THE SECTOR STRUCTURE OF THE ACTIVE LONGITUDES IN SOLAR CYCLES

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Abstract. The longitudinal distributions of the polar faculae, bright K Ca^+ points, and sunspot areas have been investigated in three-year intervals at the minima and maxima of the last five solar cycles in the rotation system which corresponds to the background magnetic field: $T = 27.23$ days (Mikhailutsa, 1994b). It has been shown that there were three specific features of the polar faculae and bright K Ca^+ point longitudinal distributions: (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 of each hemisphere. (3) The distributions of the northern and southern hemispheres were in opposite phase. The extremes of the sunspot area longitudinal distributions were preferentially between the longitudes of the polar facular extremes. The period of the sector structure rotation was defined more precisely: $T = 27.227 \pm 0.003$ days. The results found can serve as an indication that there is a global four-sector structure seated in the solar interior which plays a visible role in the polar facular and sunspot distributions.

1. Introduction

The longitudinal distribution of solar activity is poorly known. It had been established that active regions emerge preferentially in certain areas on the Sun (Bumba and Howard, 1965; Vitinskij, 1969). Sometimes for several years or solar cycles the solar activity is stronger in certain longitude bands than in other places, and such longitude bands were named 'active longitudes' (Dodson and Hedeman, 1971; Trellis, 1971). It was suspected that these concentrations of sunspot activity in its longitudinal distribution demonstrate three kinds of the opposite twin locations on the solar surface (Waldmeier, 1955). There are: (1) ϕ_0, λ_0; ϕ_0, $\lambda_0 + 180°$; (2) ϕ_0, λ_0; $-\phi_0$, $\lambda_0 + 180°$; (3) ϕ_0, λ_0; $-\phi_0$, λ_0, where ϕ_0, λ_0 are the latitude and longitude of the mean point of the complex of activity. However, the reality of active longitudes and their properties have not been widely accepted. In these investigations the Carrington rotation period (27.2753 days synodic) was usually adopted as the real rotation period. But a small change of the rotation period results in a drift in longitudes in several years. For this reason Wilcox and Schatten (1967) pointed out that the Carrington rotation period is not the rotation period of the Sun, and the rotation rate should be used as a free parameter to study the longitude distributions. Many different rotation periods of active longitudes have been found. For example, Dodson and Hedeman (1968) noticed a band of active longitudes whose Carrington longitude values had increased in time with a corresponding rotation

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period of 27 days. They also noticed that often strong solar activity occurs in places separated by 180 deg in longitude. But later (Dodson and Hedeman, 1975) the Carrington rotation period was identified by them as the rotation period of active longitude bands. Bumba and Hejna (1990) found that the 27-day maximum of longitudinal distribution recurrency had a fine structure consisting at least of two active longitudes rotating faster than the Carrington rotation. Their synodic rotation values were 26.77 days and 27.16 days. So, the results of studies of active longitudes do not agree with each other. Even the results of studies by the same authors often contradict each other.

We chose another way to study active longitudes. A four-sector background magnetic field polarity structure has been found on the solar surface at maxima of solar activity recently (Mikhailutsa, 1994b). And while the polarity boundaries in sectors located on opposite sides of the solar surface demonstrate meridional migrations in the north-to-south direction over the solar cycle, the boundaries in the other two sectors are moving in the south-to-north direction. The rate of this sector structure rotation has been estimated. It was faster than the Carrington rate by a value of 8 heliographic degrees per year ($T = 27.23$ days). It should be noted that about twenty years ago the interplanetary magnetic-field sector-boundary data for each year were separated into four categories by Svalgaard (1975), which correspond to this four-sector structure of the background magnetic field obvious on the solar surface. Having in mind the fundamental role of the solar background magnetic field in solar cycles (Simon and Legrand, 1992; Mikhailutsa, 1994a, b), it is of interest to research the active longitude properties in the equatorial region of the Sun (sunspots) and in polar regions (polar faculae and bright K Ca^+ points) as well in a system of sector structure rotation. It stands to reason that in this case the results depend on the synodic rotation values. The aim of the present investigation is to acquire new data about the role of that fundamental sector structure in solar cycles.

