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# APPEARANCE OF ACTIVE REGIONS AT THE END OF SOLAR CYCLE 24 AND AT THE BEGINNING OF CYCLE 25

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**Abstract.** The spatial-temporal picture of appearance of active regions and the relationship of their appearance with the structure and development of a large-scale magnetic field were studied during the transition from solar cycle 24 to 25. During this period, solar activity is low, and therefore the dynamics of a large-scale magnetic field in the appearance of new active regions is most noticeable. We have used SDO/HMI data on the longitudinal magnetic field to determine the time and heliographic coordinates of the origin of an active region, as well as daily WSO maps (Wilcox Solar Observatory) to compare with the structure of the large-scale magnetic field. We have obtained the following results. During the transition from one cycle to another, new active regions appeared in half of the cases in the polarity inversion line of the large-scale magnetic field, and almost exclusively at the Hale boundaries in the corresponding hemispheres and solar cycles. In other cases, the places of appearance were unipolar regions of the large-scale magnetic field without a clear advantage in the location of the field regions according to the Hale law. The formation of active regions is preceded or accompanied by changes in the structure of the large-scale magnetic field. At the same time, in the fine structure of the magnetic field in the photosphere we can observe an increase in the magnetic field network on a spatial scale of the size of supergranules and larger, as well as the appearance of small regions of a new magnetic field of both polarities. The appearing active regions were concentrated in two narrow longitudinal zones that covered both hemispheres of the Sun. The new cycle began in the same longitudinal zones, where the activity of the old cycle decayed.

**Keywords:** magnetic field, active regions.

## INTRODUCTION

Studying the patterns of appearance of solar active regions (ARs) is one of the main problems of solar physics. Some aspects of the relationship between the structure of a large-scale magnetic field (LMF) and AR appearance have been discussed in [Bumba, Howard, 1965; McIntosh, Wilson, 1985; Stepanyan, 1985; Grigoriev, Peshcherov, 1986; Ograpishvili, 1988]. Bumba, Howard [1965] have shown that there is a correlation between localization of new regions and the old magnetic field. The results of the works indicated a connection between appearance of ARs and global changes in the LMF system. The presence of a sequence of sigmoid structures in soft X-ray solar corona images [Matsumoto et al., 1998] can be associated with the large-scale process of AR appearance. Such features can sometimes be seen in the near-equatorial zone during periods of high solar activity. In the above work, it was assumed that their appearance is associated with the emergence of a large-scale twisted magnetic flux tube from the convective zone.

The question about the relationship between the places of appearance of new ARs and the LMF structure remains unresolved. In general there is a correspondence between the picture of location of large-scale ARs on the solar surface and the LMF synoptic maps based on Mount Wilson magnetograms or Hα filtrograms [McIntosh, 1981; McIntosh, Wilson, 1985]. Large-scale ARs were observed to appear near the polarity inversion line of LMF. Ograpishvili [1988], using a large amount of material (about 200 ARs), has concluded that ARs that appear near the polarity inversion lines develop faster and more intensively. Note that the author analyzed the time period 1979–1982, the maximum of solar cycle 21.

In some cases, the formation of new LMF structures was detected before the appearance and development of ARs (e.g., [Grigoryev, Peshcherov, 1986]). Grigoryev et al. [2012] spatially averaged the longitudinal magnetic field in the NOAA 10488 formation region according to SOHO/MDI data. The averaging was carried out over cells 40″×40″. Three hours before the emergence of a new magnetic flux, the sign of the magnetic field changed directly at the site of emergence of the new flux.

In all previous works, the appearance of ARs was analyzed on a long time interval within the solar cycle. In addition, synoptic maps of distribution of magnetic fields based either on daily magnetograms or on Hα filtrograms were usually used. Such an analysis of the relationship between the site of appearance of ARs and the LMF structure can lead to a method error. The synoptic map is based on daily measurements of the magnetic field near the central meridian and reflects the average magnetic field structure we consistently observe during solar rotation. The true distribution of LMF at the time of emergence of a new magnetic flux and the picture determined from a synoptic map are most often different. If AR appears to the east of the central meridian, the synoptic map reflects the changes that happened in the LMF structure; if to the west, the field structure preceding the time of AR appearance.

The spatio-temporal pattern of AR appearance still remains unclear. The purpose of this work is to further study the relationship of LMF with local magnetic fields, as well as the spatio-temporal distribution of AR appearance sites.

