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EFFECTS OF A TWISTED MAGNETIC ROPE AT THE STAGE OF THE APPEARANCE OF A NEW ACTIVE REGION IN THE PHOTOSPHERE

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Abstract. Using SDO/HMI data, we have studied the dynamics of small-scale magnetic field elements in the photosphere during the formation of small active region USAF/NOAA 12761. The choice of this region is due to the fact that it formed near the central meridian at the minimum of the 11-year solar activity cycle in the absence of strong background magnetic fields. It has been established that two days before the formation of the first pores, the initially observed small-scale structure of the magnetic field forms chains of elements of both polarities. The structure of the chains creates a stable polarity inversion line (PIL). During the first day, the orientation of PIL changes from quasi-latitudinal to quasi-meridional. After comparing observations with a number of theoretical models, we concluded that the observed dynamics of elements of magnetic chains is consistent with the models of emergence of a magnetic flux rope in the photosphere.

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

INTRODUCTION

Active regions (ARs) are the most noticeable manifestations of large-scale magnetic activity in the solar photosphere. Understanding the appearance of magnetic fields provides insight into the relationship between dynamo in the convective zone and magnetic activity in the photosphere and higher layers of the solar atmosphere. Parker's assumption [Parker, 1955] that the formation of sunspots is due to the emergence of a magnetic flux tube from a convective zone is consistent with the results of numerous theoretical and observational studies.

Here are some of the observational studies. The Sayan Observatory has for the first time traced from day to day the pattern of changes in the magnetic field vector in the photosphere upon the appearance of AR [Bappu et al., 1968]. The first changes in the background magnetic field occurred three days before the appearance of a sunspot group. A day before the appearance of the first sunspot, there appeared an extensive region of transverse magnetic field crossing the polarity inversion line (PIL) and spatially coinciding with the regions of appearance of the main sunspots of the group. The transverse field was the strongest near PIL. These results have been considered by many researchers as an experimental confirmation of the hypothesis that a magnetic flux tube emerges from under the photosphere and that the photospheric magnetic field dynamics associated with this process begins before the formation of a sunspot group. The low spatial resolution in this pioneer work (18"×1.8") does not affect the mentioned results, which were later confirmed with 2"×4" resolution [Grigoryev et al., 1986]. Observations with a 1"-resolved Stokes polarimeter [Lites et al., 1998] have shown that the region of magnetic flux emergence is filled with horizontal magnetic elements rising at a velocity of ~1 km/s.

Noteworthy among recent papers based on observational data are [Mac Taggert et al., 2021; Levens et al., 2023; Magara, 2019; Weber et al., 2023; Poisson et al., 2024].

In addition to numerous models that deal with the emergence of a Ω-loop magnetic flux in the tachocline region, there are alternative models that consider the formation of an AR magnetic flux in the convective zone itself as a result of magnetic convection. Magnetic convection is examined in detail in [Jabbari et al., 2016; Getling et al., 2016; Getling, Buchnev, 2019; Brandenburg, 2005]. Theoretical models are more often discussed, and only a small number of papers analyze observations at the earliest stage of appearance of ARs. Only in [Getling, Buchnev, 2019] the appearance of AR from the moment of appearance of the first pores in the photosphere is studied with high temporal resolution.

Formation of ARs begins with the complex dynamics of appearance of small-scale magnetic fluxes. Regions with a dominant concentration of magnetic flux elements are gradually formed. Later on, sunspots appear. In the chromosphere at an early stage of AR formation, arch filament systems develop — small bright plages intersected by dark fibrils whose ends are located in magnetic field regions of opposite polarities. These are assumed to be the tops of ascending magnetic arches. Frazier [1972] attributed the observed change in the angle of inclination of the arch filament system in the plane of the photosphere to the sequential emergence of magnetic loops.

Some models predict that the emerging magnetic flux tube should be twisted in order to pass through the convective zone [Emonet, Moreno-Insertis, 1998;

Cheung et al., 2006; Martinez-Sykora et al., 2015]. Under the influence of convective motions, the emerging flux tube gets disheveled [Hood et al., 2012]. We should, therefore, first expect the appearance of individual “strands”.

In a number of works [Archontis et al., 2009; Luoni et al., 2011; Poisson et al., 2015], signatures of twisted magnetic flux tube emergence were found: the sigmoid structure of magnetic field lines and the presence of tongues on magnetograms. Nonetheless, these features can also appear when a preliminarily untwisted flux tube emerges [Prior, Mac Taggart, 2016; Syntelis et al., 2013] when acted upon by motions; therefore, the issue about twisting of an emerging flux tube remains controversial and is widely discussed (e.g. [Mahlmann et al., 2023; Sadeghi et al., 2023]).

In this paper, we analyze the dynamics of small-scale magnetic field elements in the photosphere during the formation of a small bipolar AR under conditions of low solar activity 2 days before the appearance of pores. The goal is to try to find signs in the morphology of the magnetic flux appearing in the photosphere, which may indicate the twisting of the rising magnetic tube.

