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ASYMMETRY IN APPEARANCE OF THE LEADING AND FOLLOWING POLARITIES IN THE PHOTOSPHERIC MAGNETIC FIELD AT THE EARLY STAGE OF ACTIVE REGION FORMATION

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Abstract. We study the evolution of the photospheric magnetic field at the early stage of active region development. We use data on longitudinal component of the magnetic field and line-of-sight velocities from SOHO/MDI and SDO/HMI. The visual inspection of 48 cases of birth of active regions and the detailed analysis of the magnetic flux dynamics in 4 active regions have shown that at the time of emergence of a new magnetic field, the field of the following polarity is the first to be detected in the photosphere. The flux asymmetry of the leading and following polarities persists for several tens of minutes. The observed asymmetry of magnetic fluxes supports the results of the numerical simulation of emergence of the active region magnetic field in the upper layers of the convective zone, which has been carried out by Rempel and Cheung [2014].

Keywords: magnetic field, active regions.

INTRODUCTION

Active regions (ARs) in the solar atmosphere are formed due to emergence of a magnetic field from the sub-photosphere. The magnetic field is generated at the base of the convection zone of the solar dynamo mechanism. The AR bipolarity occurs when the top of an emerging Ω-shaped magnetic flux tube crosses the photosphere. The observed distribution of magnetic field densities suggests that the tube emerges not as an integrated object but as a coherent system of magnetic flux tubes of the toroidal magnetic field subjected to convection in the solar interior.

When emerging and evolving, ARs exhibit a number of asymmetries related to the leading and following polarities. Let us list the main ones. The axis that links the opposite polarities is nearly in the east-west direction, but the leading part is shifted to the equator. The magnetic field of the leading polarity tends to concentrate into a compact region and further evolves into a large sunspot, while the field of the following polarity remains more fragmented. Tian, Alexander [2009] have found out that the leading polarity carries 3–10 times more helicity flux than the following one. This may mean that the leading part is more twisted before emergence or there is a difference in the rate of emergence of magnetic loop footpoints.

Early studies made using data from Mount Wilson Observatory [Bumba, Howard, 1965] have found an imbalance in the magnetic polarities when AR emerges, namely a predominance of the following polarity. This might have been due to the low spatial resolution of magnetograms — 23″. At the same time, chromospheric observations in the K CaII line have shown that the following part of a plage also develops before the leading one [Knoska, 1977]. Bappu et al. [1968] have first detected a region of the transversal magnetic field oriented in a direction that links longitudinal field hills, where then sunspots are formed. AR also evolved from the following polarity to the leading one.

The nature of the asymmetry in emergence and evolution of magnetic fluxes of the leading and following polarities is not clear, although there are models capable of describing satisfactorily some details of this process [Fan et al., 1993; Fan, 2008; Rempel, Cheung, 2014]. Properties of appearance and development of the polarities are critical to select a model of emergence of a magnetic field, so it is necessary to study the emergence of a magnetic flux at the early stage of AR evolution with high spatial resolution.

The purpose of this paper is to study the asymmetry in emergence of a magnetic field associated with the time of emergence of magnetic fluxes of the leading and following polarities at a very early stage of AR evolution from high spatial and temporal resolution data.

OBSERVATIONAL MATERIAL AND PROCESSING TECHNIQUE

We have used SOHO/MDI and SDO/HMI data for ARs observed during solar cycles 23 and 24. Spatial resolution of the data in the former case is ~2″; in the latter case, ~0.5″. When selecting objects for the study, we have partially used information from [Schunker et al., 2016]. We conducted the analysis by visually inspecting magnetograms. Later on, for several ARs we made quantitative processing with data on a longitudinal magnetic field and Doppler velocities. In calculating the magnetic flux, we took into account a reduction in the Sun's visible surface due to projection.

When examining magnetograms, in some cases we can quite confidently identify the polarity of the element that appears first. Nonetheless, the area of one polarity is more often seen to increase much faster than that of the other. In this case, at a very early stage, the polarities are not mixed, and it seems as if from a point a veil is thrown which is then broken to pieces of the opposite polarity. Of course, this is easier to see when a large active region is formed.