To study the relationship of sites of AR appearance with the LMF structure and development, we have chosen the period January 2019 – May 2021 because it coincides with solar minimum and covers the end of cycle 24 and the beginning of cycle 25. At that time, the background magnetic field in the solar atmosphere was almost not disturbed by the previous solar activity, which is why the information about sites of appearance of new ARs and the changes in the LMF structure preceding their appearance is most reliable. On the other hand, this period is remarkable for the fact that the birth of ARs of both cycles can be observed simultaneously on the Sun, which can contribute to understanding the interrelation of successive activity cycles.

## OBSERVATIONAL DATA

We have used SDO/HMI data on the longitudinal magnetic field [Scherrer et al., 2012] and Stanford (Wilcox Solar Observatory, WSO) LMF maps [Duvall et al., 1977]. In the former case, the time resolution of the data we use is 3–15 min; in the latter, ~1 day. The spatial resolution is ~0.5″ and 3′ respectively. We have analyzed all ARs that appeared on the visible solar disk in the heliolongitude range E70–W50 during the given period. The ARs for which the initial data was incomplete were excluded from consideration. We also excluded two ARs (NOAA 12762 and 12747) because of the uncertainty of the type of LMF structural relationship. Furthermore, the second AR (low-latitude) should belong to solar cycle 24, but it was either anti-Hale or came from another hemisphere. In total, for cycles 24 and 25 there are respectively 11 and 22 ARs suitable for determining the relationship between the site of AR appearance and the LMF structure. The location of magnetic field polarities in the ARs considered corresponds to the Hale law. The location of the site of AR appearance relative to LMF was found on the first day for the time closest to the time when an LMF map was obtained.

To draw the synoptic map of AR appearance, we took the period 2019–2020 when 61 ARs appeared, 21 of which belong to solar cycle 24; 40, to cycle 25.

In what follows, we will use three definitions: the AR magnetic field (SDO/HMI), LMF (WSO), and the background magnetic field (the field visible on SDO/HMI or WSO magnetograms before the appearance of AR).

## RELATIONSHIP BETWEEN THE AR APPEARANCE SITE AND THE LMF STRUCTURE

Below are two tables. Table 1 lists the numbers of the ARs considered, the date of emergence of a magnetic field, heliographic coordinates, LMF sign (in parentheses) at the site of AR formation, and its characteristics relative to the Hale polarity distribution law in AR in this cycle and solar hemisphere (f — following, l — leading). The boundary between polarities of the LMF regions is designated as +/– or –/+ (from east to west), and Hale/anti-Hale. Table 2 presents the overall results.

The results of the analysis presented in Tables 1 and 2 show that in half of the cases (17) new ARs appeared at the boundaries between polarities of LMF regions, and almost exclusively at the Hale boundaries in respective hemispheres and solar cycles. Only in one case did a new flux appear at the anti-Hale boundary. In the remaining cases (16), ARs appeared in unipolar LMF regions, yet there is no clear advantage in the location of the field regions according to the Hale law. The apparent predominance of the negative polarity of the LMF regions is considered insignificant due to the uneven appearance of ARs in cycles and hemispheres.

During the transition from one cycle to another, small ARs mainly appeared which contained pores and sunspots with an area of ~100 m.s.h. The magnetic field in them systematically corresponded to the Hale law in cycles 24 and 25. Simultaneous existence of sunspot groups of the new and old cycles in the transition period 2019–2020 was rarely observed.

## CHANGES IN THE STRUCTURE OF THE BACKGROUND MAGNETIC FIELD AT THE APPEARANCE OF AR

One of the first works that detected magnetic field changes before the appearance of ARs is [Bappu et al., 1968]. The observations were carried out with the vector magnetograph of the Sayan Solar Observatory with a spatial resolution of 18″. The magnetic field changes were recorded three days before the formation of a sunspot group. This result was confirmed [Grigoryev, Ermakova, 1976] by observations at the Sayan Solar Observatory at the panoramic magnetograph with a spatial resolution 4″×2″.

The simultaneous analysis of SDO/HMI and WSO data makes it possible to identify large-scale and fine-structure changes in the background magnetic field preceding the emergence of a new magnetic flux in AR.

### Active region NOAA 12761

According to the SDO/HMI magnetograms, a region of a pronounced increase in the magnetic field of both polarities was formed in the southeastern quadrant of the solar disk at the latitude S17 on April 25, 2020 (Figure 1). At about 01:00–01:30 UT on April 27, a magnetic field began to emerge and AR of the new cycle appeared. During the day, several small sunspots formed, after which the AR began to decay.

