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# ACTIVE LONGITUDES AND THE STRUCTURE OF THE LARGE-SCALE MAGNETIC FIELD AT SOLAR MINIMUM

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**Abstract.** We have studied deep minima of 11-year solar activity cycles 13–14, 14–15, 22–23, 23–24, 24–25, using the RGO and USAF/NOAA sunspot group catalogs. All of them have a large number of spotless days. Nonetheless, active longitudes as preferred zones, where sunspots occur, manifest themselves at this solar cycle phase. Analysis of synoptic maps and WSO daily magnetograms reflecting the structure of a weak large-scale field has revealed a non-axisymmetric component of the solar magnetic field. At solar minimum in the structure of the large-scale magnetic field, there are regions of the magnetic field of positive and negative polarity elongated along the meridian and crossing the equator. The most pronounced of them are located in the zone of active longitudes and are often connected with the polar magnetic fields.

We discuss the possible nature of the meridional structures of the large-scale field during solar minimum. This might be due to giant convection cells with a banana cell structure.

**Keywords:** large-scale magnetic field, active regions.

## INTRODUCTION

The paper addresses the problem of activity distribution over the solar surface. Regularities of the latitudinal dependence of the occurrence of sunspots on the solar surface have long been known. They serve as criteria for theoretical description of solar cycle evolution in numerous solar dynamo models. Later, a number of studies showed a non-random distribution of active regions (ARs) over the heliographic longitude too. Active formations were found to appear more often in certain longitude intervals. Such objects were described as hearths of sunspots [Becker, 1955], activity nests [Gastenmiller et al., 1986], activity complexes [Gaizauskas et al., 1983; Bumba, Howard, 1965b], hot spots [Bai, 1988], active longitudes [Berdygina, Usoskin, 2003; Obridko, 2010]. All these active formations, regardless of their names, are determined by the appearance of a magnetic field in the solar atmosphere [Bumba, Howard, 1969] and its large-scale distribution.

One of the first studies on the large-scale structure of the magnetic field in the photosphere is based on magnetographic measurements made at the Mount Wilson Observatory. A series of daily magnetograms with a spatial resolution of 23" for 4.5 years was analyzed and synoptic maps for each solar rotation were constructed in [Bumba et al., 1964], where large regular magnetic field structures were shown to exist. Later on, Bumba and Howard [1965a, b] demonstrated that large-scale magnetic field structures to 400000 km in size form activity complexes that produce several activity pulses in certain longitude ranges. The activity complexes reveal a magnetic cell structure that can exist for several rotations.

Most studies on the large-scale distribution of magnetic fields based on the analysis of synoptic maps confirm the tendency for a new magnetic flux to appear in preferred longitude zones. Data on sufficiently strong magnetic fields during maximum solar activity (SA) or in the solar cycle descending phase has generally been used [Berdygina, Usoskin, 2003; Obridko, 2010]. It seems important to trace the emergence of a new magnetic flux, in particular as small short-lived sunspots, at solar minimum, especially during the transition from one cycle to another.

At solar minimum, the structure of a large-scale magnetic field (LMF) is least subject to active processes. There are few studies in the literature on the transition period from cycle to cycle, but most observations concern periods of relatively high SA [Kostuchenko, Benevolenskaya, 2014; Kramynin, Mikhalyna, 2016; Vernova et al., 2020]. Bumba [1970] analyzed several solar rotations during the low SA period of 1966, immediately after the transition from cycle 19 to cycle 20, using Mount Wilson synoptic maps. Active longitudes were also detected at that time. It was noted that although the polarity of magnetic field structures changed from the previous cycle to the new one near SA minimum at that time, the regular magnetic cell structure could be traced.

The periods of transition from cycle 21 to cycles 22, 22–23, and 23–24 are analyzed in [Benevolenskaya, 2010; Benevolenskaya et al., 1999]. The former work employed synoptic maps from the Mount Wilson Observatory; the latter, synoptic maps based on daily SOHO/MDI magnetograms. Recent data demonstrates the distribution of significantly stronger fields, but confirms the general dynamics of a weak magnetic field. Magnetic fluxes of the previous and new cycles are grouped and exist in the same preferred longitude zones. The transition from cycle 23 to 24 exhibits extremely low activity.

