ISSN 1063-7737, Astronomy Letters, 2007, Vol. 33, No. 11, pp. 766–770. © Pleiades Publishing, Inc., 2007.
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Dynamics of Line-of-Sight Velocities and Magnetic Field in the Solar Photosphere During the Formation of the Large Active Region NOAA 10488

V. M. Grigor'ev*, L. V. Ermakova, and A. I. Khlystova

Institute for Solar–Terrestrial Physics, Russian Academy of Sciences, Siberian Branch, P.O. Box 291, Irkutsk, 664033 Russia

Received February 12, 2007

Abstract—Analysis of SOHO longitudinal magnetograms and Dopplergrams has revealed the appearance of a region of enhanced upflow of matter in the photosphere when the top of a loop-shaped magnetic flux tube forming a large active region passed through it. The maximum upflow velocity reached 2 km s^{-1}, the maximum size exceeded 20 000 km, and the lifetime was about 2 h.

PACS numbers : 96.60.-j; 96.60.Hv; 96.60.Q-

DOI: 10.1134/S1063773707110072

Key words: *Sun, active regions, magnetic field.*

INTRODUCTION

Active regions result from the emergence of a magnetic field at the surface. A magnetic flux tube formed beneath the convective zone (or deep in the convective zone) emerges due to magnetic buoyancy (Parker 1955). This hypothesis has been actively developed by a number of authors and has been predominant over half a century. When a magnetic flux tube emerges in the photosphere, two effects should be observed at an early formation stage of an active region: (i) the appearance of a magnetic field whose vector was initially parallel to the surface and subsequently inclined to the polarity reversal line and (ii) the rise of a horizontal magnetic field and matter.

There are observations that are regarded as a direct confirmation of this hypothesis. Daily records of the magnetic field vector in the active latitude zone of one hemisphere obtained in May 1966 at the Sayan Observatory (Bappu et al. 1968) allowed the formation of a medium-sized active region to be studied. On the first day of the existence of a sunspot group, the magnetic field was strongly pressed to the surface; on the subsequent days, the angle between the field direction and the normal to the surface decreased, with the oppositely directed magnetic field vectors being inclined to one another. The described observations had low temporal and spatial resolutions.

Higher-quality observations were made thirty years later. Using a Stokes polarimeter, Lites et al. (1998) recorded not only the emergence of a magnetic field, but also the line-of-sight velocities of a magnetized plasma. The spatial resolution was ~1 arcsec. These authors showed that the zone where the magnetic field emerged was pocked with small transient horizontal magnetic elements aligned along the sunspot group axis and rising with a velocity of 1 km s^{-1}. These data suggested that the horizontal magnetic fields are the tops of rising magnetic loops. In this work, the measurements were begun already after all three observed active regions had been detected in white light as pores.

Modern ground-based instruments have high temporal and spatial resolutions, but such complex characteristics as the magnetic field vector can be obtained under these conditions only for local areas of the solar surface. There are no reliable predictors for the formation of an active region that would allow one to begin observations before it appears in white light or in the Hα line. Weather conditions and nighttime also introduce their restrictions. Using SOHO/MDI (Michelson Doppler Imager) data on the longitudinal magnetic field and line-of-sight velocities extends significantly the possibilities for studying of the magnetic field dynamics. Continuity of the observation of the full solar disk and a high temporal resolution allow information to be obtained from the first minute of the life of an active region.

In this paper, we investigated the dynamics of the magnetic field and the line-of-sight velocity field in the photosphere at an early stage of development of