Table 1

ARs considered

| Cycle | Hemisphere | AR number in NOAA catalog | Date of appear-ance | Coordinates | LMF |
|---|---|---|---|---|---|
| **24** | **N** | 12735 | 15.03.19 | N03E63 | (+) f |
| | | 12736 | 19.03.19 | N08W16 | (+/–) Hale |
| | | 12737 | 31.03.19 | N13E50 | (+) f |
| | | 12739 | 17.04.19 | N06W17 | (+) f |
| | | 12742 | 23.06.19 | N03W17 | (+/–) Hale |
| | | 12743 | 24.06.19 | N02W50 | (–) l |
| | | 12748 | 31.08.19 | N13E37 | (+/–) Hale |
| | | 12751 | 02.11.19 | N06W15 | (+/–) Hale |
| | | 12766 | 02.07.20 | N07E50 | (+/–) Hale |
| | **S** | 12745, 12746 | 05.08.19 | S06E22 | (–) f |
| | | 12760 | 23.04.20 | S07E68 | (–/+) Hale |
| **25** | **N** | 12763 | 30.04.20 | N31E20 | (+) l |
| | | 12772 | 16.08.20 | N18E00 | (+) l |
| | | 12784 | 19.11.20 | N32E60 | (–/+) Hale |
| | | 12799 | 20.01.21 | N23 E00 | (–) f |
| | | 12800 | 25.01.21 | N18 E10 | (+) l |
| | | 12801 | 30.01.21 | N31W03 | (–) f |
| | | 12804 | 22.02.21 | N19W03 | (–/+) Hale |
| | | 12813 | 03.04.21 | N20W20 | (+) l |
| | | 12817 | 17.04.21 | N19W17 | (+/–) anti-Hale |
| | | 12826 | 24.05.21 | N24W35 | (+) l |
| | **S** | 12744 | 06.07.19 | S28E58 | (+/–) Hale |
| | | 12750 | 31.10.19 | S28E46 | (+/–) Hale |
| | | 12761 | 26.04.20 | S17E05 | (+/–) Hale |
| | | 12771 | 11.08.20 | S19E67 | (+) f |
| | | 12778 | 24.10.20 | S20E12 | (+/–) Hale |
| | | 12796 | 15.01.21 | S22W04 | (+/–) Hale |
| | | 12805 | 22.02.21 | S23E06 | (+) f |
| | | 12806 | 28.02.21 | S31E30 | (+) f |
| | | 12815 | 15.04.21 | S20W07 | (–) l |
| | | 12820 | 23.04.21 | S21E23 | (+/–) Hale |
| | | 12821 | 24.04.21 | S22W04 | (+/–) Hale |
| | | 12823 | 09.05.21 | S23E52 | (+/–) Hale |

Table 2

Overall results of AR location relative to LMF in cycles and hemispheres

| Cycle 24 | | Cycle 25 | | Cycles 24 and 25 |
|---|---|---|---|---|
| N polarity | S polarity | N polarity | S polarity | (+) — 11 |
| (+)f — 3<br>(–)l — 1<br>(+/–) Hale — 5<br><br>9 in total | (–)f — 1<br>(–/+) Hale — 1<br><br><br>2 in total | (–)f — 2<br>(+)l — 5<br>(–/+) Hale — 2<br>(+/–) anti-Hale — 1<br>10 in total | (+)f — 3<br>(–)l — 1<br>(+/–) Hale — 8<br><br>12 in total | (–) — 5<br>f — 9<br>l — 7<br>Hale — 16<br>anti-Hale — 1 |