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The lowest SA level also features the transition from cycle 24 to 25. Grigoriev et al. [2022] have analyzed the spatio-temporal pattern of the appearance of ARs at that time and their relationship with the LMF structure and development. WSO data [Duvall et al., 1977] with a spatial resolution of 3' was used. A low spatial resolution provides more correct information about weak LMF. Two longitude zones of preferred sunspot formation were observed. Moreover, a meridional component was manifested in the LMF structure on daily maps.

The above studies indicate that there are active longitudes during SA minima. Questions arise whether this applies to the period when sunspot formation does not occur for a long time at solar minimum, and what the structure of weak LMF is during the quietest SA period.

## OBSERVATIONAL DATA AND MATERIAL UNDER STUDY

We have used RGO USAF/NOAA data on distribution of sunspots over Carrington longitudes [http://SolarCycleSciences.com], WSO data on LMF, daily and synoptic maps [http://wso.stanford.edu]. To test the hypothesis of the existence of active longitudes in minima of 11-year cycles, we have selected five deep minima from 1900 onwards, four of which had the largest number of spotless days.

Table 1 presents characteristics of the SA minima under study from [https://www.sidc.be/silso/spotless; https://wiki5.ru/wiki/List_of_solar_cycles].

Figure 1 (taken from [http://SolarCycleSciences.com]) shows the number of sunspots and spotless days for the minima indicated in Table 1. Minimum 22–23 is seen to be the shortest and less deep.

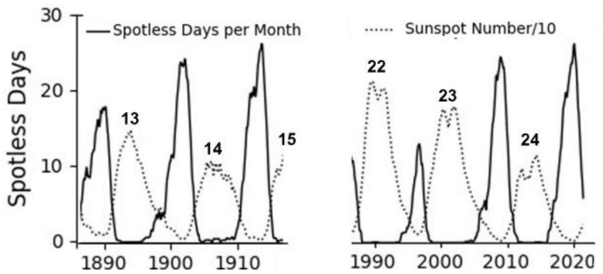


*Figure 1*. Number of sunspots (dotted line; solar cycle numbers are indicated) and number of spotless days (solid line) for selected time periods

We have analyzed the LMF structure for the last three minima.

## RESULTS

Since the term "active region" is physically more complete, we apply it to data on sunspots. In Figure 2 are histograms of ARs over the Carrington longitude during solar minima.

At solar minimum, the rate of AR formation is low — there are no sunspots for a long time. Although the total number of formed ARs is small, 1–2 longitude intervals with a higher concentration of ARs can be identified in all SA minima, which allow us to consider them as probable active longitudes. In Table 2 in Column 4 is the percent of ARs in each active longitude versus the total number of ARs at a given solar minimum; in Column 5, the cumulative percent of ARs. Thus, the active longitude during solar minimum contains from 23 % (minimum 14–15, interval 20°–80°) to 50 % (minimum 23–24) of all ARs observed. Column 5 shows that more than half of all ARs during solar minimum may occur in the preferred sunspot formation zones.

For the last three minima there is data on LMF — regular measurements at WSO have been performed since 1976. To understand the LMF structure in the region of active longitudes, synoptic maps averaged over several Carrington rotations have been constructed. A time interval was selected near a conventional minimum. Figure 3 presents synoptic maps of LMF for solar minimum 22–23. This minimum (see Table 1 and Figure 1) is the shortest and the least deep. The range of Carrington longitudes, which comprises 25 of 74 ARs, is 220°–300° (marked with white lines in Figure 3). For Carrington rotations 1912–1915, synoptic maps have been constructed from which we can trace how the LMF structure is formed in an active longitude region from August to October 1996. This period terminates with the end of the period of complete absence of sunspots on the front side of the Sun. The last fragment, obtained by averaging four previous ones, gives an LMF pattern closest to the real one during this solar minimum. Two elongated meridional structures, linked at one end to polar magnetic fields, cross the equator, reaching a heliolatitude of 50°. Their position coincides with the zone of active longitudes. Meridional orientation of the structures is also seen outside the active longitude; there is some periodicity of the location of the structures along the longitude. We have observed earlier [Grigoriev et al., 2022] that the meridional component manifests itself in the LMF structure on daily maps during SA minimum.