Objects are selected according to the following criteria:

- An active region emerges at a relatively free area without old magnetic fields and enhanced network fields.
- It is desirable that the rate of field emergence would be high, there would be a single center of field emergence, and, if there are several centers, they would not work simultaneously.
- To reduce distortions of signs of the longitudinal field that result from the projection, ARs were selected in the longitude interval ~E45–W35. We allowed for the insertion of ARs at a higher heliolongitude in the number of those considered if at the stage of their occurrence the polarity inversion line for AR in general or for an individual, previously isolated arch was oriented at an angle of >45° to the equator.
- A minimum length of AR at its maximum development is ~7°. We allowed for insertion of ARs of shorter lengths if they emerged near the central meridian.

Note that when large active regions are formed, emergence of a magnetic field often begins with small arches oriented at different angles. The main flux emerges at the highest rate. It may contain several arches. Later, footpoints of arches of one polarity show a tendency to join together. From the very beginning, the largest arch is most often oriented E–W. It most clearly shows patterns of distribution of fields of different polarities. This fact has been taken into account in the analysis.

RESULTS

Table lists numbers of ARs, their coordinates for the beginning of emergence of a magnetic field, date and time of emergence of a new magnetic field, a maximum length of AR, and the polarity prevailing at the beginning of the emergence (f — following, l — leading).

We have examined a total of 48 ARs. Formation of 33 ARs began with the following polarity; in 5 ARs, the leading polarity prevailed. In ten cases, we did not identify the predominant polarity. To the east of the central meridian, 26 ARs were formed (f — 22; l — 0; f and l — 4), to the west, 22 ARs (f — 11; l — 5; f and l — 6).

Using four active regions as an example, we examined emergence of the magnetic field in more detail. We largely randomly selected ARs, but gave preference to the ARs that were not of the smallest size and were located as close to the central meridian as possible. We chose the following active regions: NOAA 11431 (W11), 12175 (E14), 12632 (E01), and 12715 (E40). The last one was located at a high heliolongitude, but there was an interesting feature of the magnetic field dynamics.

NOAA 12175 appeared at a site with coordinates N14E13 on September 24, 2014. Emergence of a new flux began in the vicinity of old fields of both polarities after 07:00 UT as multiple centers (see Figure 1, *a*). The dynamics of the new magnetic field is difficult to trace because of the old magnetic fields. After two hours in the south-west region without old fields, a bipolar magnetic flux emerged which resulted in the formation of the leading part of the active region. The field emerged in a place free of background fields, therefore we can compare the dynamics of magnetic fluxes of opposite polarities. First at 09:08 UT, an area with negative line-of-sight velocities appeared (arrow in Figure 1, *b*). For this heliographic position, this means the rise of matter. After 3 min, a field of the following polarity appeared; 2–3 min later, a field of the leading polarity. The described variations are caused by the emergence of a magnetic arch. When a horizontal magnetic field of the top of the arch appears in the photosphere, the rise of matter is recorded. There is no vertical component of the magnetic field vector that time. Figure 1, *b* plots the evolution of the magnetic fluxes. We can see that for about one hour a flux of the following polarity prevailed.

The emergence of the magnetic field of NOAA 12715 began at ~05:00 UT on June 19, 2018 at a site with coordinates N08E43, surrounded by old fields of both polarities. A few hours later, the old magnetic fields were included into a magnet system of a new active region (see Figure 2). A significant increase in the new magnetic flux occurred after 06:00 UT, first due to the following polarity. Let us examine in detail the dynamics of the magnetic fields for the southwestern part of the AR (Figure 2, middle row, frame for 09:15 UT), on which there are no background fields. First, a rapidly growing region of negative line-of-sight velocities appeared (arrow in the left bottom panel of Figure 2). At such a heliocentric distance (E41), it rather suggests rise of matter than its possible horizontal movement. Then, the following polarity shifted eastward appears (Figure 2, the frame for 09:30 UT). At 09:42 UT on the west side, a field of the leading polarity adjoins it. Now, the region of negative line-of-sight velocities is centered on the polarity inversion line. Suppose that these polarities are closed on each other. Then, there are two directions of closing of the polarities: east–west and south–north (see pairs of arrows in the bottom right panel of Figure 2). This is indicated by the two-peak region of line-of-sight velocities. In the former direction at such a heliolongitude, there may be distortions of the visible structure of the magnetic field which are caused by the projection; in the latter, not. Thus, the beginning of the rise of matter and of the appearance of magnetic fields of both polarities is similar to that described above for NOAA 12175.

