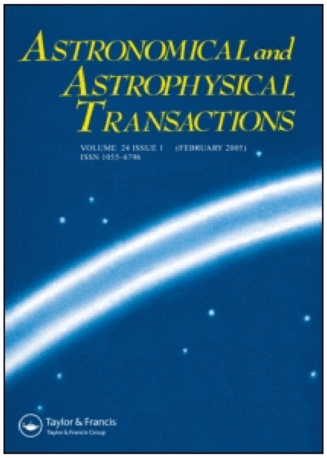

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V. P. Mikhailutsa [a]; V. V. Makarova [a]
[a] Kislovodsk Solar Station of the Pulkovo Observatory, Kislovodsk, Russia

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THE GLOBAL SECTOR-HEMISPHERICAL ASYMMETRY OF THE SOLAR ACTIVITY

V. P. MIKHAILUTSA and V. V. MAKAROVA

Kislovodsk Solar Station of the Pulkovo Observatory, Kislovodsk, 357700, Russia

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It has been found that the longitudinal distributions of the number of sunspot groups in Bartel's rotational system ($T_s = 27.0^{\rm d}$ synodic) in the last five solar cycles have demonstrated similar sectoral-hemispherical features as were previously found for the number of polar faculae and bright KCa^+ points (Mikhailutsa and Makarova, 1994). The number of groups alternates up and down in 90° sectors with opposite phase north and south of the equator. In these sectoral bands the polar faculae and the similar bright-limb-point number distributions have been investigated in the 10° latitudinal bands at the minimum of solar activity (years 1985 and 1986). It has been found that these points were concentrated again in four sectors with the same sectoral-hemispherical features and covered the solar surface from one pole to another: the faculae and bright-points show a different phase at low and high latitudes. It has been shown that this phase difference could be interpreted as an inclination of the sector boundaries to the solar meridians. These facts suggest that the global solar field is organized over very long time intervals with a very precise "clock". The structure has four inclined sectors per Bartel rotation in each solar hemisphere.

KEY WORDS Solar cycle, rotation, sector structure, magnetic field

1 INTRODUCTION

For the first time, a global sector-hemispherical asymmetry has been found for the longitudinal distributions of the polar faculae and bright KCa^+ points at high solar latitudes (Mikhailutsa and Makarova, 1994). It was shown that the polar faculae and bright KCa^+ point longitudinal distributions in the rotation system $T_p = 27.227$ days (synodic) demonstrate three specific features:

(1) the longitudes of maxima and minima of the distributions were approximately the same in the last five solar cycles;

(2) there were predominantly two opposite longitudinal maxima and two opposite longitudinal minima in the distributions in each solar hemisphere;

(3) The distributions of the northern and southern hemispheres were in opposite phase.

These are the common features of the global sector-hemispherical asymmetry of the extreme situations of polar activity. But sunspot areas have not demonstrated these features. Does the sunspot activity not "feel" that global long-lived structure, or there is another reason? This presentation is dedicated to that problem.

The question touches upon a problem of the origin of solar large-scale magnetic fields. At the present time there are two opposing views about large-scale patterns of solar surface magnetic flux. One is that once flux erupts, large-scale patterns are simply the result of observable surface motions. The other view is that the large-scale patterns are controlled by processes deep within the Sun. The flux transport model, developed mainly by Wang *et al.* (1991), nicely explains in latitude-time coordinates (the one-dimensional Sun) nearly all the observations of large-scale magnetic flux patterns and their evolution. The model reproduces also some of the large-scale longitude structures seen in polar regions over the course of solar cycle 21 (Wang and Sheeley, 1994). There are some difficultes in the model in explaining the poleward surges of magnetic flux during some parts of the cycle, but on balance, the model works surprisingly well. There are physical objections to the first view, but we suppose that the main crucial question now is whether this model of the axisymmetrical or special local meridional magnetic-flux migration of the remnants of the active region is of any physical importance for the evolution of large-scale background magnetic patterns. Another crucial question is whether the Carrington rotation and the differential rotation are real rotations of the background magnetic patterns or whether the rotation rate might be used as a free parameter to study the evolution of this field in latitude–longitude coordinates? The positive answers to these questions lend physical support to the second view. We adopt the second view and take into account the global sectoral structure of large-scale patterns in an attempt to create a satisfactory scenario for the solar cycle. The flux transport model cannot reproduce some observed phenomena, which are very important for the two-dimensional Sun. For example:

(1) At times of solar polar magnetic field reversal the large-scale magnetic flux patterns have a sectoral quadrupole-like structure dominately, together with a considerable equatorial dipole (Hoeksema and Scherrer, 1986; Hoeksema, 1991; Mikhailutsa, 1995). Why are there quadrupole and sectoral dipole interrelations among unipolar patterns of the large-scale fields when magnetic flux arises on the solar surface (according to the first view) as bipolar ephemeral and active regions?

