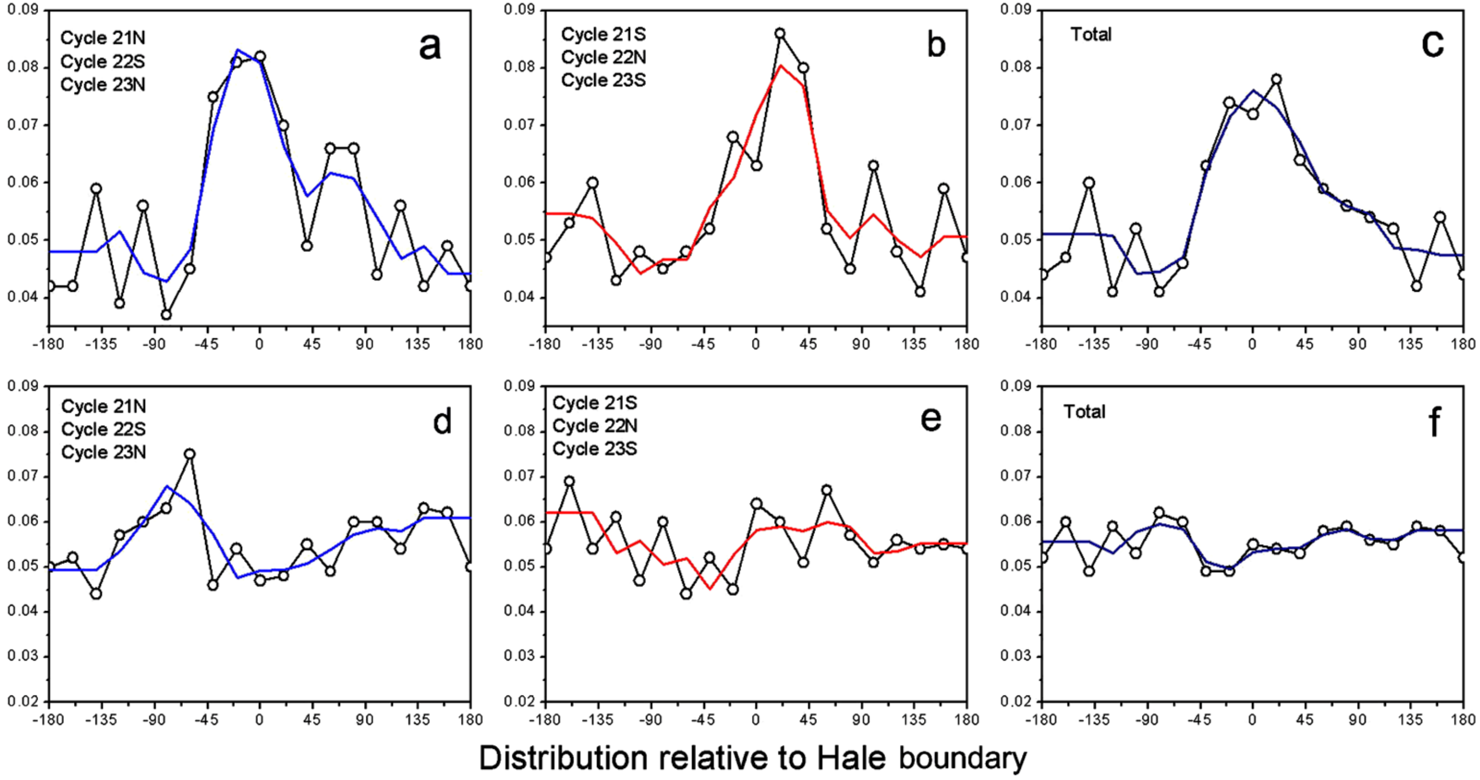

Figure 6 Comparison for Cycles 21N, 22S, 23N (a), Cycles 21S, 22N, 23S (b), and for all cycles under consideration. (c) (d), (e), and (f) show the results of the comparison for a random distribution for the same groups of cycles accordingly. The red and blue lines are the smoothing curves.