2. The Longitudinal Distributions of the Polar Faculae Numbers and Bright K Ca^+ Points in Latitudes Higher Than 50° in the Last Five Minima of Solar Cycles

The Kislovodsk high-contrast photographic observations of polar faculae for the years 1976–1978 and 1985–1986 were used to count the polar faculae mean-year numbers. The bright K Ca^+ point numbers come from the spectroheliograms of the Kodaikanal Observatory (India) for the years 1944–1946, 1954–1956, and 1964–1966. These data were used by courtesy of Prof. V. I. Makarov. It is known that polar faculae are observed in both white-light or chromospheric lines like K Ca^+ (Makarov *et al.*, 1988). We counted the polar faculae and bright K Ca^+ in 30° longitude bands in the one-year time interval. The total number was about 200–300 per year. The frame of reference was displaced every year along longitude at a value

TABLE I
The largest correlation coefficients and longitudinal displacements

Years	1944–1946	1954–1956	1964–1966	1976–1978	1985–1986
1944–1946	–	0.45/350°	0.70/350°	0.30/230°	0.39/250°
1954–1956	0.90/80°	–	0.68/60°	0.86/180°	0.95/240°
1964–1966	0.78/140°	0.60/70°	–	0.42/50°	0.60/170°
1976–1978	0.77/270°	0.79/190°	0.83/40°	–	0.70/140°
1985–1986	0.84/340°	0.65/260°	0.92/200°	0.86/120°	–

of $+10°$. We suppose that the difference between 10° and 8° per year is too small to produce visible confusion in longitude distribution for three-year intervals. The mean-year distributions in each period of time were used to create the mean-epoch distributions with a system of longitudes corresponding to the first-year longitude system of the epoch. In Figure 1 the longitudinal distributions normalized to the largest values of polar faculae and bright K Ca^{+} points in the solar hemispheres are illustrated. The distributions for the northern hemisphere are shown by means of continuous lines, for the southern hemisphere – by dashed lines. We used the cross-correlation method with longitudinal displacements to compare the distributions. In Table I are the results which demonstrate the largest correlation coefficients and longitudinal displacements for distributions of the northern (higher and to the right of the diagonal) and the southern (lower and to the left of the diagonal) hemispheres.

Taking into account the mean values of longitudinal displacements with correlation coefficients more than 0.60, except for the northern hemisphere in the years 1944–1946, a strong dependence with time ($r = 0.99$) can be obtained: $\Delta\lambda^0 = 8.2t$ (t is the mean time in years). This result supports our choice of the method of distribution determination. So, the frames of references of the distributions were shifted in Figure 1 in longitude relative to the years 1944–1946 by the following values: 90° for years 1954–1956, 180° for years 1964–1966, and 270° for years 1976–1978, in accordance with rotation of the fundamental sector structure. The scale of amplitudes of the distributions is shown on the right-hand side of Figure 1. The extremes of the distributions are marked by black and white points. The vertical dash-and-dot curves connect these extremes. And four equally-spaced vertical dashed lines demonstrate the mean positions of these curves. Near these places the distributions have extremes over the last five cycles. There is a good similarity between the shapes of southern polar region distributions in different cycles in Figure 1. At first glance the northern polar region distributions demonstrate some discrepancies, especially for the years 1944–1946. But in bulk, three main features of distributions in Figure 1 should be noted. These are:

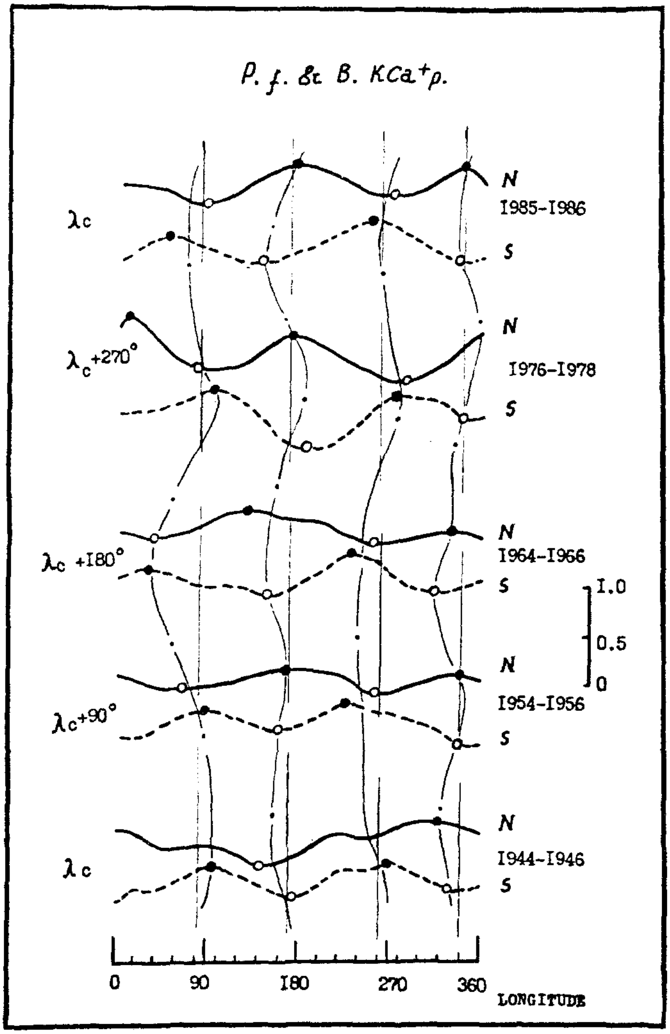

Fig. 1. The normalized longitudinal distributions of the mean polar faculae numbers (for years 1976 –1978 and 1985–1986) and bright K Ca^{+} points (for years 1944–1946, 1954–1956, and 1964–1966). The continuous curves demonstrate the northern polar region distributions, the dashed lines – the southern polar region distributions. All distributions were found for latitudes higher than 50°. The frames of references are shifted along longitudes by a value indicated on the left side of the figure. On the right side the scale of the normalized amplitudes is shown. The vertical dashed lines indicate the mean longitudes of maxima and minima connected by means of dash-and-dot lines.

(1) The longitudinal distributions consist mainly of two maxima and two minima.

(2) The shapes of the longitudinal distributions of the northern and southern solar hemispheres are in an opposite phase.

(3) The maxima of the longitudinal distributions are located at opposite longitudes in each hemisphere, the same is true for the minima.

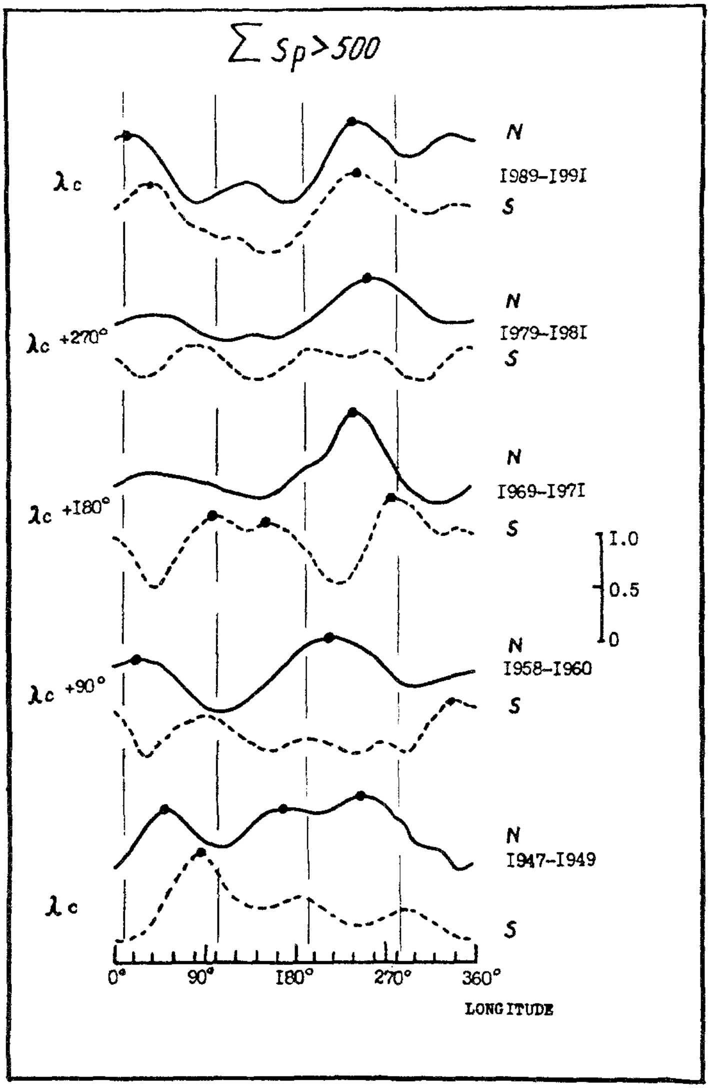

Fig. 2. The same as Figure 1, but for the mean three-year summary sunspot areas. Sunspot areas more than 500 area units were taken into account. The vertical dashed lines correspond to those in Figure 1 shifted by a value of +25° to take into account the rotation of the fundamental sector structure.