(2) The connections between important eigenmodes of the large-scale magnetic field polarity distributions at epochs of minima and daily mean sunspot areas at epochs of maxima of solar cycles demonstrate that the sectoral mode ($m = 1$) is a key to solar cycle magnitudes and, in principle, the subsurface motion idea is better than the surface motion scenario (Mikhailutsa, 1993; 1994).

In that respect the absence of global sector-hemispherical asymmetry in sunspot activity extremes raises some doubts.

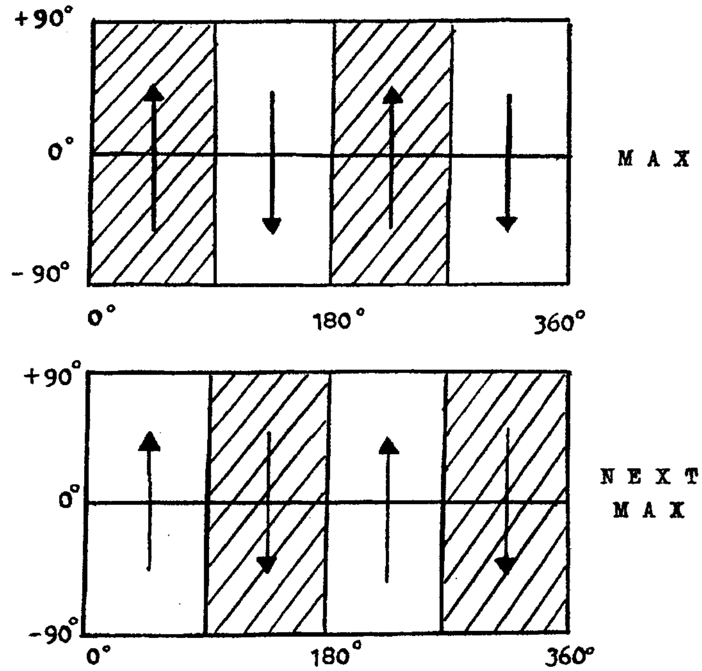

Figure 1 Scheme of the observed sector polarity structure of the background magnetic field in cylindrical coordinates in two successive solar cycle maxima. The polarities are distinguished by retouching. The arrows indicate the directions of the background magnetic flux migration. The period of rotation of the longitudinal frame of references is equal to $T_p = 27.23^d$ synodic (Mikhailutsa, 1995).

2 THE POSSIBLE VALUES OF THE FOUR-SECTORAL STRUCTURE ROTATION RATE

The aforementioned period of rigid sector structure rotation ($T_p = 27.227^d$) was revealed due to the synoptic line charts of the equatorial-coronal hole magnetic flux polarities (Mikhailutsa, 1995). The polarities were reversed in four longitudinal sectors at solar cycle minima, passing through the global dipolar configuration. At maxima, the solar polar fields were reversed, while the equatorial quadrupole was most intensive. The scheme of this large-scale background magnetic field polarity configuration at two successive solar cycle maxima is shown in Figure 1. The arrows indicate the direction of polarity migration in sectors (Mikhailutsa, 1995). Note that this scheme presents the background large-scale magnetic field structure without the active region magnetic fields, which strongly mask the picture. Certainly there is nothing that reaches the polar regions that looks like this figure. It should be a global subsurface process. One can see in Figure 1 that at successive solar cycle maxima the positions of the equatorial quadrupole-like sectors of similar polarity differ in longitude by a value of $\pm 90° + 180° n$, where n is an integer to be determined

($n = 0, 1, 2, \ldots$). These longitudinal polarity shifts can be interpreted as an apparent displacement of the large-scale polarity patterns due to the difference between the real and used ($T_p = 27.227^d$) rotational rates of the longitudinal frames of reference. Here we have simply correlated similar structures that exist in several cycles. In that respect the question arises: What is the real period of the sector structure rotation? The rotational rate has to be determed correctly by the rotation of sector boundaries. Let T_d be the mean solar cycle duration (the average of the last five solar cycle durations is: $T_d \approx 10.5$ years). Then one can estimate the value of the real period of the sector boundary rotation, T_s (having in mind Figure 1), from the relation:

$$T_d \cdot (1/T_s - 1/T_p) \cdot 360^\circ = \pm 90^\circ \cdot n. \tag{1}$$

From this equation it follows that for an observer on Earth the period $T_s = T_p = 27.227^d$ (for which $n = 0$ in equation (1)) can be a harmonic of any real period of the sector structure rotation. Essentially, the absence of the sectoral-hemispherical features in sunspot longitudinal distributions found by Mikhailutsa and Makarova (1994) can be caused by this discrepancy between the real and used rotational rates, because the result depends radically on the rotation of the frames of reference.