*E-mail: vgrig@iszf.irk.ru

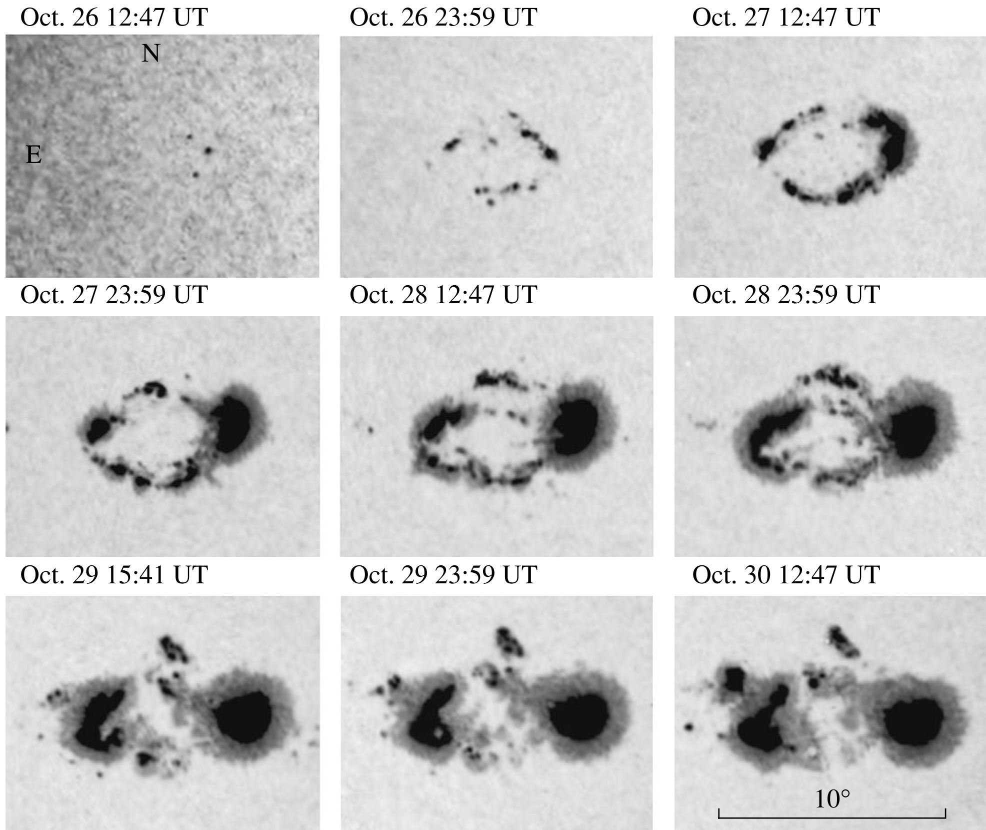

Fig. 1. Formation of a sunspot group in the active region NOAA 10488 from SOHO MDI continuum images.

a large bipolar active region based on SOHO MDI data.

OBSERVATIONAL DATA AND THE OBJECT OF INVESTIGATION

We studied the active region NOAA 10488 formed on October 26, 2003, at the location with coordinates N08 and E28. We used longitudinal magnetograms, Dopplergrams, and SOHO MDI continuum images in fits format. The magnetic field and line-of-sight velocity data have a temporal resolution of 1 min; the continuum images have a resolution of 96 min. The spatial resolution is 4 arcsec. The Dopplergrams were preprocessed. To eliminate the five-minute oscillations, we applied a moving average over five Dopplergrams and then cut out the analyzed area taking into account the shift due to solar rotation. To determine the zero point of line-of-sight velocities and to eliminate the solar rotation rate, we constructed an additional array that was subtracted from the original one. For this purpose, we averaged three upper and three lower rows of the area being cut out and linearly smoothed the averaged rows. As a result, we obtained the upper and lower rows of the additional array. To obtain the internal field of the array, we performed a linear interpolation between the upper and lower pixels of the columns belonging to the smoothed rows. For the magnetograms, we also applied a moving average over five frames.

Figure 1 shows white-light images for the first 4 days of the existence of the sunspot group, from October 26 through October 30, when the main sunspots were formed. The longitudinal magnetic field of the active region appeared in the photosphere on October 26 at 09:07 UT; the first pores were formed before 11:12 UT. The rise in magnetic flux with an approximately constant rate continued until October 29 and then slowed down. By October 30, the total group sunspot area reached 1800 m.p.h. According to the data by Newton (1958), the fraction of sunspot groups of such a size is less than 0.4%. In this paper we restricted our analysis to the interval 06:06–13:00 UT on October 26, which began 3 h before the appearance of a new magnetic field in the photosphere.

RESULTS

The picture of the emergence and distribution of a new magnetic field appeared as follows. By the end of the first hour, the magnetic field formed many small