The exceptional behaviour of the northern polar region distribution in years 1944–1946 will be discussed below in the Discussion.

We do not claim here that the coincidence of all curves representing the longitudinal distributions is excellent. Some coincidence among the positions of southern and northern extremes (±20°–40°) exists. But these positions can be associated with four equally-spaced longitudes. These features of the distributions were revealed by using the special frame of reference.

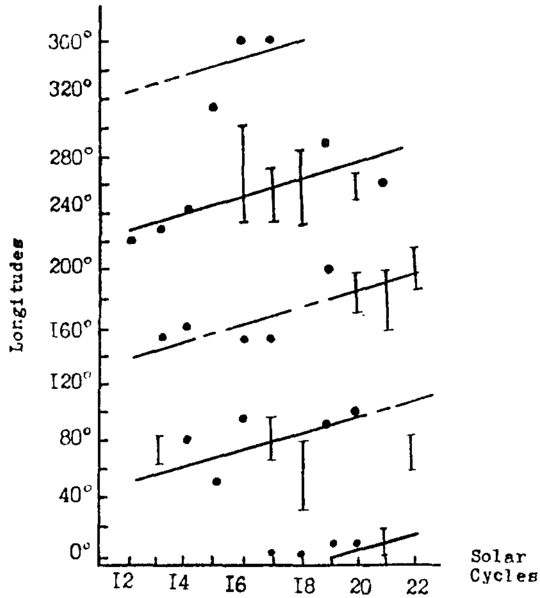

Fig. 3. The active longitudes of solar cycles Nos. 12–22 indicated in the rotation system of the fundamental sector structure ($T = 27.23$ days). The short vertical lines connect the active longitudes of the northern and southern hemispheres if their difference is less than 60°. Four equally spaced inclined lines point out sector boundaries, which are the places of active longitude concentration. The inclination of the boundary lines gives a more precise value of the synodic period of rotation of the fundamental sector structure: $T = 27.227$ days.

3. The Longitudinal Distributions of the Summary Mean-Year Sunspot Areas in the Last Five Maxima of Solar Cycles

We used the Kislovodsk sunspot data for solar cycles from No. 18 to No. 22. These data were published by R. S. Gnevysheva in the *Katalog solnechnoi deyatel'nosti* of the Pulkovo Observatory. Active regions with summary spot areas more than 500 area units were used for longitudinal distribution in three-year time intervals at epochs of maxima of solar activity. The sunspot areas of the same year were summarized inside 30° longitude bands. These longitude bands were shifted by a value of $+10°$ for every next-year data set, to keep in mind the rotation of the sector structure. As a result, three mean-year longitudinal distributions of the summary sunspot areas in each solar maximum have been obtained. From these mean-year distributions, the mean three-year distributions have been constructed for each maxima of the solar cycles. In Figure 2 are the sunspot areas in both solar hemispheres for solar cycles Nos. 18–22 normalized to largest values of longitudinal distributions. The frames of reference of the distributions were shifted in longitude relative the Carrington longitude system of years 1947–1949 by the following values: 90° for years 1958–1960, 180° for years 1969–1971, and 270° for years 1979–1981, in accordance with the rotation of the fundamental sector