The role of the sectoral sources is extremely interesting in reviewing the solar cycle scenario. Having investigated the properties of the sector structure, three aims of the present work have been formulated:

(1) to determine the value of T_s, which reveals the three specific features of the sectoral-hemispherical asymmetry of the sunspot region's distributions (T_s can be interpreted as the "real" period of sector structure rotation);

(2) to determine the sunspot characteristics that match other analyses;

(3) to find the shape of sectors on the solar surface.

3 THE METHOD OF INVESTIGATION AND RESULTS

We have used archive and current Kislovodsk sunspot data for solar cycles Nos. 18–22. The number of sunspot groups, their areas and mean longitudinal coordinates have been taken into account.

The number and areas of sunspot groups were summarized separately inside 30° longitudinal bands for each half-year time interval. These longitudinal bands were shifted by a corresponding value of longitude toward the west to keep in mind the difference between the Carrington rotation and the rotation of the sectors. We have checked several possible variants of the sectoral rotational rates: $T_s = 27.18^d$ ($n = 1$); $T_s = 27.13^d$ ($n = 2$); $T_s = 27.08^d$ ($n = 3$); $T_s = 27.04^d$ ($n = 4$); $T_s = 26.99^d$ ($n = 5$); $T_s = 26.94^d$ ($n = 6$); and $T_s = 26.89^d$ ($n = 7$), up to finding the "real" rotation rate. A positive sign for n in equation (1) has been chosen, because the harmonic $n = 0$ ($T_s = 27.227^d$) indicates that sectors have to be rotated faster then the Carrington rotation rate (Mikhailutsa, 1995).

Table 1. The distributions of sunspot group numbers in 30° longitudinal bands in Bartel's system of rotation

Northern hemisphere

Longitudinal bands in heliographical degrees: 1 = 45–75; 2 = 75–105; 3 = 105–135; 4 = 135–165; 5 = 165–195; 6 = 195–225; 7 = 225–255; 8 = 255–285; 9 = 285–315; 10 = 315–345; 11 = 345–15; 12 = 15–45

Cycles	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
18	102	97	125	90	104	98	107	102	138	92	110	96
19	221	216	200	188	192	184	222	212	215	179	217	187
20	155	143	160	140	132	120	151	148	172	148	168	118
21	149	142	165	147	133	146	162	146	150	163	146	123
22	122	102	111	92	109	110	133	122	125	100	125	97
Sum	**749**	**700**	**761**	657	670	658	**775**	**730**	**800**	682	766	621

Southern hemisphere

Cycles	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
18	102	100	107	99	108	128	99	107	100	104	108	114
19	132	134	136	153	134	130	109	125	118	123	102	182
20	105	112	98	119	102	115	97	87	97	130	163	120
21	127	131	151	157	160	207	139	140	134	174	164	189
22	101	88	119	147	147	135	108	101	108	145	157	143
Sum	567	565	611	**675**	**651**	**715**	552	560	557	**676**	**694**	**748**

In addition, we have examined two characteristics of the sunspot activity: the sum of the sunspot areas and the total number of sunspot regions in separated longitudinal bands. The summation was carried out for each group of solar cycle data. We have searched for combinations of the inferred periodicities and sunspot characteristics that reveal sectoral-hemispherical features on the solar surface. This was the criterion for making the choice of the "real" sector structure rotational rate.

The sunspot areas – a commonly used characteristic of sunspot activity – in these variants of rotation had a tendency to be concentrated toward four equally spaced longitudinal boundaries (as was shown in Figure 3 of Mikhailutsa and Makarova, 1994 for $n = 0$), but the hemispherical asymmetry of the sunspot areas was absent.

This kind of asymmetry has been found for numerous sunspot groups, and only the inferred period of sector rotation $T_s = 26.99^d$ ($n = 5$) has given good result: the number of groups alternates up and down in 90° sectors with opposite phase north and south of the equator. All other periodicites give smoothed distributions of the spot group numbers in sectors. This period practically coincides with the famouse Bartel period of rotation ($T_s = 27.0^d$). The result is presented in Table 1.

To strengthen the evidence of the result, each cycle number of the sunspot regions in 30°-longitudinal bands were added. In Table 1 the bold-faced numbers in the sum rows indicate the 90°-longitudinal bands of the enhanced sunspot group productivity in comparison with the neighbouring sectors. The sector boundary