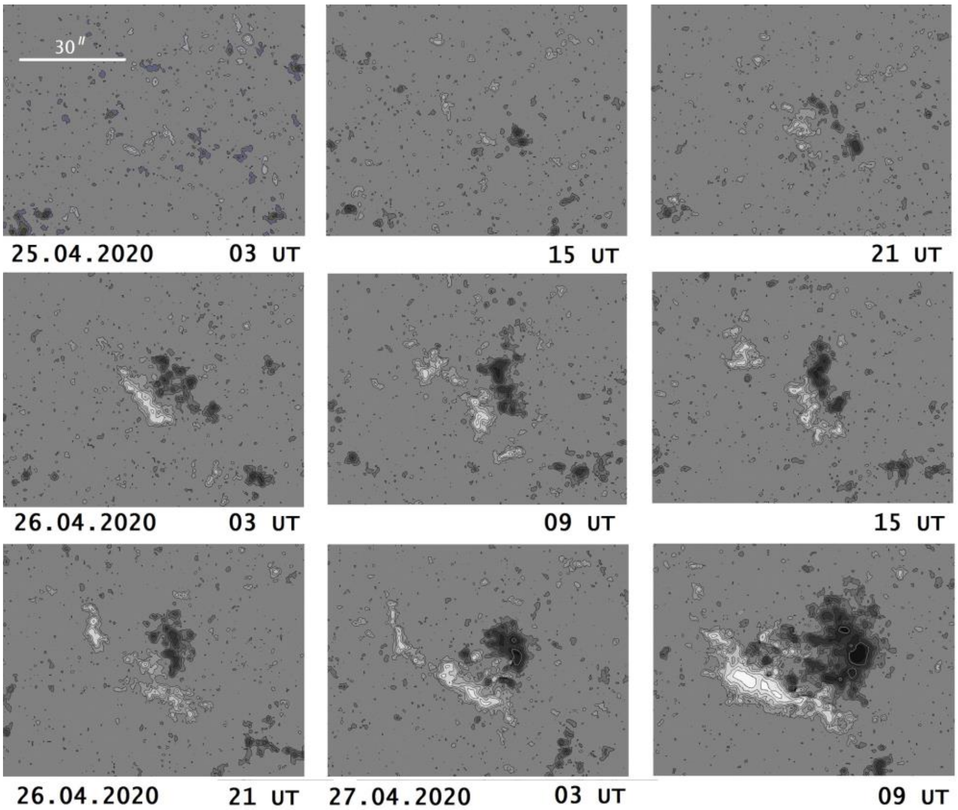


*Figure 1*. Fragments of SDO/HMI magnetograms for NOAA 12761. Black color marks a negative magnetic field; white, positive

Note that the increase in the magnetic field before the formation of AR occurred on a scale exceeding the size of one supergranule. Figure 2 shows WSO LMF maps. In this quadrant on April 24 at 00:00 UT, there was an extensive LMF region of positive polarity; at the end of the day, a negative polarity island appeared in it (indicated by an arrow). During the following days, the LMF configuration changed, but the negative field region was kept unchanged. The location of the new AR is seen to coincide with that of the new structural feature of LMF.

Thus, about two days before the appearance of the first pores of the future AR, dynamics is observed in the structure of the background magnetic field, which leads to the formation of a large-scale region of a new magnetic flux. The changes are seen on SDO/HMI and WSO magnetograms.

## Active region NOAA 12748

NOAA 12748 appeared at a site with coordinates N13E37 on August 31, 2019. According to SDO/HMI magnetograms, the magnetic flux began to emerge at 15:30 UT. We plotted the location of the magnetic flux emergence on the WSO LMF map obtained on August 31 at 01:40 UT (Figure 3). It fell into the center of the positive polarity cell. On the WSO map for 22:01 UT on the same day, the AR center was already located near the boundary between the LMF polarities (+/–); and to the west of it there was a small positive polarity island. Obviously, during August 31 at the site of AR appearance, a negative LMF emerged which divided the positive LMF region into two parts. It is impossible to figure out whether this happened before the AR appearance or after it, but we may assume that both processes are interrelated.

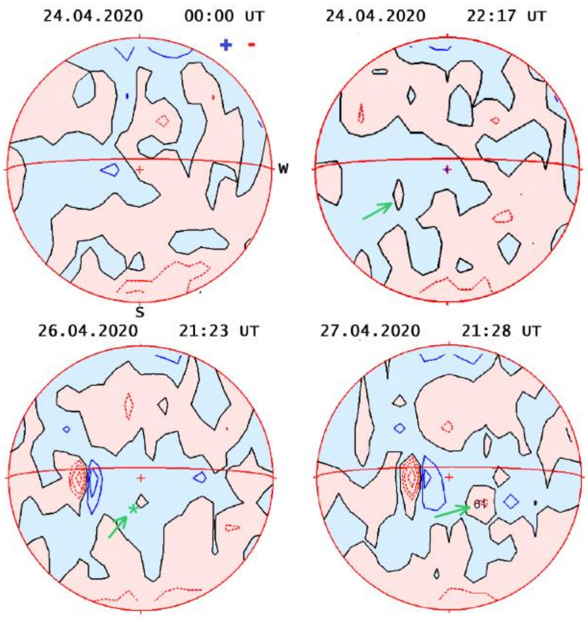


*Figure 2*. WSO LMF maps for the period of appearance of NOAA 12761. The asterisk marks the site where AR is formed; the two-figure number (the last two figures of the AR number) is its location; additionally these regions are indicated by arrows. Explanations are given in the text