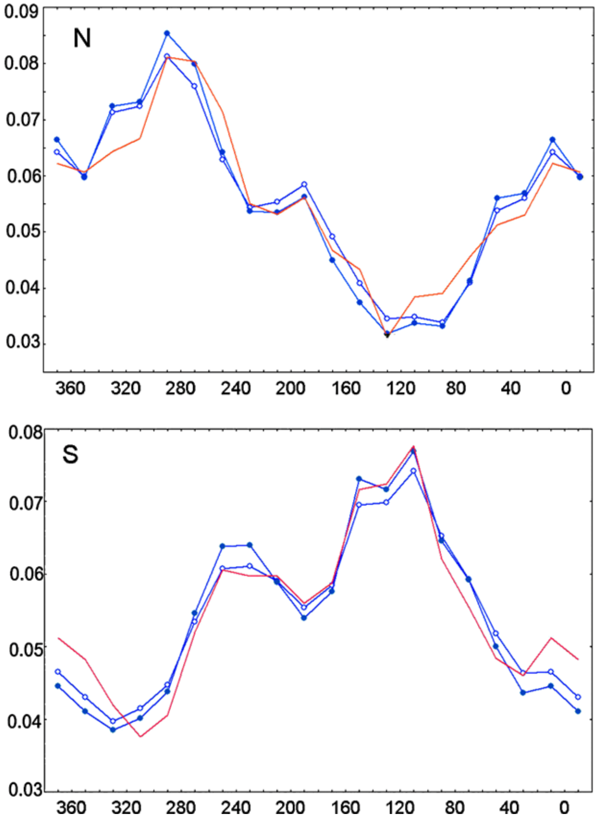

Figure 7 Distribution of the sums of the magnetic field intensity to the second power for the period 1998 – 2003 – blue curves (open circles correspond to $|B| > 100$ G and filled circles, to $|B| > 500$ G) and distribution of sunspot areas – red curve. The abscissa shows the longitude in the heliomagnetic reference frame.

interplanetary magnetic field sector structure were specified by the method of correlation-periodogram analysis. The analysis revealed discrete periods of 27.0 and 28.2 days, not coinciding with the Carrington rotation rate (*e.g.*, see Kuklin, Obridko, and Vitinsky, 1990; Obridko and Kuklin, 1994).

The results obtained here, using a physics-based reference frame, are in general agreement with the results published earlier by Berdyugina and Usoskin (2003) and Usoskin, Berdyugina, and Poutanen (2005), who used an *ad hoc* differentially rotating frame. The longitude migration of the pole (see Figure 3) strikingly resembles the longitude migration in the reference frame used by Berdyugina and Usoskin (2003) (see their Figure 3), both in shape and amplitude. We have not studied possible flip-flops on time scales shorter than a solar cycle; thus, we cannot conclude about the ∼ 3.7 year flip-flop period found in Berdyugina and Usoskin (2003); however, the 11-year flip-flop inferred in this paper is consistent with earlier results in that, if averaged over a cycle, there is a switch in the active longitudes between odd and even cycles. The use of the heliomagnetic reference frame made it clear why the active longitudes in the Carrington coordinates were unstable, but were often restored in the following cycle or one cycle later (Ivanov, 2007; Mordvinov and Kitchatinov, 2004; Kitchatinov and Olemskoi, 2005).

As seen from Figure 4, the zero longitudes at the odd maxima coincide in both systems, while at the maximum of the even cycle, they differ by 180°. As a result, the active longitudes in both systems are close at cycle maximum, but after about 20 – 40 rotations, the zero longitudes will depart from each other by ∼ 40° so that the longitude, which is active in the heliomagnetic system, will not be so in the Carrington system. This situation repeats every 11 years. Therefore, the analysis over a long time interval suggests the existence of two stable active longitudes in the heliomagnetic reference frame. Thus, the sunspot data confirm the existence of two preferred longitudes separated by 180°, which migrate in a fixed rotation frame but are persistent throughout some cycles.

The use of integral parameters (solar irradiance and magnetic field of the Sun as a star) combining the data from both hemispheres leads to the same conclusion.

Note that in the discussion of Figure 2, we tentatively proposed that one Hale and one anti-Hale basic longitudes might exist in each hemisphere in the heliomagnetic coordinates. We did not suggest the existence of only two such longitudes; therefore, we extended our investigation whose results are illustrated in Figure 5. It turned out that the higher concentration was observed in the vicinity of the longitudes spaced by 180° in the heliographic coordinate system. The existence of four sectors is also clearly marked in Figure 5. This figure, based on experimental data, allowed us to conclude that the Hale boundary in Cycles 21N, 22S, and 23N is located at the 270° heliomagnetic longitude, while it is located at the 90° longitude in Cycles 21S, 22N, and 23S. Then, based on Figure 5, we combined data for three cycles and plotted Figure 6. Thus, the existence of two preferential longitudes in the heliomagnetic system is not *a priori* a statement but follows from our statistical analysis.

Mikhailutsa and Makarova (1999) showed that the four-sector structure was most frequent. However, their conclusion was drawn from the analysis carried out in the Bartels coordinates. Of course, the four-sector structure exists in the Sun as a consequence of the quadrupole component, but the longitudinal stability of this component has not been investigated so far. There are no reasons to suggest that the quadrupole in the Sun always takes a fixed position with respect to the dipole, which would ensure a stable two-sector structure in the heliomagnetic coordinates.

It is the dipole that determines the heliospheric equator and is the main harmonic of the global field during most of the cycle (*e.g.*, see Bravo, Stewart, and Blanco-Cano, 1998, Figure 1c).

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