Table 1

Characteristics of solar cycle minima

| Cycles | Conventional time of minimum | Conventional duration | Amplitude of smoothing minimum | Long periods of spotless days (≥30 days) or their total number | Analysis period |
|---|---|---|---|---|---|
| 13–14 | January, 1902 | 2 years | 4.5 | 203 days | January 1901–December 1902 |
| 14–15 | July, 1913 | 2 years | 2.5 | 205 days | July 1912 – June 1914 |
| 22–23 | August, 1996 | 1 year | 11.2 | September 13 – October 24 , 1996 | February 1996 – February 1997 |
| 23–24 | December, 2008 | 2 years | 2.2 | July 21 – August 20, 2008<br>July 31 – August 31, 2009 | January 2008 – December 2009 |
| 24–25 | December, 2019 | 2 years | 1.8 | November 14 – December 23 , 2019<br>February 2 – March 6, 2020 | January 2019 – December 2020 |

Table 2

Active longitudes during solar activity minima

| Minimum | Number of ARs | Act. longitude, degrees | Percent of ARs, % | Cumulative percent of ARs, % |
|---|---|---|---|---|
| 13–14 | 52 | 100–200 | 42 | 42 |
| 14–15 | 69 | 20–80; 160–240 | 23, 35 | 58 |
| 22–23 | 74 | 220–300 | 34 | 34 |
| 23–24 | 60 | 180–260 | 50 | 50 |
| 24–25 | 62 | 40–120; 240–320 | 31, 32 | 63 |