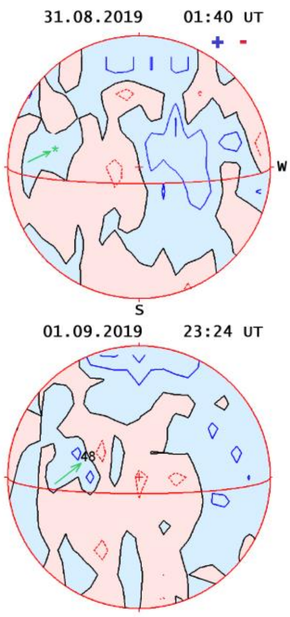


*Figure 3.* WSO LMF maps for the period of appearance of NOAA 12748. Designations are the same as in Figure 2

### Active region NOAA 12750

According to SDO/HMI magnetograms, the magnetic flux began to emerge on October 31, 2019 at ~04:30 UT (coordinates S28E52). The WSO magnetogram was received at 21:16 UT, and the appearing AR fell on the Hale boundary of LMF (+/–) (Figure 4). On the previous day, October 30, in this place, the LMF was positive. The AR formation began 4–5 hrs after receiving the WSO magnetogram on October 30. Hence, during the day the boundary of the negative LMF region shifted from west to east.

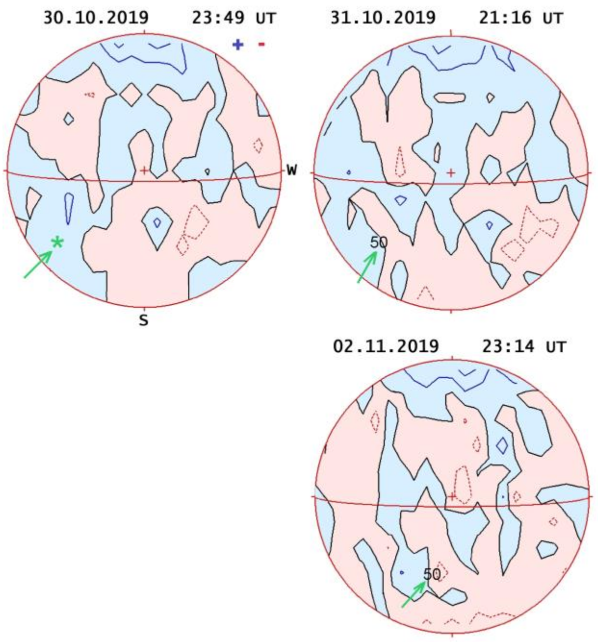


*Figure 4.* WSO LMF maps for the period of appearance of NOAA 12750. Designations are the same as in Figure 2

### Small-scale AR of cycle 25

A small-scale AR (coordinates S20E11, no number assigned) of the new cycle appeared on June 29, 2019. It existed for 2 days. A magnetic field began to emerge around 21 UT. The first pores formed on June 30 around noon, intensified on July 1, and disappeared the next day. The AR is interesting because a few hours before its appearance a noticeable increase in network magnetic fields in an area exceeding the size of several supergranules began. This can be seen in Figure 5, *a*. The frame size is 90″×90″. From 15:00 UT, a black-and-white network gradually appears. The place of AR appearance is indicated by an arrow. Panel *b* displays fragments of the WSO LMF maps for June 30 and July 1 and the AR location. There is no data for June 27–29, therefore the LMF dynamics at the early stage of the AR formation is unclear, but further changes suggest the development of a negative polarity area in this place and its merging with the south pole field.

Thus, the given examples show that the AR formation is preceded or at least accompanied by LMF changes. Before the emergence of the AR magnetic flux, small areas of a new magnetic field of both polarities appear in the fine structure of the quite photosphere, and an increase in the magnetic field network can be observed on scales exceeding the size of a supergranule. This is followed by the emergence of a bipolar structure forming the AR. At the same time, a new LMF region is being formed.

## ACTIVE LONGITUDES DURING THE CYCLE CHANGE

The AR appearance is known to be subject to certain spatio-temporal patterns [Vitinsky et al., 1986; Bai et al., 1995]. The size of the latitudinal zone of sunspot concentration is 10°–15°, and it moves from high to low latitudes during the cycle. The longitude distribution is characterized by significant inhomogeneity. There are longitude intervals in which ARs mainly appear and develop for a long time (up to 20–40 solar rotations). The nature of this phenomenon is still unknown and continues to be discussed. To study the spatial distribution of appearing ARs during the transition from cycle 24 to 25, we have drawn a synoptic map that, in accordance with the Carrington coordinates, shows all ARs containing pores and sunspots for 2019 and 2020 (Figure 6). Blue and red circles mark the ARs that appeared in 2019 and 2020 respectively. Sunspots of the new and old cycles are widely spaced in latitude intervals. The sunspot and pore groups in cycle 24 are located in the near-equatorial zone, from 15° N to 10° S. In cycle 25, solar activity is mainly in the northern hemisphere above 20°, and in the southern hemisphere above 15°. Horizontal lines on both sides of the equator separate ARs of the old and new cycles. At the end of solar cycle 24, activity prevails in the northern hemisphere; at the beginning of cycle 25, in the southern hemisphere. Most sunspots during this period were small.