NOAA 11431 (S28W11) was formed at a site with weak background fields of both polarities on March 04, 2012. It is difficult to detect the initial emergence of a new magnetic field; therefore Figure 3 does not show isolines of line-of-sight velocity. A significant increase

Active regions under study

Active region NOAA	Coordinates	Date/time (UT) of appearance of a magnetic field	Size, deg.	Polarity
8782	N09E15	1999.11.26/17:05	10	f
10132	N18E17	2002.09.21/14:27	8	f
10488	N08E28	2003.10.26/09:00	17	f
10559	N07W20	2004.02.13/06:23	5	f
10671	S10W20	2004.09.06/03:15	10	l
10770	N13E19	2005.05.28/11:11	5	f
10939	S04W08	2007.01.20/01:25	8	f and l
10964	N03W05	2007.07.12/09:24	8	f
11066	S26E38	2010.05.01/12:06	9	f
11080	S23W24	2010.06.09/22:24	9	f and l
11081	N22W35	2010.06.11/07:12	9	f
11103	N26W14	2010.09.01/07:00	8	f
11130	N14E18	2010.11.27/06:28	10	f
11132	N12E16	2010.12.03/17:40	10	f
11148	S28W20	2011.01.16/13:22	8	f and l
11154	N08W35	2011.02.07/23:52	10	l
11158	S20E54	2011.02.10/00:40	11	f
11174	N18W19	2011.03.16/09:00	6	f
11194	N31W17	2011.04.12/23:10	7	f
11198	N26W30	2011.04.21/09:04	9	l
11199	N20E02	2011.04.25/04:10	10	f
11214	S24E32	2011.05.13/13:40	17	f
11241	N20E30	2011.06.22/08:10	7	f and l
11242	N14E14	2011.06.27/19:40	8	f
11297	S14W30	2011.09.13/13:23	10	l
11311	S13E40	2011.10.03/12:55	8	f and l
11322	S26W45	2011.10.15/10:13	7	f
11327	S21E40	2011.10.18/21:24	10	f and l
11406	S23W30	2012.01.15/18:30	7	l
11416	S28E44	2012.02.08/02:15	10	f
11431	S28W11	2012.03.03/23:03	9	f
11531	N15W20	2012.07.24/00:30	8	f and l
11645	S13E18	2013.01.02/12:45	7	f and l
12003	N06E18	2014.03.08/21:00	9	f
12011	S07W10	2014.03.18/00:30	8	f and l
12048	S20W10	2014.04.26/08:45	10	f
12175	N14E14	2014.09.24/07:00	14	f
12273	S03E27	2015.01.15/01:00	8	f
12363	N04E03	2015.06.04/06:00	7	f
12423	S09E14	2015.09.22/01:00	8	f
12433	N20W33	2015.10.11/05:00	6	f
12493	S07W10	2016.02.02/06:00	7	f and l
12543	S06E43	2016.05.07/06:15	7	f
12632	N15E01	2017.01.31/06:30	9	f
12663	N14E11	2017.06.14/07:15	9	f
12715	N08E40	2018.06.19/05:00	10	f
12735	N03E40	2019.03.17/11:00	9	f
12736	N08W13	2019.03.19/01:00 the main arch	10	f

in the magnetic flux started after 01:00 UT, and it became immediately obvious that the flux of the following polarity prevailed. Figure 3 indicates that the rate of increase in the magnetic flux of the following polarity is higher.

The magnetic flux emergence in NOAA 12632 (N15E01) began on January 31, 2017 at 05:00 UT. First, small parts of the following polarity appeared, and then, after 06:00 UT, the massive emergence of the field began. The dynamics of the longitudinal field and negative line-of-sight velocity in the region of emergence is the same as for NOAA 12175 and 12715: after the rise of matter (arrow in Figure 4) a magnetic field of the following polarity appears, and then that of the leading polarity. The following polarity prevails for several hours. Thus, the above examples for ARs that occurred in the heliolongitude interval E43–W11 confirm the reality of the asymmetry in the time of emergence of magnetic fluxes of the leading and following polarities, namely, when a magnetic arch emerges a longitudinal field of the following polarity is detected first.