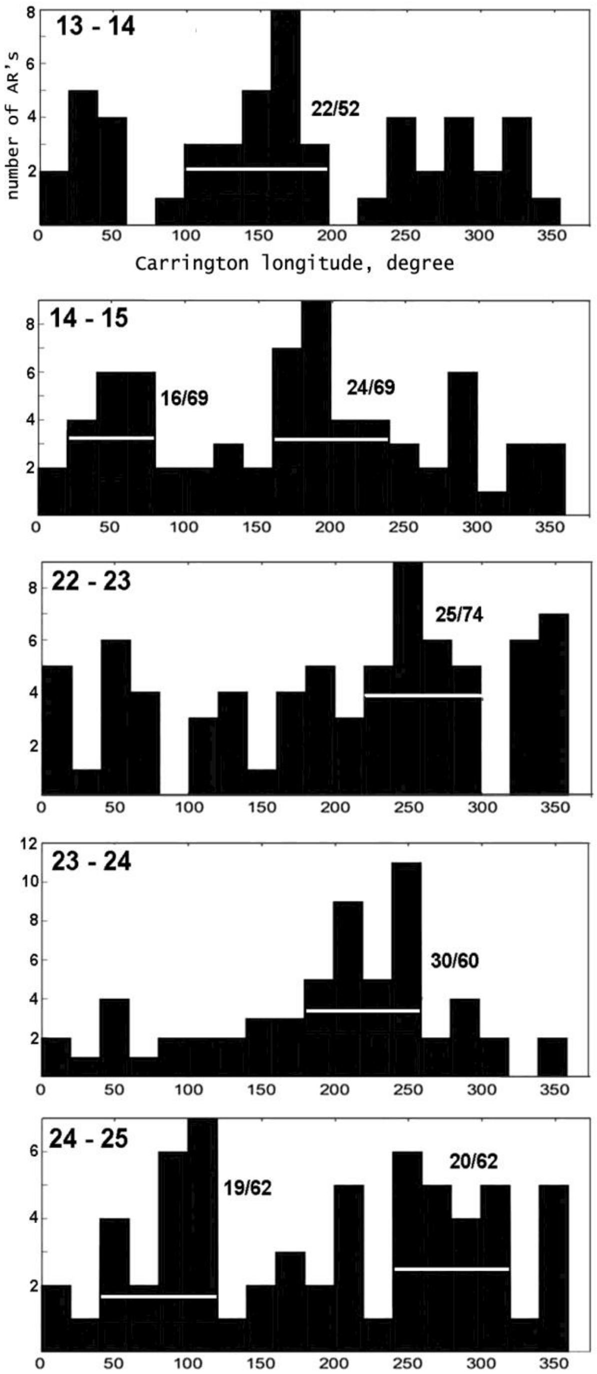


*Figure 2*. Histograms of ARs over Carrington longitude during SA minima. White lines mark active longitudes; the ratio of the number of ARs in the active longitude region to the total number of ARs is presented

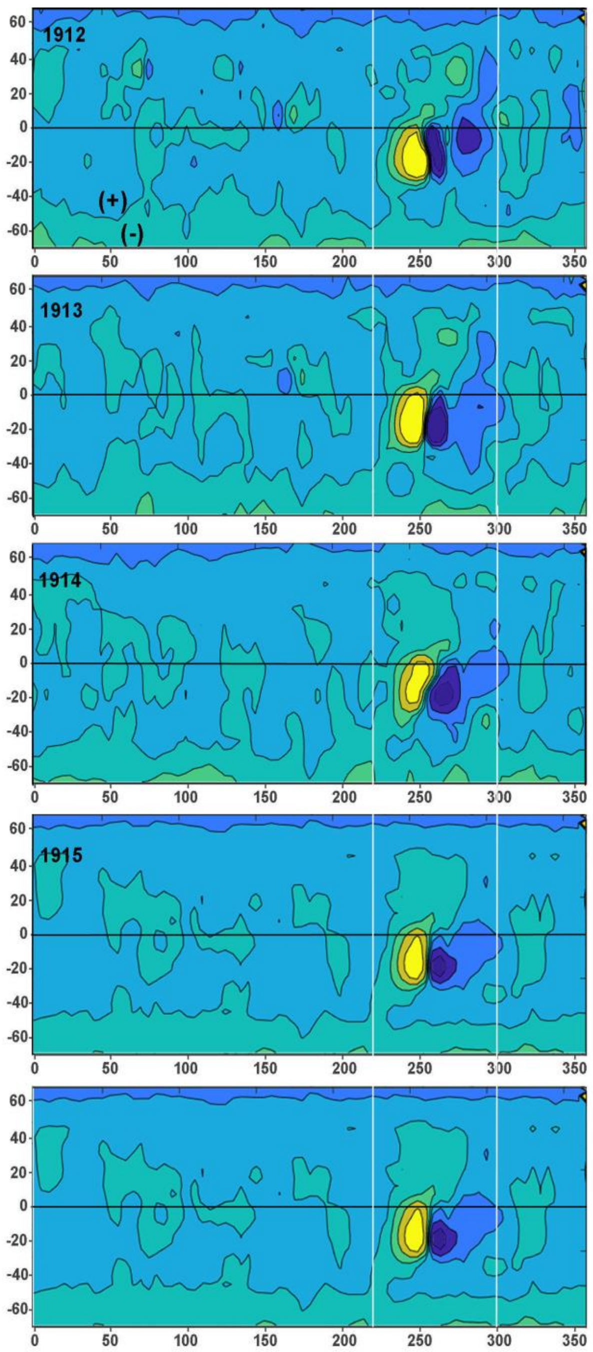


*Figure 3*. Synoptic maps for Carrington rotations 1912–1915 (in the top left corner) and a map averaged over four rotations (at the bottom). The X-axis is a Carrington longitude; the Y-axis is a heliolatitude. Isolines of LMF: 0, ±100, 200, 500 μT. Explanations are given in the text

From LMF daily maps for minimum 22–23 we can observe how a meridional component, which disappears with increasing activity (Figure 4), is formed in the active longitude zone. From May onwards, a pair of large meridionally oriented poles containing remnants of ARs of two hemispheres and two cycles appear. For example, in May near the 260° Carrington longitude there were ARs 07962, 07964 of the previous cycle in the southern hemisphere at a 5°–10° latitude and small AR 07963 of the new cycle in the northern hemisphere at a 24° latitude. A stable meridional bipolar LMF structure is gradually formed in the zone of active longitudes.