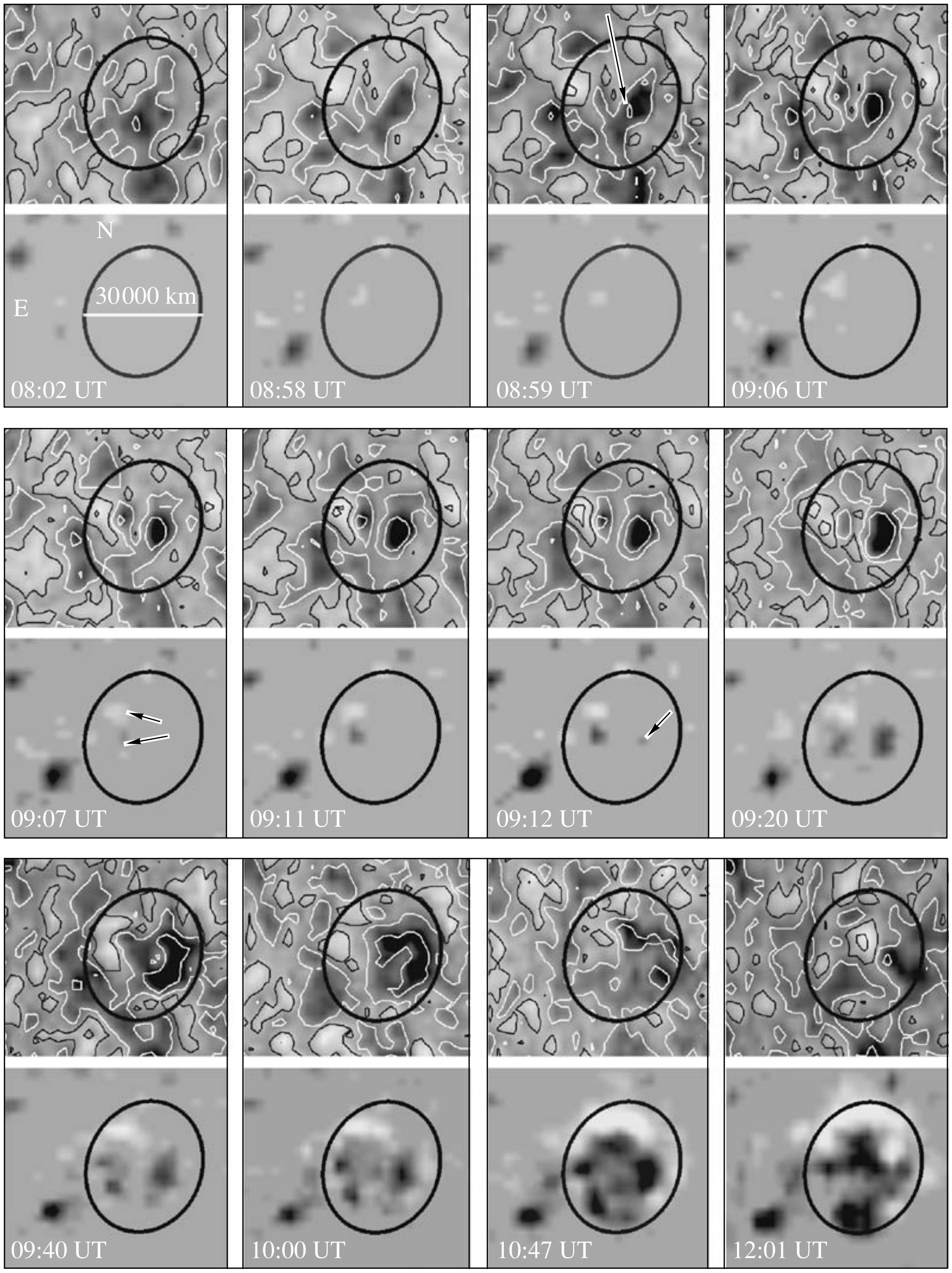

Fig. 2. Maps of the line-of-sight velocity field with ±100 and ±400 m s^{-1} isolines and longitudinal magnetograms showing the dynamics of material and magnetic field during the formation of an active region.

hills of both polarities adjacent to one another. There was no alignment of the magnetic dipoles along any axis. The region of magnetic field emergence was round in shape and occupied an area comparable to the supergranule one; during 2–2.5 h, a statistically significant magnetic field emergence took place only in this area. Subsequently, an additional zone of emergence was formed to the east, but it was weaker.

This is illustrated by Fig. 2, which shows pair frames consisting of a map of the line-of-sight velocity field (top) with isolines and a map of the longitudinal magnetic field (bottom). The region of emergence of a new magnetic flux is delineated by the oval. On the line-of-sight velocity maps, the areas of motion toward (negative velocities) and away from the observer are shown in black and white, respectively; the isolines

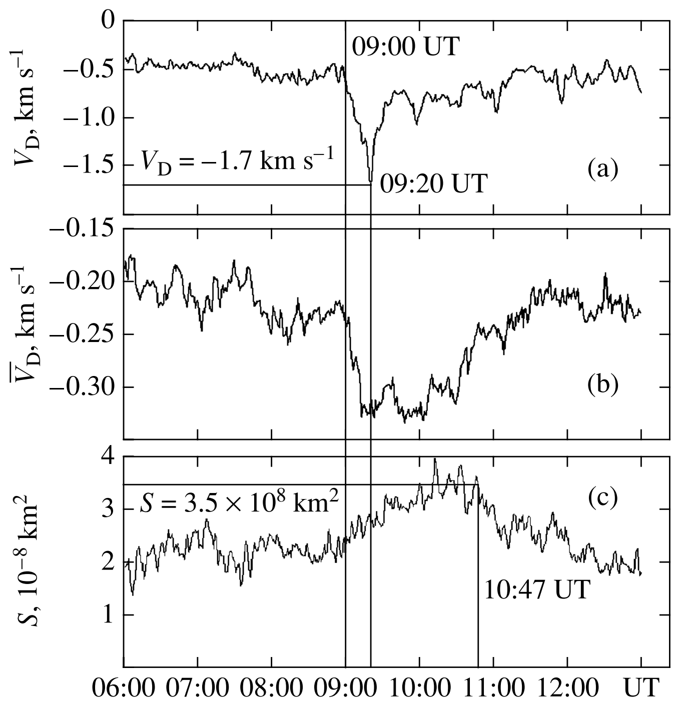

Fig. 3. Time variations of maximum Doppler velocity V_D (a), mean velocity $\overline{V}_D$ within the contour outlined by the -100 m s^{-1} isoline (b), and area S bounded by the -100 m s^{-1} isoline (c) in the region of magnetic flux emergence.