OBJECT INVESTIGATED AND RESULTS

We analyze the appearance of a local magnetic field in the photosphere at an early stage of formation of AR USAF/NOAA 12761, using SDO/HMI data. We use data on longitudinal magnetic field and continuum images with an interval of 3 min. The choice of this small AR is due to the fact that it was formed near the central meridian at solar minimum of cycles 24–25. There were no old magnetic fields during this time, and the proximity to the central meridian allows us to consider the measured longitudinal magnetic field as vertical. From 01:00 UT on April 27, 2020, a rapid emergence of the bipolar magnetic field began; at 01:40–02:00, the first pores appeared. At that time, the AR was located on the central meridian. The dynamics of the magnetic field began to be studied on April 25, two days before the formation of the sunspot group. On that day, a bipolar magnetic field region formed in an area of the solar surface with coordinates S17E27. When constructing magnetograms, we found areas with the same coordinates. Figure 1 presents the magnetograms. Dimensions of the area are 70 (vertical) × 80 px, 1 px ~ 0.5 arcsec. The first seven magnetograms are hourly — this is enough to trace the dynamics. The next five ones have been selected to show the characteristic features. At the initial moment, there are scattered magnetic features of several arcsec with strength under 100 G. The observed dynamics of the magnetic field does not reveal a connection between opposite polarities except that by 02:00 UT due to the seemingly random appearance, disappearance, and motion of magnetic elements, stable PIL 20–25 arcsec long was formed which was oriented to the equator at an angle less than 40° (Figure 1, frames 02:00, 03:00, 04:00 UT). The magnetic features on both sides of PIL form a chain structure, they are still scattered, but the same form of PIL from frame to frame indicates a connection between the magnetic elements on both sides. Later on, when the above small-scale dynamics of the magnetic field elements remained generally unchanged, by 06:00 UT PIL rotated counterclockwise by 65°. This occurred in less than two hours.

The size of the flux emergence region gradually increased, the strength grew. This was especially evident after 19:00 UT. By 21:00 (see Figure 1), a compact bipolar region had formed. Small magnetic features can be seen in the central part, some disappear, others merge with larger ones. The dynamics of the small magnetic elements indicates emergence of magnetic loops. PIL continued to rotate counterclockwise, now its slope is similar to that typical of young ARs. The same slope is maintained the next day (frame 26/09:18). There were no pores either that day or the next. From 01:00 UT on April 27, a rapid emergence of the bipolar magnetic field began; at 01–02:00 UT, the first pores appeared. Figure 2 shows the diurnal dynamics of PIL directions on April 25 for three frames. We can see that at the same place on the solar surface there was a successive rotation of PIL.

The following conclusions can be drawn. The magnetic field of new AR appeared in the photosphere two days before the appearance of the first pores. At first, when the emerging flux was very small, it seemed that the magnetic field elements were scattered, but after a short time stable PIL was formed. The continued emergence of the magnetic flux caused it to rotate, during the first day (02:00–21:00) the rotation was ~90° counterclockwise (see Figure 2). Most magnetic flux is concentrated in large features. Such dynamics of the longitudinal magnetic field may reflect the emergence of magnetic loops from under the photosphere. Their equatorward orientation successively changed. At first, it was quasi-latitudinal, by the end of the first day it became quasi-longitudinal, which is typical of ARs.

DISCUSSION

Results of the analysis of observational data on the appearance of magnetic flux of small AR demonstrate the evolution of small-scale features reflecting the cross-section of individual magnetic flux tubes crossing the photosphere. The concentration of magnetic elements of the same polarity and the formation of generally latitudinally oriented PIL resemble a rising Ω loop formed by magnetic flux tubes twisted into a rope. Near the boundary of the photosphere, this loop forms a system of disheveled flux tubes comprising the outer boundary of the rope due to a sharp decrease in gas pressure [Hood et al., 2012].

The kinematic model of the rising magnetic flux torus formed by a magnetic flux rope is discussed in [Magara, 2012], where Figure 1 presents the moment when a flux tube crosses the surface of the photosphere. The structure of the vertical field in the photosphere forms two regions of opposite polarities, oriented at this time so that PIL is located in the plane of the torus rise. This pattern corresponds to the observed field structure at the appearance of AR 12761. Due to a sharp change in gas pressure, the rope at its apex will be strongly deformed