We can see that already in August both magnetic poles connect with the polar cap regions of the corresponding sign, pass through the entire hemisphere, and reach a 45°–50° latitude of the opposite hemisphere. The width is ≥40°, a deformation takes place on December 16, after which the LMF meridional structure in the active longitude zone breaks down. Thus, at solar minimum 22–23, it is observed from July to October. The period August–October reveals the most correct meridional structure. It was formed at low activity for a month and a half before a spotless period, persisted during the spotless period (September 13 – October 24), and then began to break down.

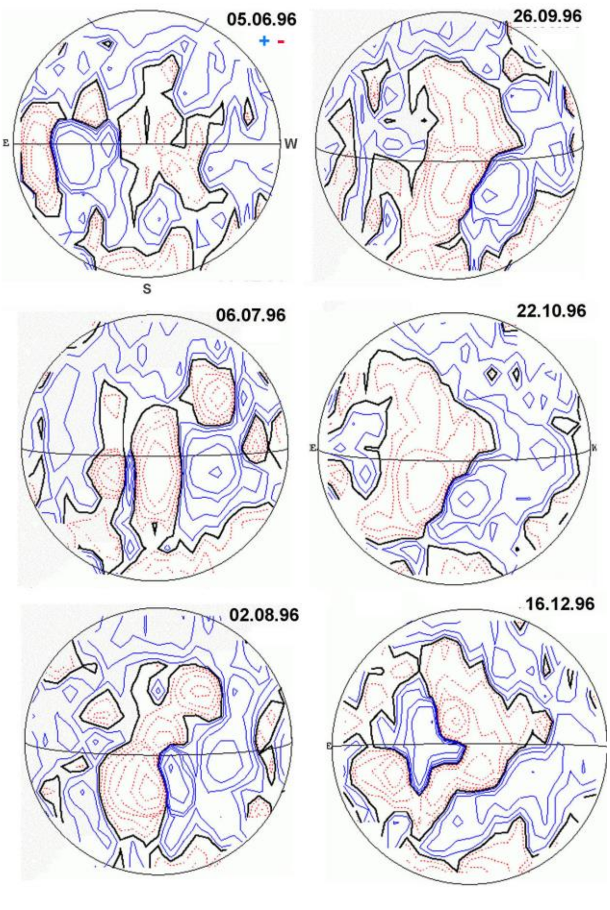


*Figure 4*. WSO maps of LMF for solar minimum 22–23. The Carrington longitude of the central meridian is within 255°–265°. LMF isolines: 0, ±20, 50, 100 ... μT. The neutral line is drawn in black

At solar minimum 24–25 there are two groups of active longitudes: 40°–120° and 240°–320° (see Figure 2, Table 2), which contain more than 60 % of ARs. This minimum is longer and deeper. Long spotless periods fall on November 14 – December 23, 2019 and February 2 – March 6, 2020; they are separated by a time interval of a little more than a month. This period features a conventional minimum (December 2019).

There is no data on magnetic fields for December 2019 – January 2020. Averaging was therefore performed for the subsequent time period. Figure 5 displays a synoptic map of LMF averaged over four Carrington rotations (February – May 2020). The magnetic field during this longer minimum is much weaker than during the previous one, so to the isolines correspond lower strengths. White lines indicate active longitudes.

In each active longitude region, there are two sectors of positive and negative polarities from the corresponding polar caps to the 50° heliolatitude of the opposite hemisphere. Beyond the active longitudes, large LMF structures are also oriented along the meridian.

In Figure 6 are LMF maps for the first group of active longitudes 40°–120°. Small magnetic poles of both signs are seen to be arranged in some order relative to the meridian. The meridional structure is more pronounced in March–June 2020, immediately after the end of the second spotless period. In June, AR 12765 enters the structure in the southern hemisphere at a latitude of 25°. The overall pattern still remains unchanged, but by August it breaks down due to increased activity in the northern hemisphere.