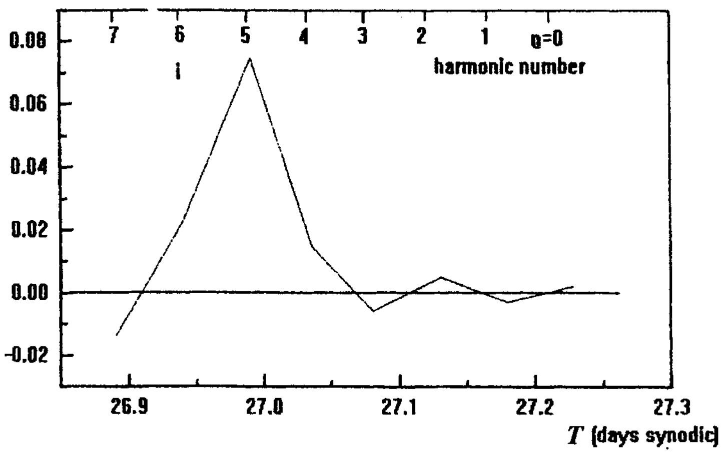

Figure 2 Sector-hemispherical contrast relative to the inferred periods of rotation.

positions are well definded by averaging over the last five solar cycles. The Bartel longitudes of the sectoral boundaries were: 45°–135°; 135°–225°; 225°–315°; and 315°–45° (the start epoch for longitudes is the beginning of the year 1945).

Note that the value of 766 in zone 11 in the northern hemisphere in Table 1 disagrees with all others (mainly due to solar cycle No. 19). This may have been caused by the 30°-longitudinal harmonic of the four sector structure, the tracks of which can be seen in Table 1. The limited data does not allow us to find the correct explanation. We have explored only a small range of possible periods and found, using the number of sunspot groups as their definition, a good correspondence with the organization of other characteristics of solar activity (polar faculae and bright KCa^{+} points). The "true" (Bartel) rotation rate was chosen because it best fits the data.

To present a quantitative description of how well the various periods actually organize the different data sets, we have constructed the "sector-hemispherical contrast parameter", C. Let the sectors be marked correspondingly by numbers: 1,2,3, and 4, and by hemispherical index N or S. Then the C parameter can be calculated from the following relation:

$$C = \frac{K_1^N - K_2^N + K_3^N - K_4^N + K_2^S - K_1^S + K_4^S - K_3^S}{K_1^N + K_2^N + K_3^N + K_4^N + K_1^S + K_2^S + K_3^S + K_4^S}, \tag{2}$$

where K_1^j, is a sunspot group number in any sector-hemispherical pattern ($i = 1,2,3,4$; $j = N, S$). The bigger the sectoral and/or hemispherical differences of group numbers, the bigger the numerator in equation (2) and the larger the value of the C parameter. In Figure 2 C values are shown relative to the used periods of the sectoral structure rotation. The sharp peak corresponds to Bartel's period of rotation.

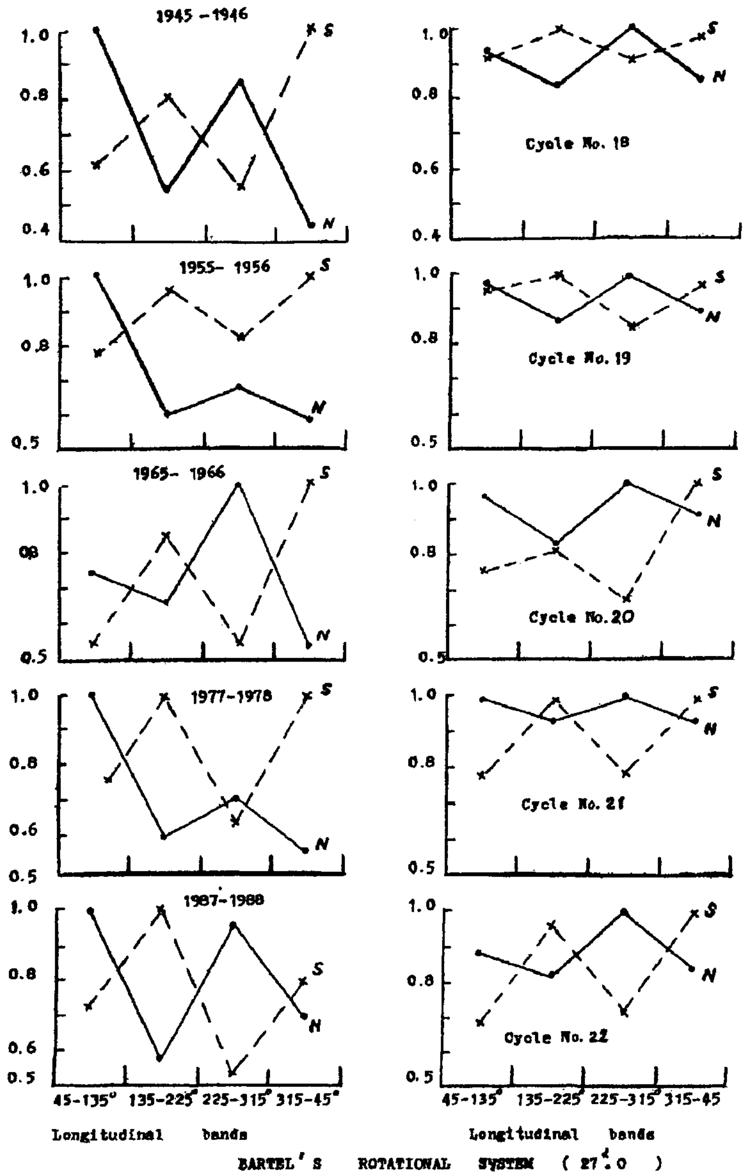

Figure 3 Normalized four-sectoral distributions of the number of sunspot groups for the northern and the southern hemispheres in the last five solar cycles. The first two-year-cycle distributions and the whole-cycle distributions are shown separately.