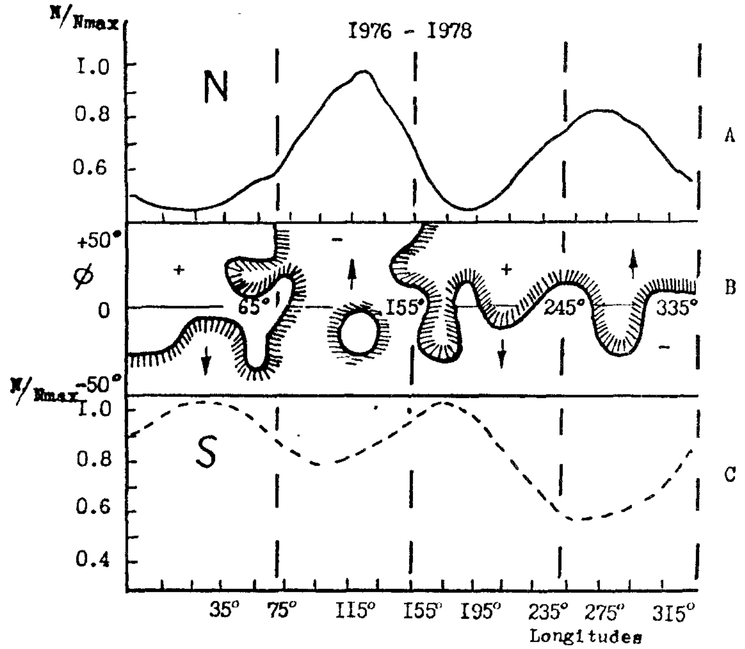

Fig. 4. The comparison of the synoptic chart of equatorial coronal hole polarity migrations (the mean part of figure with arrows) with the longitudinal distributions of mean polar faculae numbers for years 1976–1978. The shadowy lines mark the approximative position of the neutral polarity lines. This part of the figure was taken from Mikhailutsa (1994b). The top and bottom parts of the figure demonstrate the normalized longitudinal distributions for the northern and southern polar regions, respectively. The Carrington longitudes for year 1976 are shown at the bottom. Note that arrows point toward the maxima of polar faculae numbers.

structure. The sunspot-area longitudinal distributions on the northern hemisphere of the Sun are shown by means on continuous lines and on the southern hemisphere – by dashed lines. The vertical dashed lines mark the longitudes of polar faculae and bright K Ca^+ point extremes from Figure 1. These lines were displaced by a value of $+25°$ due to the three-year difference between epochs. The well-pronounced first maximum on the curves from the northern hemisphere is situated between 195° and 285° longitude boundaries. The second maximum is not so well-pronounced. In regard to the southern-hemisphere distributions, one can see that there is some evolutionary behavior and a very unclear situation concerning the curves. Looking at Figure 2, some tendency of separation of the peak positions (black points) by four vertical dashed lines can be noted. In order to check this tendency, the additional active longitude data for solar cycles Nos. 12–17 were also used (Vitinskij, Ohl, and Sazonov, 1976). These data were corrected in longitude due to the difference between Carrington and fundamental sector structure rotation. We change the presentation of the data to lay emphasis on the peaks of the distributions. The result is shown in Figure 3. The points indicate the active longitudes in the solar cycles. Some points were connected by short vertical lines if active longitudes

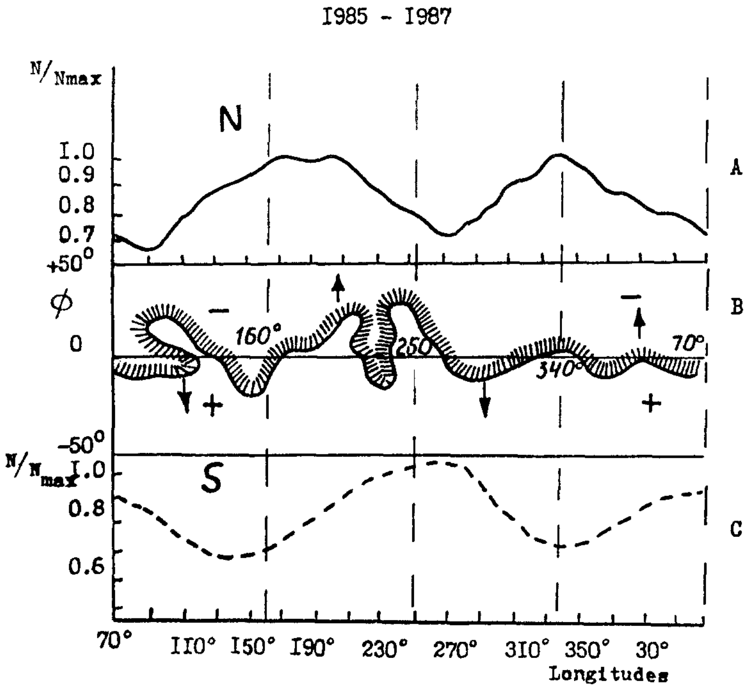

Fig. 5. The same as Figure 4, but for years 1985–1986.

of both solar hemispheres differed by a value less than 60°. Four equally-spaced lines were drawn through the point and segment accumulations. These lines give account of the four-sector structure of the active longitudes in solar cycles. In some cycles the active longitudes disappeared (dashed lines), but appeared again in the next cycle on the correct longitudes. These facts can serve as an indication that the fundamental four-sector structure has an influence on sunspot production. The active longitudes concentrated at the boundaries of sectors. The mean inclination of the boundary lines in Figure 3 brings home to us that the synodic period of rotation of the fundamental sector structure is approximately equal to 27.227 ± 0.003 days. The range of errors corresponds to the uncertainty in the straight-line directions. The horizontal direction leads to $T = 27.230$, the most possible inclined direction to $T = 27.224$.