Figure 7 presents LMF maps for the second group of active longitudes 240°–320°. In April–May 2019, there are strong ARs of the previous cycle in the northern hemisphere. After their decay, there are LMF structures extending from the corresponding heliographic pole to high latitudes of the opposite hemisphere. The most orderly pattern exists from July to September 2019, but in general the meridional orientation remains unchanged until August–September 2020.

Minimum 23–24 is also long. The active longitude 180°–260° stands out. Figure 8 shows an averaged synoptic map for November 2008 – February 2009 with the conventional minimum in December 2009. At the active longitude there is a wide sector of positive polarity, touching the south pole and reaching 50° N. Beyond its borders are narrower meridionally oriented structures. Synoptic maps for minima 22–23 and 24–25 have been constructed for the time periods including long intervals of spotless days. The peculiarity of minimum 23–24 is that two long periods of

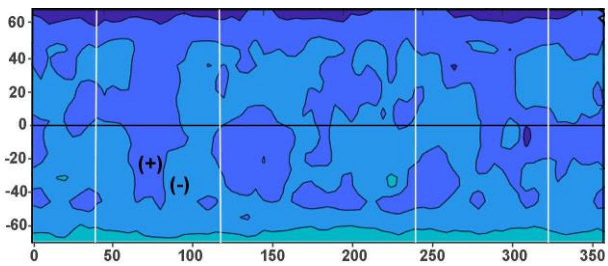


*Figure 5*. Synoptic map averaged over four Carrington rotations (2227–2230). LMF isolines: 0, ±50, 125 μT. Explanations are given in the text

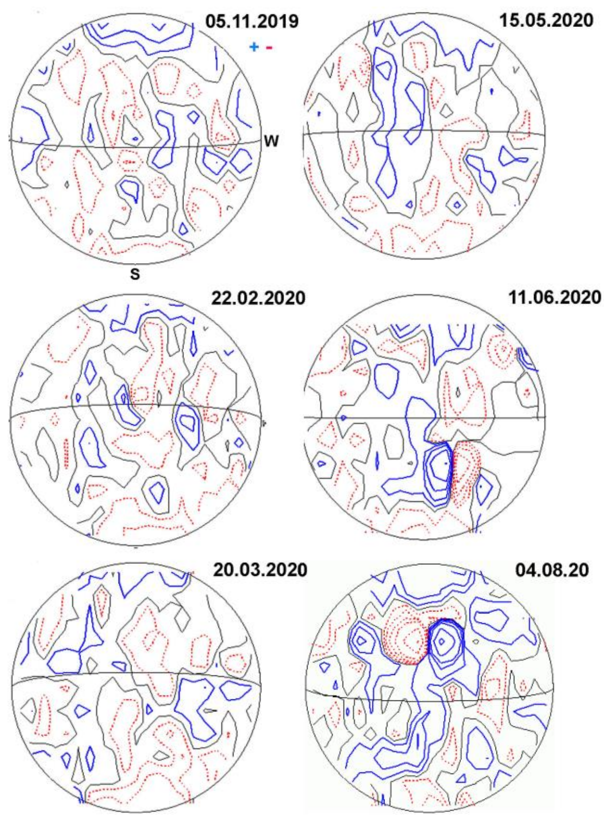


*Figure 6.* Daily WSO maps of LMF for minimum 24–25. The Carrington longitude of the central meridian is close to 90°