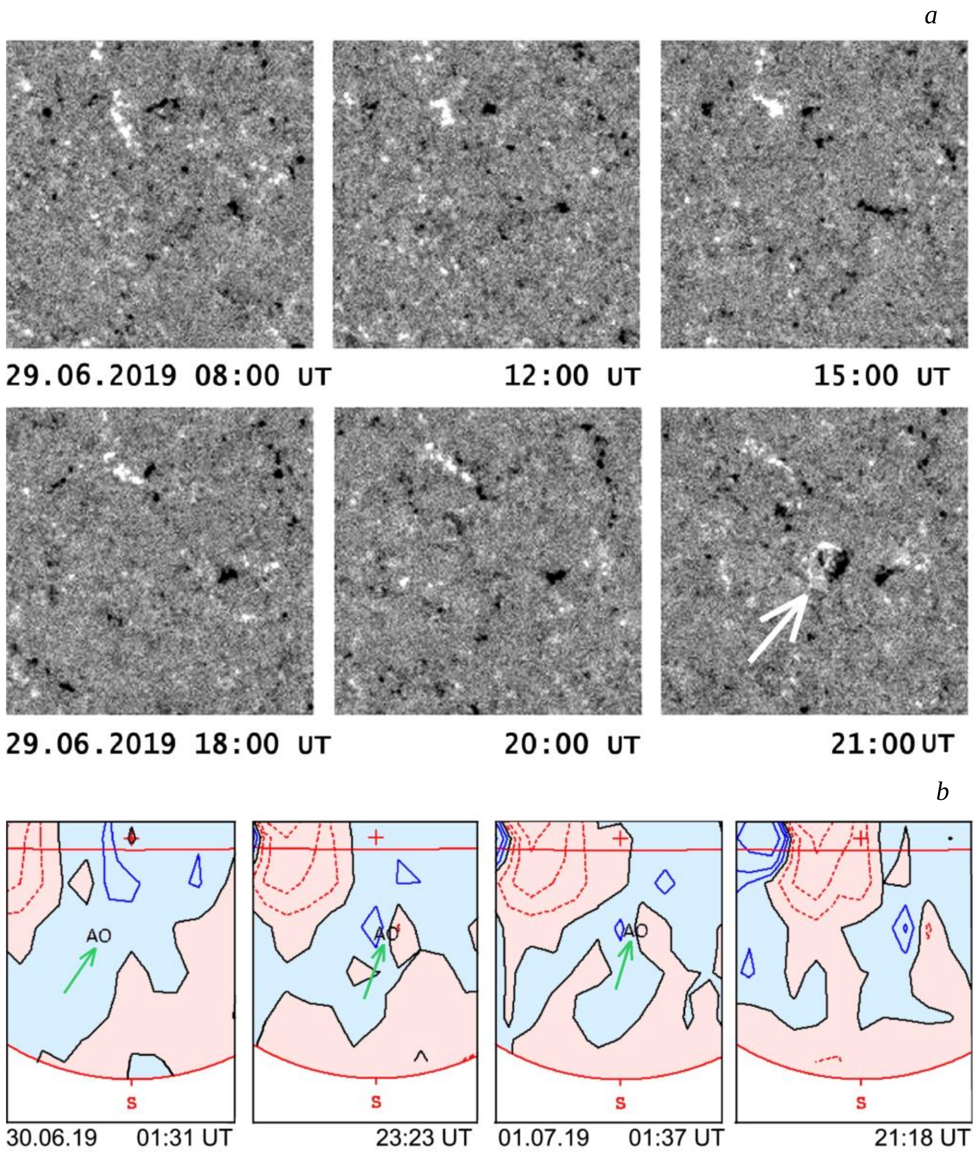


*Figure 5*. Fragments of SDO/HMI and SWO magnetograms at the site of appearance of small-scale AR. Explanations are given in the text