4. Discussion

Helioseismology is the main source of knowledge about the inner solar magnetic field and rotation rate. An indirect method, founded on the assumption about connections between the surface phenomena of the Sun and its interior, are also useful here. The properties of active longitudes are closely connected with the inner solar magnetic field structure and rotation.

It is in order to repeat the main properties of the active longitudes which had been demonstrated by many authors (for example, Schröter, 1985). The active longitudes have rigid rotation. Then lifetimes are of the order of several solar 11-year cycles. Very frequently they bring into action a pair of active longitudes on the opposite sides of the solar surface. Now, there is good reason to believe that due to the influences of a fundamental four-sector structure deep seated in the solar interior on sunspot production the mentioned properties exist. The active longitudes are the boundaries of the sectors. The four-sector structure of the background magnetic field is the source of the global quadrupole-like magnetic field near the maxima of solar cycles (Mikhailutsa, 1994b).

At minima of solar cycles the four-sector structure of active longitudes turns into the crossed polar faculae longitudinal distributions with two maxima in each polar region. It is of interest to determine how these longitudes of polar faculae extremes correspond to the sector boundaries. With this end in view, the synoptic charts of the equatorial coronal hole polarities for years 1976–1978 and 1985–1987 were used (Milhailutsa, 1994b; Figure 4). These charts were superimposed on the longitudinal polar faculae distribution of both hemispheres. In Figures 4 and 5 the result is illustrated. The middle parts of the figures are the synoptic charts of equatorial coronal hole polarity distributions. The arrows indicate the directions of magnetic polarity migrations in each sector. The shadowy lines are the neutral polarity lines. The top and bottom parts of the figures demonstrate the normalized longitude distributions of polar faculae. The migrations of magnetic polarities are directed to the places of maxima of polar faculae, beyond all shadow of doubt. In virtue of this fact, we suggest that polar faculae and bright K Ca^+ points 'feel' the fundamental four-sector structure. Comparison of the boundary longitudes (vertical dashed lines) of Figures 4 and 5 with the active longitudes in Figure 2 (the middle of the intervals shown) of the same epoch shows their identity. It brings home to us that sector boundaries may be associated with *extreme* sunspot production. It should be noted that McIntosh and Wilson (1985) pointed out that sunspot birth currently occurs on the pre-existing inversion lines of the photospheric field, each spot emerging inside the photospheric field of its own polarity. Mouradian, Martres, and Soru-Escaut (1988) came to the conclusion that most of the sunspot groups were born close to the inversion line. The conclusion had been made also, that this inversion line is the surface signature of phenomena seated in the solar interior which play a crucial role in sunspot field emergence. These results support our analysis.

It had been established earlier that new polar faculae cycles began after the polar field reversal (Makarov, Makarova, and Sivaraman, 1989) and for the last five cycles, in each hemisphere, the monthly number of polar faculae correlated, with a delay of 5.8 to 6.2 years, with the monthly sunspot area. Recently, the correlation between the 'weight' of the largest-scale sector mode ($m = 1$) of magnetic polarity distribution in synoptic charts of minima solar activity and magnitudes of the maxima of sunspot activity after 15–17 years has been found

(Milhailutsa, 1994). The specific longitude distribution of the bright K Ca^+ points in the northern hemisphere in the years 1944–1946 in Figure 1 is similar to that of sector mode $m = 1$ configuration. By reason of these facts together, the very high magnitude of solar cycle No. 19, possibly, was a sequel of the sharp non-axisymmetric distribution of the bright K Ca^+ points in the northern polar region 15 years earlier. Without data it is impossible to verify in detail this assumption.

More and more facts can serve as an indication that global fundamental structure is a basis of the solar cycle phenomena (Simon and Legrand, 1992). Apparently the kernel of this structure is in the four sectors of meridional migration of the background magnetic field polarities (Mikhailutsa, 1994b).

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