Separately, we have counted in these Bartel sectors the sunspot groups which appeared during the first two years of each solar cycle. The normalized numbers of the sunspot region for the northern and the southern hemispheres are shown in Figure 3. What does this Figure demonstrate for solar physics?

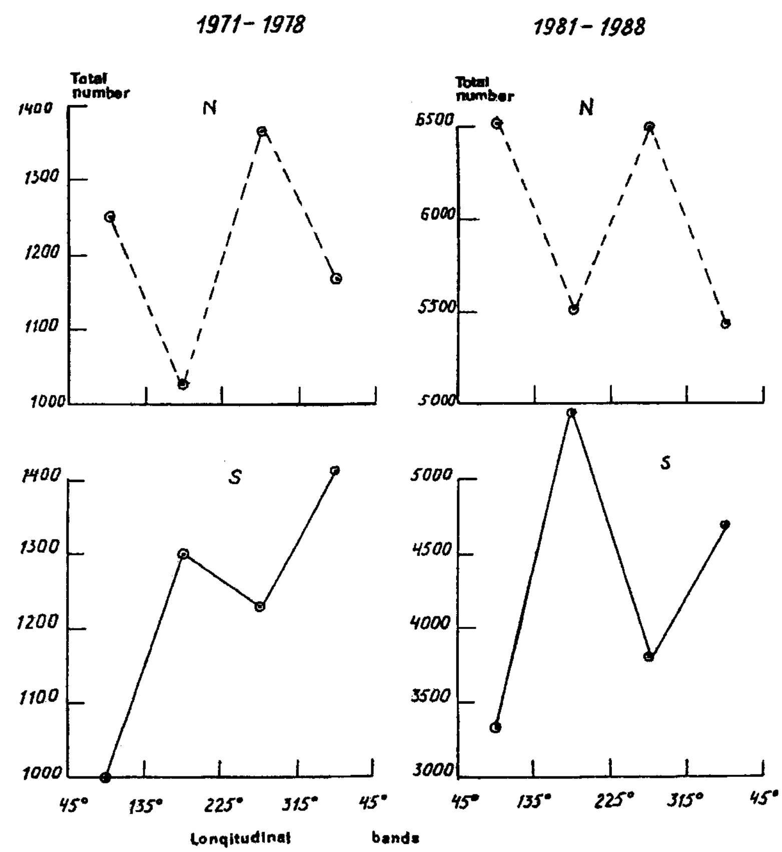

Figure 4 Four-sectoral distributions of the number of polar faculae in Bartel's rotational rate of the northern and southern solar hemispheres for eight-year time intervals which are indicated at the top of the figure.

Firstly, the sectoral symmetry and the hemispherical asymmetry are phenomena clearly seen in Bartel's rotational system. Secondly, the contrast of the sectoral-hemispherical distributions for the beginning of the cycles is higher than for the whole-cycle data. As a consequence we can describe three specific features of the sunspot number distributions in Figure 3 as:

(1) the 90°-sectoral bands of maxima and minima of the distributions were the same in the last five solar cycles;

(2) there were two opposite sectoral maxima and two opposite sectoral minima in the distributions of each hemisphere;

(3) the distributions in sectors of the northern and southern hemispheres were in opposite phase.

In principle, these are the same three specific features which were found firstly for the polar facula and bright KCa^+ point longitudinal distributions in the rotational system $T_p = 27.227$ days (synodic). So, one can see again that empirical evidence exists for the fundamental global four-sectoral structure. This fundamental structure influences solar surface phenomena and rotates with Bartel's period. There is good reason to believe that Bartel's period is a real period of rotation of the fundamental sector structure, because it is supported also by the recurrency of heliospherical and terrestrial magnetic phenomena, and by spatially temporal small solar figure deformations (Mikhailutsa *et al.*, 1997). It is a way to be confident that Bartel's period is the correct period of the fundamental sector structure rotation.

It should also be noted that it is very improbable that Bartel's period, in turn, is a harmonic of any unchecked period, because the appearence of the sunspot group number sectoral-hemispherical asymmetry depends strongly on the rotational frames of reference (see Figure 3).