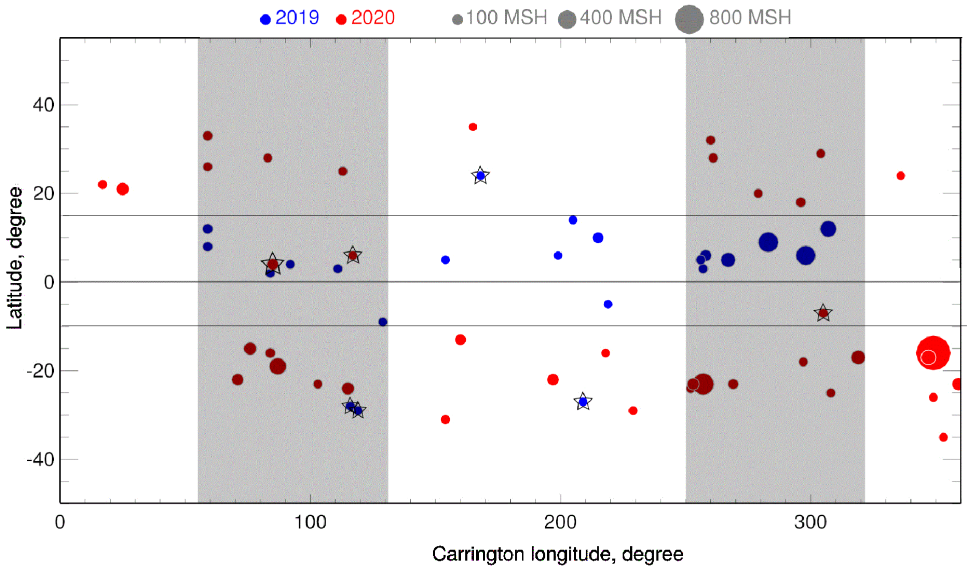


*Figure 6*. Synoptic map of ARs for 2019–2020. Explanations are given in the text

Table 3

Distribution of ARs over longitude intervals

| | **60–130** | 130–250 | **250–320** | 320–360(0)–60 |
|---|---|---|---|---|
| Cycle 24 | **8** | 5 | **8** | 0 |
| Cycle 25 | **12** | 8 | **13** | 7 |
| Cycles 24 and 25 | **20** | 13 | **21** | 7 |

Solar activity is seen to group mainly in two narrow longitude zones during the transition from cycle 24 to 25. The width of the longitude zones is ~70° (shaded in Figure 6). They are located at Carrington longitudes 60°–130° and 250°–320°, i.e. they are spaced by ~180° and separated by two low activity longitude zones of 120° and 100°. The emerging groups of sunspots and pores in the narrow longitude zones are concentrated regardless of the hemisphere. The number of ARs in all longitude intervals is shown in Table 3.

The predominant longitude zones of activity are preserved during the transition from cycle 24 to cycle 25. While there was almost no simultaneous existence of groups of sunspots of the new and old cycles, the end of cycle 24 and the beginning of cycle 25 were superimposed on each other. In 2019, four sunspot groups of the new cycle appeared at latitudes above 20°; in 2020, three groups of sunspots of the old cycle formed at latitudes below 10° (in Figure 6, the corresponding circles are depicted by asterisks).

## DISCUSSION

The most common AR models attribute its appearance on the photosphere to the emergence of an omega loop of the toroidal magnetic field from the depth of the convective zone. The first changes in the structure of weak LMF in the photosphere and the evolution of small-scale strong magnetic fields suggest that the emerging magnetic flux is not homogeneous but represents a large-scale system of magnetic arches. Thus, the AR appearance is a large-scale process of emergence of a system of magnetic loops covering a significant part of the solar atmosphere. The polarity of the sunspots that make up AR depends on the direction of the toroidal field. The sunspot polarity, and hence the direction of the toroidal field, varies from cycle to cycle according to the Hale law. The predominant longitude zones of activity were preserved during the transition from cycle 24 to 25; consequently, the decay of activity and toroidal field of the old cycle occurred largely in the same longitude zones where the new cycle began to develop.

A similar result has been obtained in [Benevolenskaya et al., 1999] when analyzing the transition from cycle 22 to 23 during the solar minimum from July 1996 to April 1998. Synoptic maps based on SOHO/MDI full disk magnetograms were used in the work. Large-scale structures of the magnetic field at successive rotations appeared at constant longitudes and thus reflected the magnetic active longitudes, as called in [Bumba, Howard, 1965].