are indicated in opposite color. The long arrow in the upper frame (08:59 UT) marks the appearance of the -400 m s^{-1} isoline. We identify this fact with the upflow of matter associated with the emergence of a magnetic flux tube. The short arrows on the corresponding frames (09:07 and 09:12 UT) mark the appearance of magnetic hills of the new active region 8 and 13 min later.

Figure 3 shows the plots that characterize the dynamics of the upflowing matter in the region of emergence of a new magnetic flux. We see from Figs. 3a and 3b that an upflow of matter with a high velocity began in the photosphere near 09:00 UT. The velocity increased for 20 min; subsequently, it began to decrease and became equal to the background one in 2.5–3 h. If we eliminate the contribution from horizontal motions to the line-of-sight velocity, then, given the heliocentric position of the area, the maximum upflow velocity was 2 km s^{-1}. The mean line-of-sight velocity toward the observer was ∼230–330 m s^{-1} for two hours; given the heliocentric angle, this corresponds an upflow velocity of ∼260–370 m s^{-1}.

The fact that the upflow of matter is ahead compared to the emergence time of the longitudinal magnetic field of the active region in the photosphere (see Fig. 2) is real. The emergence time of the bipolar magnetic field is visually determined from averaged magnetograms with a 1-min accuracy. According to the results by Lites et al. (1998), the onset of the upflow of matter can be associated with the emergence of a horizontal magnetic field located at the top of a rising magnetic loop.

The upflow region expanded as a new magnetic flux emerged for two hours; it was surrounded by a downflow zone. According to Fig. 3c, the maximum area bounded by the -100 m s^{-1} isoline was constant approximately for half an hour (10:10–10:45 UT) and was $\sim 3.5 \times 10^8$ km^2, which yields the diameter of the circular upflow region, ∼21 000 km. Some of the field hills partially went outside the upflow region, but the polarity reversal line in most cases remained inside. This suggests that the horizontal magnetic field located at the polarity reversal line was rising. Such an ordered picture broke down 2 h later. The upflow region was fragmented and a downflow of matter began in the “holes”. The pattern of motions is now probably related to smaller-scale magnetic structures. Approximately three hours after the bipolar magnetic flux began to emerge, a new field appeared to the east of the location of initial emergence (frame 12:01 UT in Fig. 2). This time, there were no such clear manifestations as those in the first case in the velocity field.

Tverskoi (1966) suggested the hypothesis that active regions are formed through the amplification of a weak magnetic field by motions in convective supergranule cells. In recent years, this hypothesis has been developed by Getling (2001). The result by Bumba (1967) that the sunspot areas are multiples of the supergranule area is suggested as observational evidence for this hypothesis. The similarity between the sizes of the region of magnetic flux emergence and convective supergranule cells noted above cannot be a serious argument that the formation of the magnetic flux of a new active region is related to the amplification of a magnetic field by convective flows, because the detected upflow velocities exceed severalfold those in supergranules. This is most likely indicative of an interaction between the emerging magnetic loop and the surrounding convection, which limits the size of the region of magnetic field emergence.

Zwaan (1985) argued that a rising loop should produce and maintain a convective bubble moving together with the loop top. We believe that we found precisely this phenomenon. Obviously, the high upflow velocity is due to the power and compactness of the flux tube.

CONCLUSIONS

We detected the appearance of a region of enhanced upflow of matter in the photosphere when the top of a magnetic flux loop forming a large active region passed through it. The size of the upflow region exceeds 20 000 km, the maximum upflow velocity is 2 km s^{-1}, and the lifetime is $\sim$2 h.

This result can be used in constructing models for the formation of active regions.

ACKNOWLEDGMENTS

We are grateful to the SOHO/MDI team for access to the databases on the Internet. We also thank the anonymous referee whose remarks and advice contributed to a further development of this work. This work was supported by the Program for Support of Leading Scientific Schools of Russia (NSh-4741.2006.2) and the "Solar Activity and Physical Processes in the Sun–Earth System" Program of the Presidium of the Russian Academy of Sciences.

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Translated by G. Rudnitskii