Taking into account the results of Mikhailutsa and Makarova (1994), where the rotational frame of reference $T_p = 27.227^{\mathrm{d}}$ has been used, it is of interest to know whether these earlier results look the same when reanalysed with this periodicity. In order to find the answer we have analysed more data of Kislovodsk's polar facular numbers. The polar facula points of years 1971–1978 and 1981–1988 have been counted in the 90°-sectoral bands found above. The result is demonstrated in Figure 4, where the longitudinal bands and the total numbers of polar faculae in sectors are shown correspondingly at the bottom and at the left edge of each plot. Figure 4 gives evidence that our earlier results look the same. It puts in an appearance due to the periodicity used earlier, which was a harmonic of Bartel's rotation rate.

4 THE SHAPE OF THE SECTORS ON THE SOLAR SURFACE

To investigate the shape of the global sector structure on the solar surface, we have chosen the epoch of the minimum of solar activity, years 1985–1986, when the active region's remnants and facular plages were absent. The polar facular and similar bright points are clearly seen in all latitudes along the solar limb in Kislovodsk's photoheliograms at the minima of solar activity (Makarov and Makarova, 1987). They can be considered as a homogeneous indicator of the surface distribution of global solar activity. By means of them we have studied the shape of sectors in Bartel's rotational system.

A question of far-reaching importance is: Are the sector boundaries directed along the solar meridians? To answer this, 47 daily photoheliograms were selected to count the total number of polar faculae and similar bright points in 10°-latitudinal bands of 30°-limb longitudinal bands of each sector. The photoheliograms of the best images of the Sun were selected and observations were clustered in time so that the Sun had not changed over the interval considered. The sector positions were defined in accordance with Bartel's rotation. Total numbers of points were

Table 2. The averaged numbers of polar faculae and similar bright points, and the total numbers of their observations in sectors, in accordance with the latitudinal bands of the northern and the southern solar hemispheres

Sectoral bands	*Latitudinal bands in heliographical degrees*								
	Northern hemisphere								
	0–10	*10–20*	*20–30*	*30–40*	*40–50*	*50–60*	*60–70*	*70–80*	*80–90*
45–135	5.8/28	4.2/28	4.0/29	3.8/30	4.5/30	5.8/29	8.4/27	5.3/28	4.5/19
135–225	8.7/33	7.8/34	6.2/33	2.8/33	3.3/34	3.0/33	2.6/31	3.0/31	1.6/23
225–315	3.4/19	2.4/19	2.6/20	3.0/20	3.4/20	4.3/20	5.2/19	4.0/18	3.8/13
315–45	11.6/31	8.5/31	6.0/31	3.2/29	3.3/31	2.4/30	2.2/26	2.5/25	2.2/16
	Southern hemisphere								
45–135	9.4/28	7.6/28	6.0/29	3.7/30	2.8/30	2.3/29	2.3/27	1.3/26	1.9/17
135–225	3.4/33	3.1/34	3.1/33	4.5/33	4.3/34	5.6/33	7.5/31	5.3/29	5.8/15
225–315	10.0/19	10.2/19	8.5/20	5.9/20	3.4/20	3.3/20	2.7/19	2.4/19	2.3/14
315–45	4.0/31	3.9/31	3.3/31	4.0/29	3.9/31	6.6/30	9.0/26	7.1/26	5.4/15

averaged in each of the four sectoral bands. These mean values and the numbers of photoheliograms used for counting are presented in Table 2.

The result of the investigation is shown graphically for best clarity in Figure 5, where the equatorial and polar regions are shown correspondingly at the top and at the bottom of each plot. One can see a change in phase between high and low latitudes. At the middle latitudes of both hemisperes (30°–40° and 40°–50°) the sectoral features were smoothed. To determine the shape of the sectors along the meridians, the counting of the bright point numbers was repeated at the 30°–60° latitudinal band, but sector boundary positions were shifted along the longitude on a value of 45°. These distributions are shown in Figure 5 by means of dashed lines. The extremes of the dashed-line distributions are shifted in longitude in comparison with the low and high latitudinal distributions. The smallest shift value is equal to 45°, and is directed toward the west or toward the east, as compared with the low or high latitudinal distributions correspondingly. Therefore, there could not be a rapid reversal of phase at the middle latitudes. Moving from polar to equatorial regions, the distributions of Figure 5 can serve as an indication that the sector boundaries (or extreme positions) are inclined to the spherical frame of reference. Since longitude decreases from 360° to 0° during one solar rotation, the east end of sector boundaries should be located at the polar regions of the Sun and the west end at the equatorial regions. The structure could not be sloped in the opposite direction with the same agreement. The shape of sectors is shown schematically in cylindrical coordinates in Figure 6. The retouched sectors relate to the enhanced polar facula and bright point numbers. Figure 6 incorporates the polar (Figure 4) and equatorial (Figure 3) sector structures.