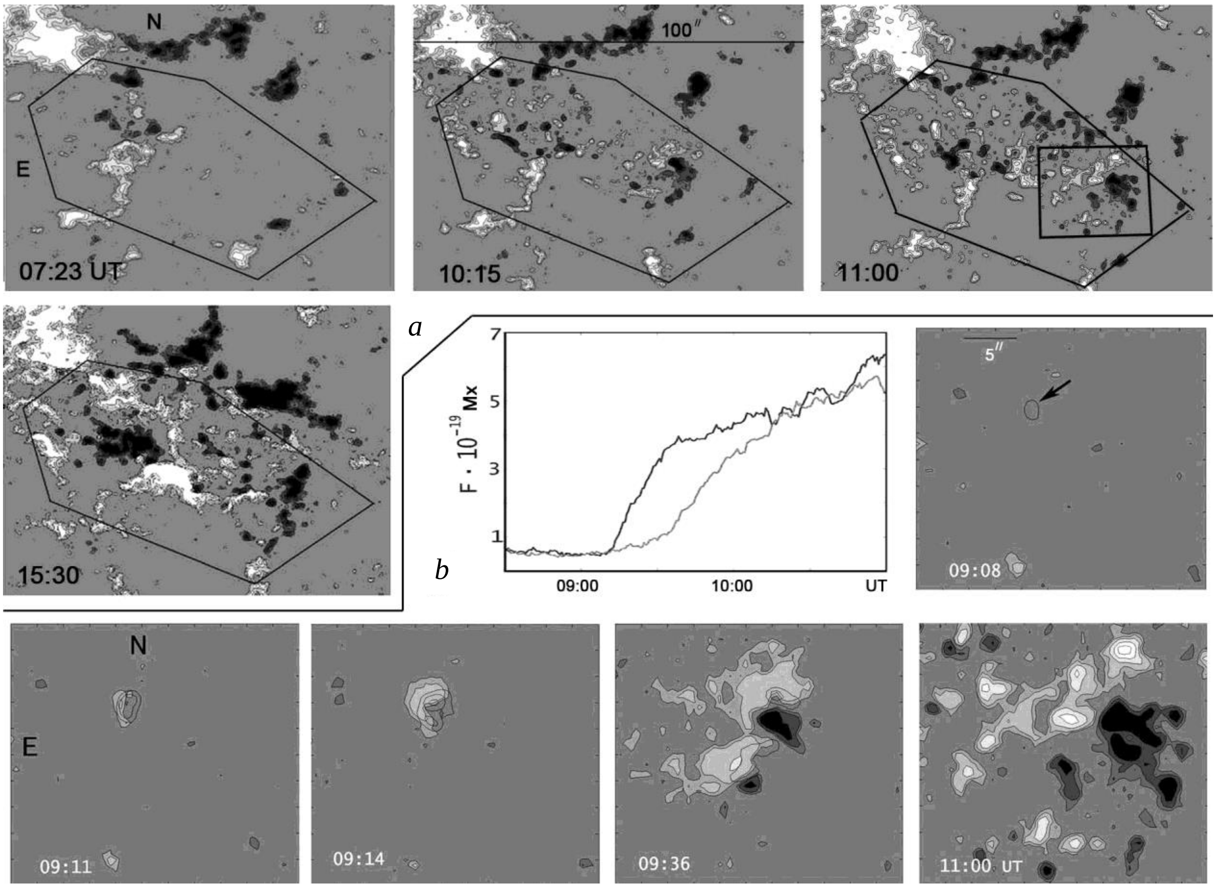

Figure 1. Magnetograms of the longitudinal field of NOAA 12175 for September 24, 2014 (*a*) and for its western part (*b*), as well as plots of magnetic field fluxes of the leading (gray line) and following (black line) polarities for the western part of NOAA 12175. The hexagon (*a*) outlines the entire region of emergence of the magnetic field; boundaries of the southwestern part are drawn out by the rectangle in the frame for 11:00 UT (right top panel). In Figure 1, *b* are isolines of negative line-of-sight velocities

DISCUSSION

The best indication of the appearance of an active region is known to be the emergence of a magnetic field in the photosphere one-two days before the formation of pores and sunspots [Barnes et al., 2014]. It is necessary to know topology and evolution of a magnetic field to verify models of emergence of magnetic flux tubes and their interaction with convective motions in sub-photospheric layers. We have shown that there is an asymmetry in the time of appearance of a magnetic field with the leading and following polarities in the photosphere, which indicate an imbalance in magnetic fluxes at the initial time of AR appearance. That time, a magnetic field is highly fragmented. The presence of a fine structure up to a spatial resolution element cause a distortion of the magnetic flux detected. Moreover, the determination of magnetic flux is limited by measurement accuracy. The observed difference between the leading and following parts of AR reflects a difference in the magnetic field structure and perhaps in plasma flows in magnetic flux tubes, and is a feature of the initial stage of appearance of a bipolar region. This imbalance in magnetic fluxes and the asymmetry in the appearance and development rate of a magnetic field in the photosphere can serve as determinants for verification of different models of emergence of a magnetic field.