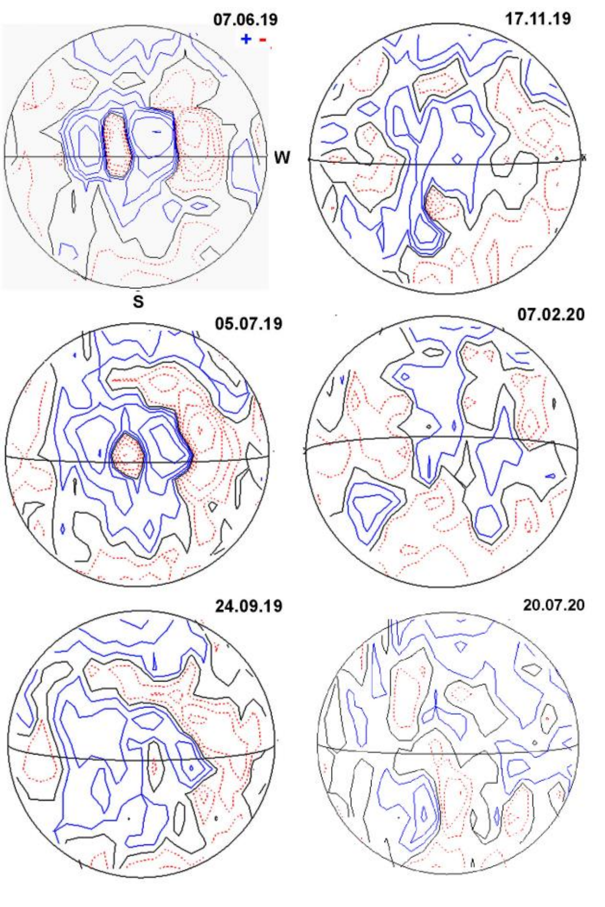


*Figure 7*. WSO maps of LMF for minimum 24–25. The Carrington longitude of the central meridian is close to 290°

spotless days were separated by an approximately annual interval. Activity was very low. The synoptic map shows the field structure during this very period.

In May 2009 in the active longitude region in the northern hemisphere and in July in the southern hemisphere, medium-sized ARs of the new cycle appeared, followed by the second long spotless period. Figure 9 demonstrates daily magnetograms for July – September 2009. The meridional orientation of LMF structures on the daily maps is seen to be similar to that observed during solar minima 22–23 and 24–25. An increase in activity of the new cycle causes the pattern to distort.

Thus, during SA minimum in the LMF structure there are magnetic field regions of positive and negative polarities, which are elongated along the meridian and cross the equator. The most pronounced of them are located in the region, where ARs predominantly appear.

## DISCUSSION

Analysis of magnetograms of weak LMF in the solar photosphere during deep solar minimum shows the presence of longitude sectors of positive and negative polarities crossing the equator. The most pronounced meridional structures are observed in the region of active longitudes and are often connected with polar magnetic fields. The longitude scale of such structures is 35°–40°. The phenomenon of active longitudes is considered as an observational confirmation of the solar

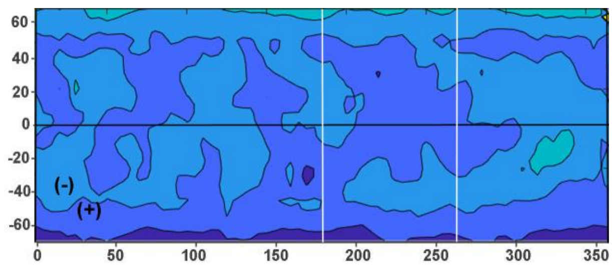


*Figure 8*. Synoptic map averaged over four Carrington rotations (2076–2079). LMF isolines: 0, ±50, 125 μT

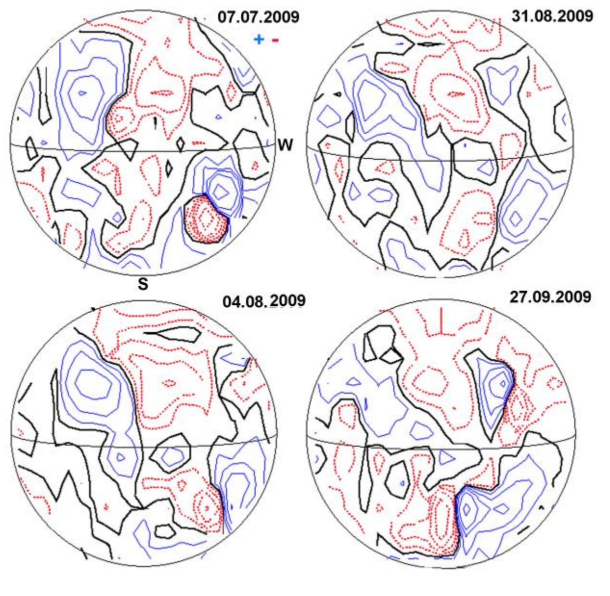


*Figure 9*. WSO maps of LMF for minimum 23–24. The Carrington longitude of the central meridian is 205°–210°