The fact of the inclination of the sectors is of far-reaching importance for understanding their origin in the Sun. It has been shown by many investigators (see

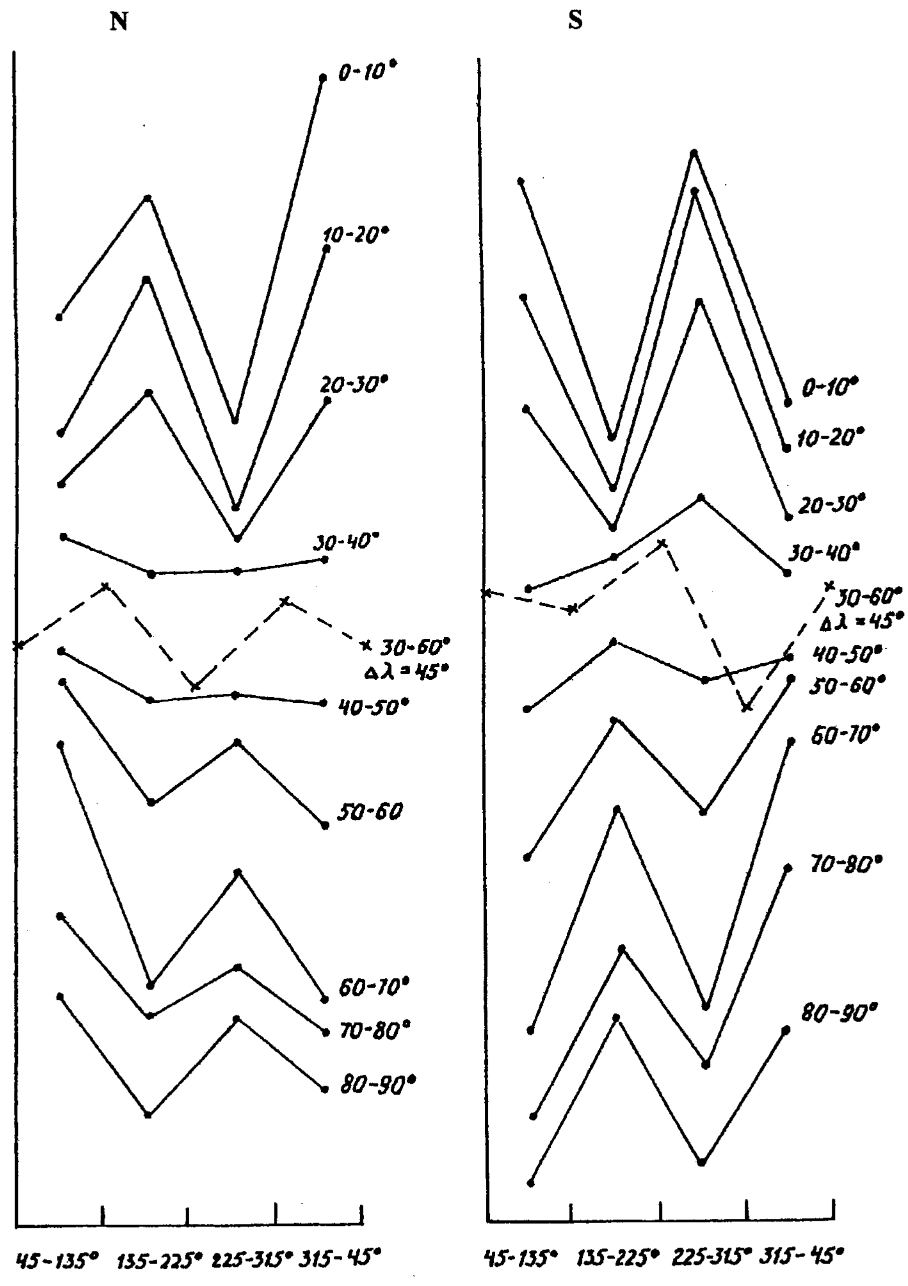

Figure 5 Relative four-sectoral distributions of the polar faculae and similar bright point numbers in 10°-latitudinal bands of the northern and southern solar hemispheres at solar cycle minimum (years 1985–1986). The latitudinal bands are marked near the curves. The sectoral features are smoothed at the middle latitudes. The dashed lines demonstrate the four-sectoral structure in mid-latitudinal bands (30°–60°), when sectors were shifted along longitudes by a value of 45°.