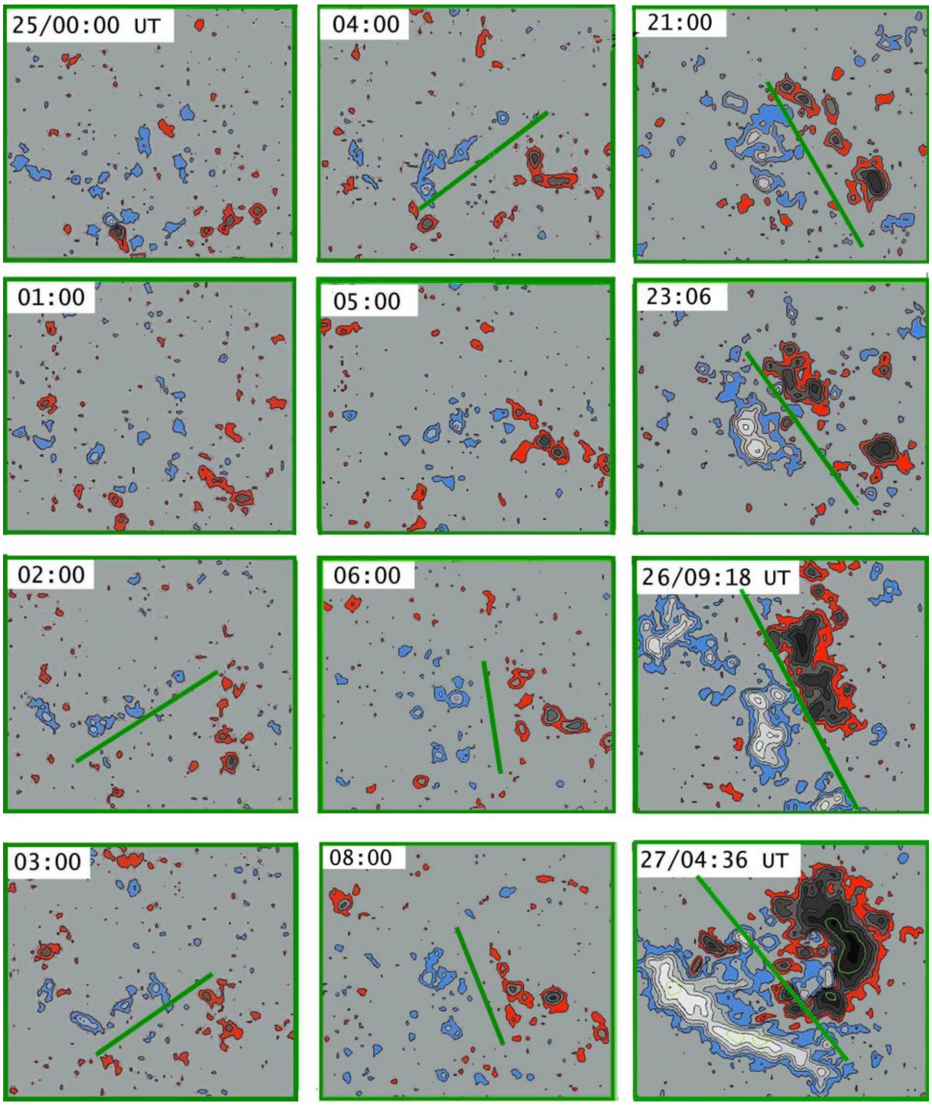

Figure 1. Magnetograms of the longitudinal magnetic field. Isolines ±20, 50, 100, 200, 500 G. The red-black color marks regions of negative polarity; blue-white, of positive one. The thin green contour represents regions with 85 % continuum contrast relative to the undisturbed photosphere (regions where pores are formed). Straight green lines indicate PIL

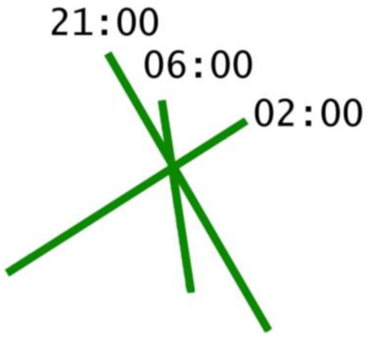

Figure 2. Dynamics of PIL directions on April 25

and, as some models indicate, magnetic field loops will acquire a flattened shape (e.g. [Hood et al., 2012]). The most realistic models of AR formation can be found in [Cheung et al., 2010; Mac Taggart, Hood, 2009; Mac Taggart et al., 2021]. The work [Mac Taggart and Hood, 2009] is one of the first to demonstrate that the magnetic sunspot structure is a twisted tube already before its emergence.

The most complete radiative MHD simulation of the appearance and formation of AR on the solar surface has been performed in [Cheung et al., 2010]. It is shown that small-scale magnetic field elements appear first on the surface, then large magnetic concentrations are gradually formed. Later, a pair of regions of opposite polarities appears. The magnetic flux emergence lasts for several hours. In the simulated magnetograms (see Figure 1 from [Cheung et al., 2010]) for the first four hours, the vertical magnetic field component exhibits a small-scale structure so that when averaged PIL is directed along the future axis of a bipolar large-scale region. Later on, concentration occurs, the synthesized magnetogram at 6.7 hr already reveals a bipolar large-scale structure, with PIL rotated by 90° relative to the magnetogram at 4.4 hr. This evolution of the magnetic field structure in the simulation agrees with the results of our analysis of observations of the appearance of AR 12761.

Thus, the initial appearance of chains of small-scale magnetic elements of both polarities and the evolution of PIL serve as additional signature of the emergence of a magnetic flux rope.

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