Note that the lifetime of large-scale magnetic structures is much longer than the lifetime of groups of small-scale sunspots and pores, the location of magnetic structures is therefore more affected by their own motions and differential rotation in the photosphere. Determination of the predominant longitude zones of appearance of sunspot and pore groups reflects the existence of AR generation sources in these longitude zones in the Sun's interior. Modern dynamo and solar cycle theories cannot yet explain the existence of longitude zones of activity. Various mechanisms for this phenomenon are proposed. For example, Ruzmaikin [1998] assumes the existence of a non-axisymmetric α-Ω-dynamo mode, which causes a new magnetic flux to emerge at the given longitudes.

Our results and those obtained by Benevolenskaya et al. [1999] show that the predominant longitude interval covers both solar hemispheres. This fact allows us to assume the existence of global convective cells elongated along the meridian and contributing to the emergence of a toroidal magnetic field at different latitudes of the new and old solar cycles. Figure 7 demonstrates how the general picture of the LMF polarity inversion lines changes

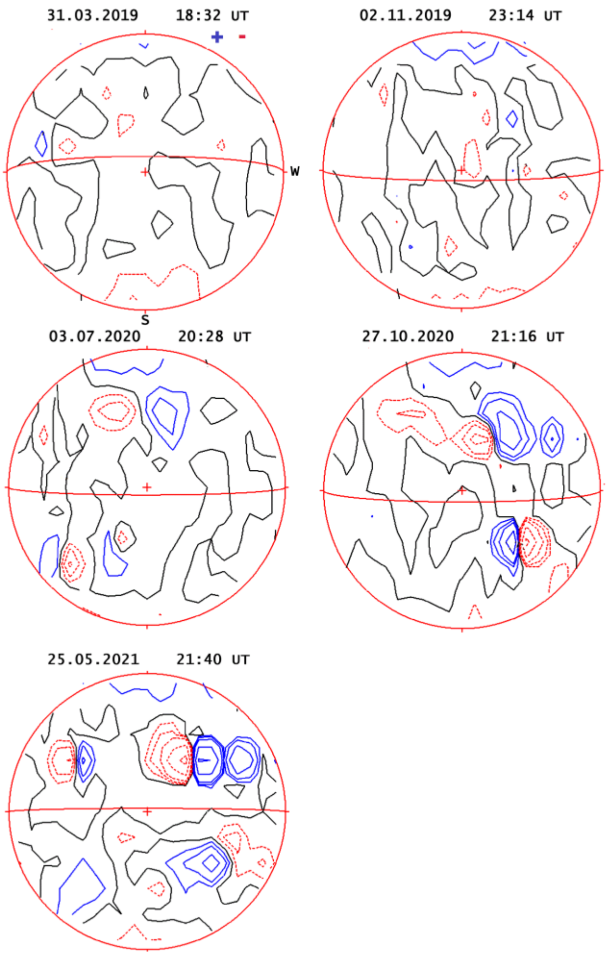


*Figure 7.* LMF structure during the transition from solar cycle 24 to cycle 25

during the transition period. The meridional component disappearing with increasing solar activity manifests itself in the LMF structure during solar minimum. Numerical simulation of solar convection usually shows giant cells in the power spectra of convective flow velocities in addition to granules and supergranules [Miesch et al., 2008]. Convincing observational evidence for the existence of the giant cells has been found by analyzing SDO data [Hathaway et al., 2013]. The size of the cells is estimated at $2\cdot10^5$ km, the flow velocity in the surface layers is very low (~8 m/s). Of particular interest have always been the sector or "banana" cells that may be responsible for the differential rotation and angular momentum transfer [Hotta et al., 2015]. The role of such cells in the appearance of ARs in preferred longitude intervals is discussed and requires a more nuanced approach to simulation.

## CONCLUSIONS

The main conclusions can be formulated as follows.

1. During the transition from cycle 24 to cycle 25, small ARs were mainly born which contained sunspots with an area of ~100 m.s.h., magnetic fields in which obeyed the Hale law in this solar cycle. New ARs appeared in half of the cases at the boundary between LMF polarities, and almost exclusively at the Hale boundaries in the corresponding hemispheres and solar activity cycles; in the remaining cases, in unipolar regions of LMF with no apparent advantage in the location of the field regions according to the Hale rule.

2. The AR formation is preceded or accompanied by changes in the LMF structure. In this case, we can observe an increase in the magnetic field network on a spatial scale of supergranule size or larger in the fine structure of the magnetic field in the photosphere, as well as the appearance of small-scale regions of a new magnetic field of both polarities.

3. During the transition from cycle 24 to 25, the appearing ARs were concentrated in two narrow longitude zones covering both solar hemispheres. The new cycle began in the same longitude zones where activity of the old cycle went down. At the same time, the old cycle decayed at low latitudes, and the new cycle simultaneously developed at high latitudes.

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