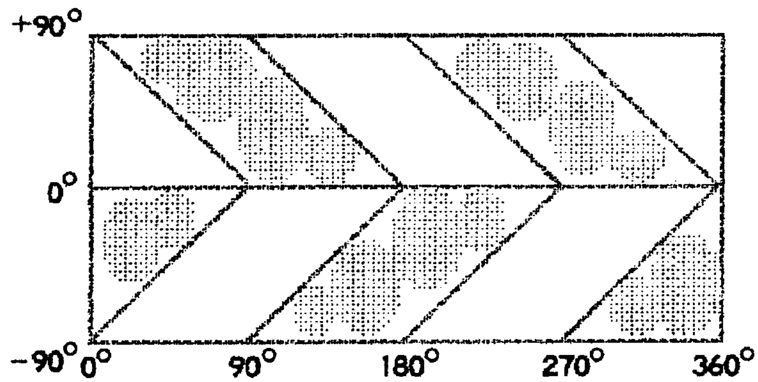

Figure 6 Scheme of the four-sectoral structure of the polar facula and bright point number extremes in cylindrical coordinates. The sectors with enhanced numbers are distinguished by retouching.

for example Wilson *et al.*, 1988) that the cycles generally overlap for several years. Perhaps there were structures from two cycles present simultaneously in Figure 6.

5 DISCUSSION AND CONCLUSIONS

The general result of this study is that in Bartel's rotational rate there is no random or axisymmetrical distribution of certain photospherical activities in the solar cycles. Instead, a four-sector structure per rotation can be seen. These sectors rotate as a rigid body. The global magnetic field of the Sun is organized over very long time intervals with a very precise 'clock'. This is of great importance for solar cycle theory.

It should be noted that in the work of Bai and Sturrock (1993) a so-called hydrodynamical rotator has been supposed to exist in the solar interior, to explain flare periodicities and hot spots located 180° apart, that last several solar cycles. The rotational rate of this rotator was estimated to be 25.5 synodic days. This period is out of line with respect to Bartel's rotation of the sectors found above. The cause of this discrepancy can be seen in different sources of the flare and spot group number activities. As a matter of fact it is the number of spot groups that revealed the four sectors in Bartel's rotational rate. The size or complexity of the spot configuration is not important here, while they are of first rate importance for flare activity. So, partially, we attribute the difference in periods to the different sensitivities of the data sets, which reflect the properties of different layers of the solar atmosphere.

Apparently, these different sensitivities are one of the reasons for the period discrepancies in other studies, too. In fact, other investigators have looked at the sunspot data and done exhaustive studies of rotation rates in the northern and southern hemispheres and found other periodicites in addition to those we have demonstrated (Oliver and Ballester, 1995). The method of investigation can be another reason for period discrepancies. The sectoral period was found due to the structural recurrence on the solar surface. The contrast level of these structures did not exeed 30%. Therefore, the sector structure corresponds to low and steady contrast features of activites on the solar surface.

The source of the sector structure works as a global structural factor rather then a global amplitudinal factor while small-scale patterns of solar activity are studied. Turning to large-scale patterns, such as unipolar elements of the background magnetic field, the four-sectoral structure is revealed on the solar surface mainly due to the domination of equatorial quadrupole-like fields (equatorial coronal holes) at the cycle maxima (Mikhailutsa, 1995). This means that structural and amplitudinal characteristics are closely connected in the case of large-scale patterns. Therefore the source of sectors on the Sun should be global and spatially periodic. Note that recently a possible source of such sector structures has been discussed in work by Mikhailutsa *et al.* (1997).

The two-dimensional inversion methods of helioseismology (Shou *et al.*, 1994) give a nearly rigid rotation of the radiative interior (with frequencies from 380 nHz (at approximatelly $0.3R_s$) to 440 nHz (at approximatelly $0.7R_s$)) and the differential rotation of the convective zone. The period of 27.0^{d} synodic corresponds approximately to 460 nHz sideric. These last results, presented at the October (1996) IAU Symposium in Nice (mainly from SOHO and GONG), strongly suggest that the solar core is not rotating more than 1.1 times faster than the overlying layers. So, probably, there are only two places in the Sun with a rotational rate of 460 nHz. They are the solar core (perhaps less then $0.15R_s$), and the central part of the convective zone near the solar equator. Having in mind the giobality of the sector structure, we come to the conclusion that the possible source of the sector structure can be situated only in the solar core.

In spite of the fact that we have explored only a small range of periods, we have found a good correspondence with the organization/rotation of other characteristics of solar activity using the number of sunspot groups as their definition. That is fine as far as it goes; however, we realize that the "true" (Bartel's) rotation rate is the best of only eight possible choices. There are many other equally likely values and there is no real reason to believe that the rates even need to be the same in the north and south.

But the aims of this presentation have been achieved:

(1) four sectors can be seen on the solar surface with Bartel's rotation rate. The sectors are broken into two different hemispherical parts;

(2) the polar and equatorial regions of the four-sectoral structure form a global sectoral structure with inclined boundaries;

(3) the boundaries are directed from the polar to the equatorial regions of the Sun, so their ends differ in longitudes by a value of $+90°$.

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