non-axisymmetric magnetic field. The non-axisymmetric large-scale magnetic field structure has been studied in many theoretical solar dynamo models ([Pipin, Kosovichev, 2015] and references therein). The appearance of the non-axisymmetric LMF mode is generally determined by nonlinear effects of magnetic buoyancy and magnetic helicity. Nonetheless, solar dynamo models examine these effects on a large time scale of the order of solar cycle and larger. We have studied a magnetic field structure in the region of active longitudes on a time scale of 10–20 solar rotations; the appearance of longitude sectors crossing the equator in the magnetic field structure indicates a nonstationary non-axisymmetric mode on a time scale of about 1 year. Due to the fact that the magnetic field structure and dynamics reflect subsurface convective plasma motions, it is fair to assume that the appearance of a non-axisymmetric magnetic field component is linked to the existence of giant convective cells.

Simon and Weiss [1968] were the first to present a model of convection in the Sun's polytropic atmosphere. This model explained the appearance of granules and supergranules and predicted the existence of giant cells with a horizontal scale of about 300000 km. It had previously been established that ARs united into activity complexes [Bumba, Howard, 1965b] whose dimensions coincided with a network of giant cells with a scale of about 400 000 km. Bumba [1970] suggested that such a large-scale field structure corresponds to giant cells living for ~4 months. Activity complexes are formed at the nodes of this network, and ARs arise at the nodes of the supergranulation network. Motions are transferred from the sub-photospheric layers to the photosphere through a magnetic field and viscosity [Pikelner, 1962; Parker, 1963]. Then, the magnetic field structure reflects the giant cells that exist in deep layers of the convective zone from the base to the heights where the supergranulation is formed. These global convection cells penetrate into the upper layers of the convective zone, and the magnetic field dynamics on the surface reflects them somewhat.

Grigoryev and Latushko [1992], using LMF structures as tracers, have shown that there are plasma flows of different signs extending in the north-south direction and crossing the equator. The size of the structures in longitude is 25°–45°, horizontal velocities are ~60 m/s. They represent large-scale convective motions below the photosphere. Similar longitude sectors of positive and negative polarities were also observed in [McIntosh, 2005] when analyzing H$\alpha$ synoptic charts. Piddington [1971] suggested that they might have resulted from the existence of giant convection cells.

The main evidence for this was observations showing large-scale structures in the spectrum of motions in the photosphere [Hathaway et al., 1996, 2000, 2013; Beck et al., 1998]. In the recent work, authors measured the transfer of supergranules from the centers to the boundaries of giant cells by large long-lived fluxes. HMI/SDO measurements of Doppler shifts of the spectral line in the photosphere were used. After preliminary data processing, velocity maps in longitude and latitude directions were constructed; they show a cellular pattern of motions, with cells at low latitudes elongated in the north-south direction.

Hydrodynamic models of convective motions in a rotating convection zone on the Sun show that the cells should be elongated in a north-south direction in the equator region [Gilman, 1979; Elliot et al., 2000; Miesh et al., 2008]. These banana cells should transfer angular momentum to the solar equator to set differential rotation. Hathaway et al. [2013] note that it would be surprising if these large-scale long-lived fluxes did not significantly affect the structure and evolution of magnetic fields. Our results confirm that giant convective cells affect the magnetic field structure, especially noticeable during solar minimum.

## CONCLUSIONS

Analysis of solar minima with the largest number of spotless days has shown that active longitudes, as preferred zones where sunspots occur, manifest themselves in this solar cycle phase. Analysis of synoptic maps and individual daily WSO magnetograms reflecting the structure of weak LMF has revealed a non-axisymmetric component of the solar magnetic field. During solar minimum in the LMF structure, there are magnetic field regions of positive and negative polarities, which extend along the meridian and cross the equator. The most noticeable of them are located in the active longitude zone and are often linked to polar magnetic fields.

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