Early models [D'Silve, Choudhury, 1993; Fan et al., 1993, 1994; Caligari et al., 1995; Abbett et al., 2000] adequately described the observed asymmetry in the morphology of an emerging magnetic field, although they were one-dimensional models of a thin magnetic flux tube. Later three-dimensional models [Fan, 2008; Cheung et al., 2010] were based on the incompressible medium approximation and therefore could not describe near-surface layers of the convection zone for depths shallower than 20 Mm. MHD models taking into account medium compressibility can most adequately describe the emergence of floating flux tubes and their evolution in the presence of convective motions [Cheung et al., 2010; Stein, Nordland, 2012; Rempel, Cheung, 2014]. The model [Rempel, Cheung, 2014] takes into account the flow of matter along a magnetic flux tube in a direction opposite to the solar rotation, due to conservation of angular momentum, which leads to a significant asymmetry in the leading and following polarities.

At a very early stage of AR formation, we can see an earlier concentration of the magnetic field of the following polarity. The formation of a following sunspot starts before the formation of a leading sunspot, but continues after the leading sunspot has already been formed. The leading sunspot is more coherent and axisymmetric.

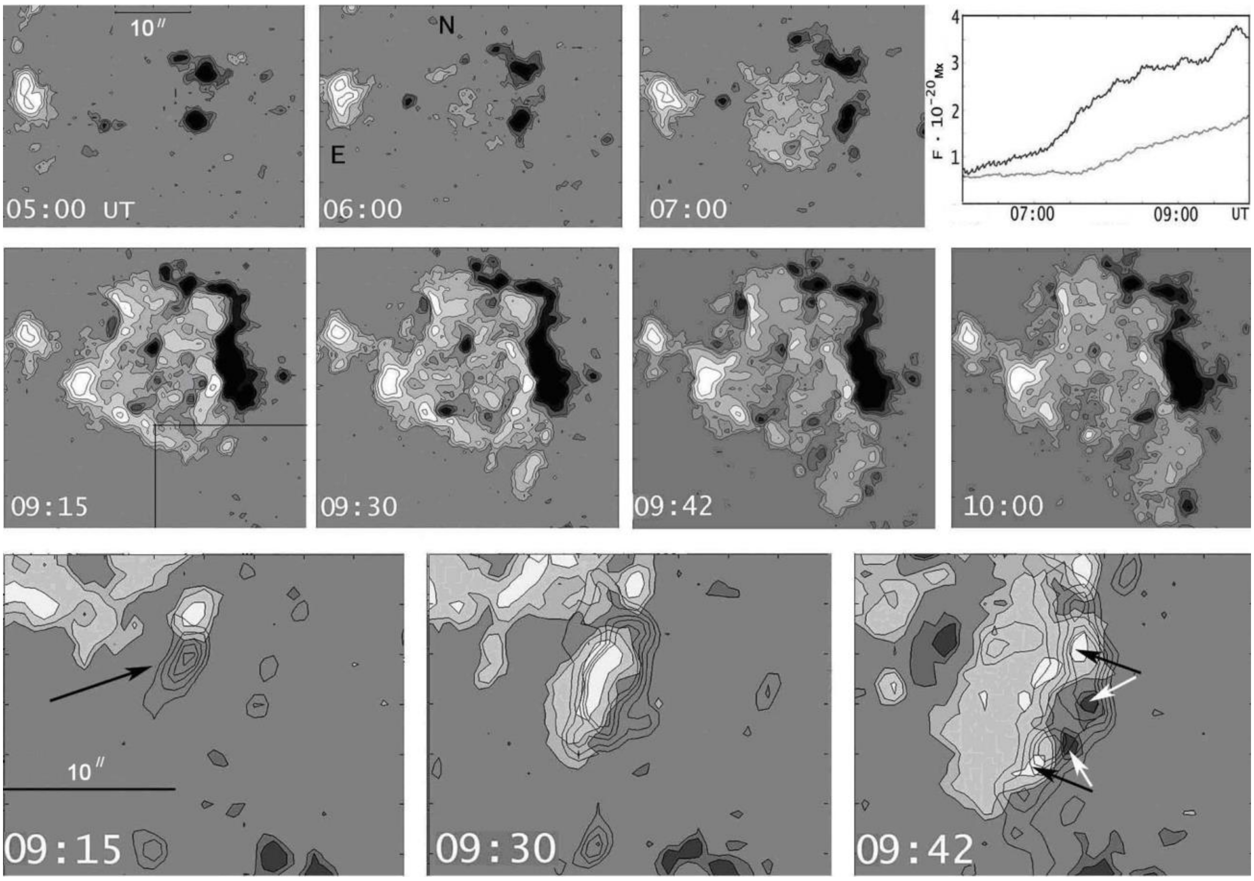

Figure 2. Dynamics of the longitudinal magnetic field of NOAA 12715 on June 19, 2018: two top rows present magnetograms of the entire active region and plot magnetic fluxes of the leading (gray line) and following (black line) polarities; the bottom row gives fragments of the southwestern part of the magnetograms (marked with a rectangle in the frame for 09:15 UT in the second row) with isolines of negative line-of-sight velocity

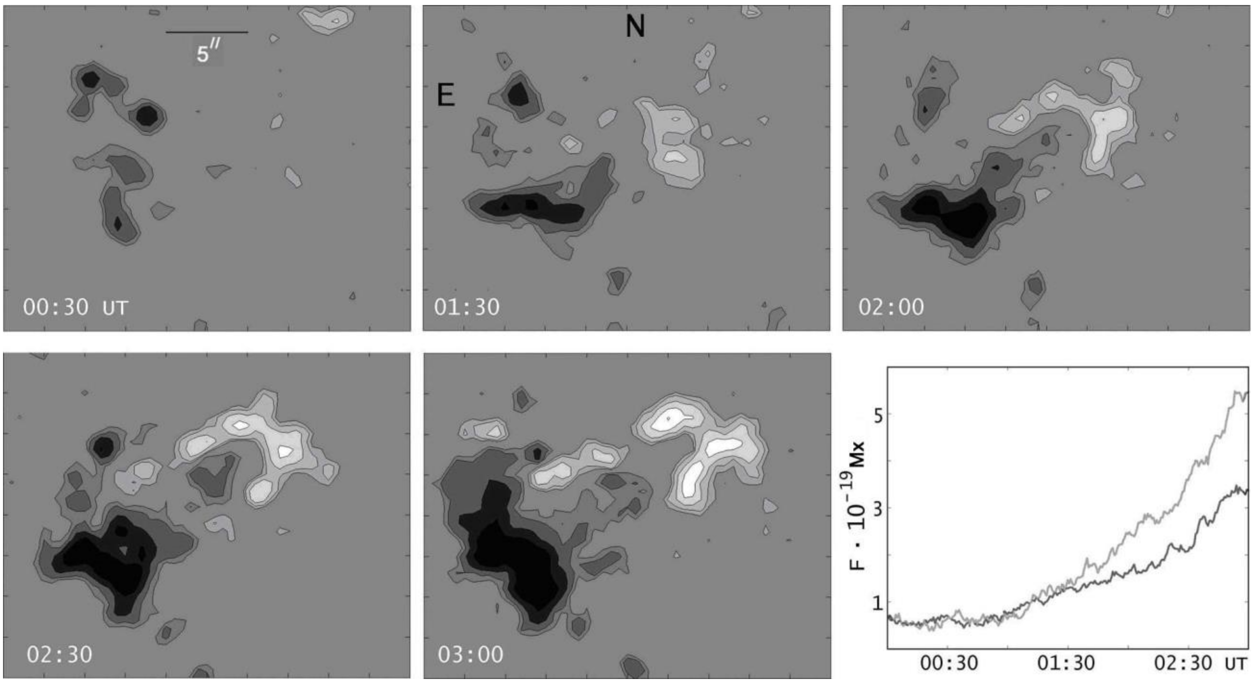

Figure 3. Magnetograms of the longitudinal field and plots of magnetic fluxes of the leading (black curve) and following (gray line) polarities for NOAA 11431 on March 04, 2012

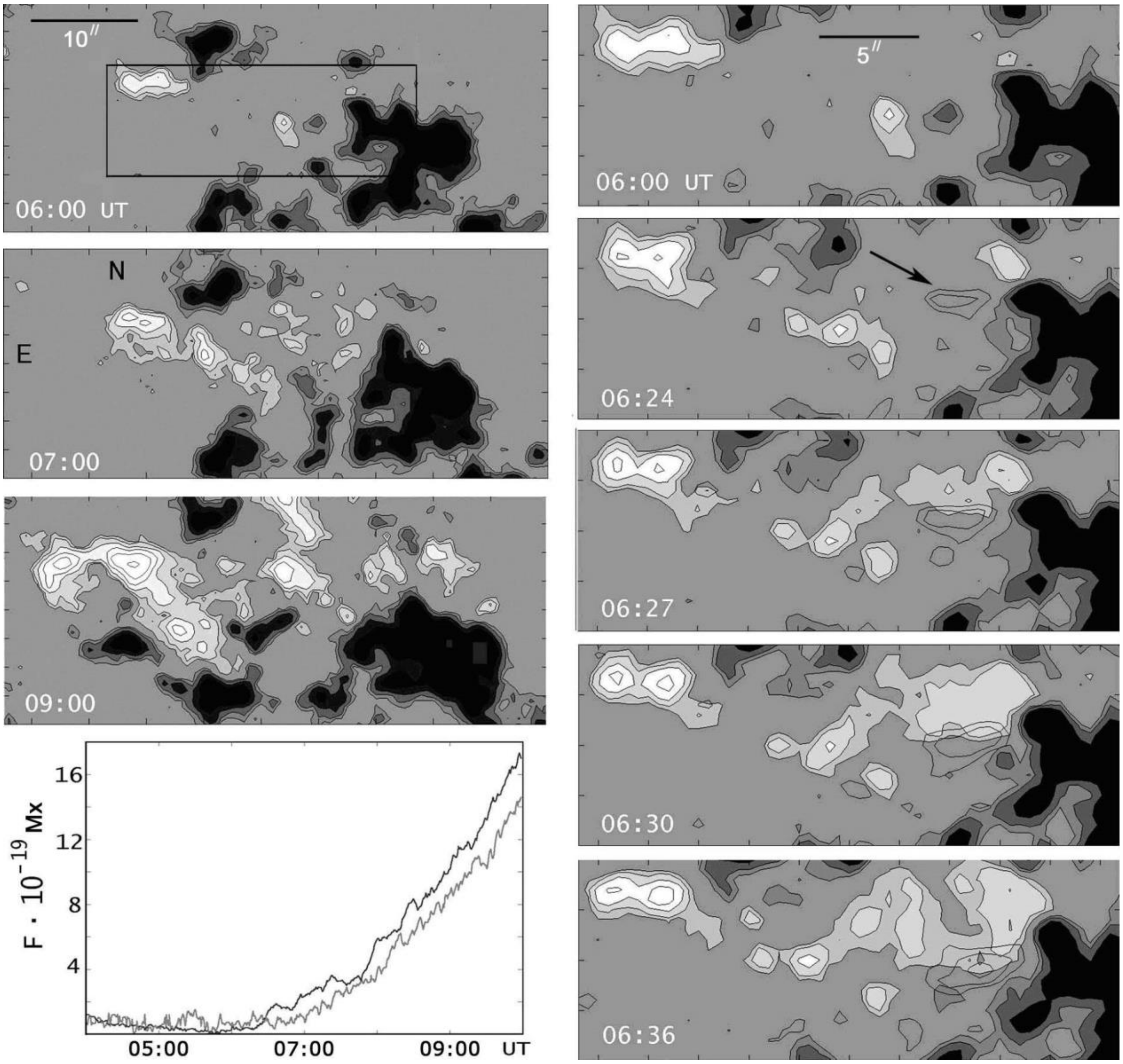

Figure 4. Dynamics of the longitudinal magnetic field in NOAA 12632 on March 04, 2012: left column — magnetograms of the entire active region and plots of magnetic fluxes of the leading (gray line) and following (black line) polarities; right column — fragments of the central part with isolines of negative line-of-sight velocity

The results of the analysis of 48 cases of AR appearance reported in this study and the presented examples of dynamics of magnetic fluxes with the leading and following polarities argue for the asymmetry in the time of emergence of a magnetic field. When a magnetic field emerges, a magnetic field of the following polarity is detected first. Our results are consistent with the model [Rempel, Cheung, 2014].

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