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Plasma Flows in Emerging Sunspots in Pictures

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Abstract. We present pictorial results of our study of plasma flows in fifteen emerging active regions using Dopplergrams, magnetograms, and white light observations from SOHO-MDI. The study focuses on: (1) asymmetric flows between two opposite polarities of the same active region, (2) search for systematic flows in area of active region development prior to flux emergence, and (3) timing between development of the Evershed flow and sunspot penumbra. Asymmetric flows are found in three active regions. In two regions, flows are directed from following to preceding polarity, and in one region material flows from the preceding to the following polarity. We observed no consistent plasma flows at the future location of an active region before its emergence. We describe one case when sunspot penumbra developed before establishing the Evershed flow.

1. Introduction

It is widely accepted now that a solar active region represents an upper portion of a magnetic flux tube distorted in the shape of the Greek letter Ω. In a framework of this description, the leading and following sunspots are the intersections of the Ω loop with the photosphere. The loop may originate in the dynamo region situated in lower portion of the solar convection zone (Fisher et al. 2000). Although the exact process of formation of magnetic flux tubes is not well-understood, the flux tube approach was successfully applied to explain several important properties of active regions, *e.g.* their tilt with respect to solar equator (Joy's Law), systematic difference in inclination of magnetic field in leading and following polarities with respect to the local solar surface, compactness of the leading polarity sunspot and more loose structure of the following polarity (*e.g.* Fan et al. 1993; Fisher et al. 1995; Caligari et al. 1995). For emerging active regions, flux tube models predict specific flows directed from the leading polarity sunspot to the following polarity. The origin of this flow was attributed to the angular momentum conservation as the tube rises from the bottom of the convection zone (*e.g.*, Fan et al. 1993). Cauzzi et al. (1996) searched for such asymmetric flows using observations of three emerging regions. All three regions showed downflows whose amplitude were not balanced between leading and following polarities. This was interpreted as the presence of a systematic flow directed from the following to leading sunspot – opposite to the theoretical predictions. Sigwarth et al. (1998) reported their observations of systematic flows in one emerging region. Weak up-flow of about 0.5 km/s was observed in the leading sunspot with a corresponding downflow of material in the following sunspot. The flow pattern was considered as an indication of counter-rotation flows, directed from leading to following polarity sunspot in agreement with the theoretical predictions. Given the disagreement between these two previous studies:

(1) The first goal of our present study is to search for systematic flows between two polarities of emerging active region. As an alternative to a commonly accepted model of an Ω loop rising from the bottom of the convection zone, several authors suggested that sunspots might be formed locally at/near the photosphere (*e.g.* Gurevich & Lebedinsky 1946; Akasofu 1984; Henoux & Somov 1987, 1991). Although these individual models of local sunspot dynamo employ different assumptions, all of them require the presence of systematic downflows at the site of future sunspot development. In general, the downflows are a common feature of developing active regions (*e.g.* Zwaan 1985). However, there are no observations suggesting that such flows develop prior to active region emergence. In 1981, one of the authors (AAP in collaboration with Dr. S. Druzhinin) observed strong downflows in an area where, about a day later, a new sunspot appeared.

(2) This single observation inspired us to search for the presence of systematic flows in areas of emerging regions prior to their formation. Sunspot development usually starts with a formation of a small pore. A transition between pore and sunspot occurs with the formation of penumbra. Numerous observations indicate that formation of penumbra coincides with the development of systematic circulation in sunspot photosphere or Evershed flows.

(3) We seek to determine if sunspot penumbral and the Evershed flow are truly inseparable, or one may be present without the other for some period of time.

The study described in this article addresses the above three issues.

2. Data Analysis

Data for this research came from the Michelson Doppler Imager (MDI, Scherrer et al. 1995) instrument aboard the Solar and Heliospheric Observatory (SOHO). Full disk magnetograms (90 minutes time cadence, $\sim 2''$ per pixel), Dopplerograms, and continuum (white-light) images were employed. Using images published in the Solar-Geophysical Data, we identified several candidate regions that developed at the Sun's visible hemisphere. Preference was given to regions that emerged within about 30° East of central meridian. After initial selection was done, we searched SOHO-MDI data for all available observations. Finally, fifteen regions were selected for the study.

We selected a box around each active region after the onset of emergence, and determined the center of the region as the center of gravity of unsigned magnetic flux within the box (Figure 1). These coordinates were used to determine rotation rate of each region by fitting the first-degree polynomial to the dependence of the heliospheric position of the region vs. time. Sub-images of magnetograms, Dopplergrams, and white light images corresponding to all observations (including those prior to flux emergence) were selected by extrapolating the position of each active region using its specific rotation rate.

For every pixel of a Dopplergram sub-image, we subtracted the contribution of the line-of-sight (LOS) component of rotational velocity of the Sun. All Doppler

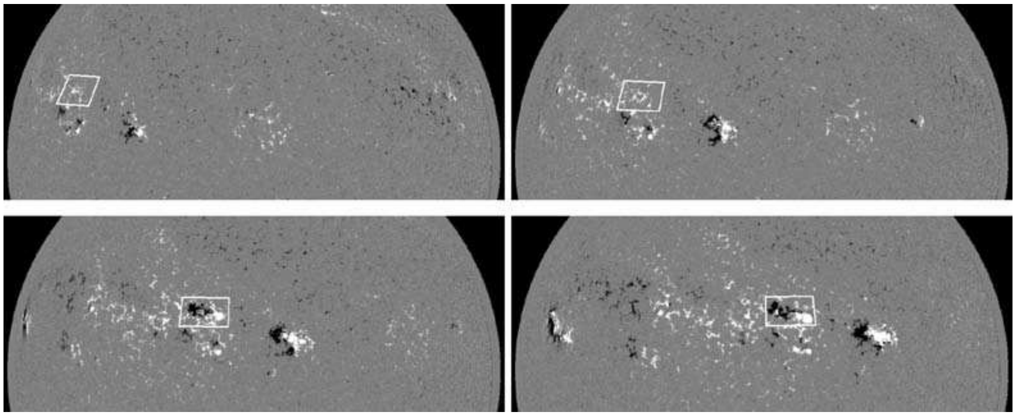

Figure 1. Example of emerging region selected for study. Upper panels shows longitudinal magnetograms prior to flux emergence, and lower panels correspond to post-emergence state. The magnetograms are taken at 36 hours time intervals. White and black halftones correspond to positive and negative polarity magnetic field, accordingly. The region of interest is marked by a white box.

sub-images were calibrated to correct for remaining inconsistencies between images. The sequences of (LOS magnetic field, LOS velocity, and white light) sub-images for each active region were analyzed to study systematic flows of our interest.

In addition, we used profiles of velocity, intensity, and magnetic field. Profiles were drawn through the center of the sunspot (center of gravity of white light image of sunspot) in the direction from solar disk center toward the limb. Normalized white-light images were used to define the photosphere-penumbra boundary for these profiles.

3. Asymmetric Flows During Early Emergence

Out of 15 emerging regions, only three showed distinct asymmetric flows. These flows in two regions lasted for about one – three hours, and in one region the flows were present for about 24 hours. NOAA AR 8699 showed significant asymmetric flows in the direction from leading to following polarity (Figure 2). The direction of flow is in agreement with the numerical simulations by Fan et al. (1993) as expected from the angular momentum conservation. This flow is similar to flows observed by Sigwarth et al. (1998). However, in NOAA AR 8617, the material flowed in the opposite direction, from the following to leading sunspot (Figure 3). Asymmetric flows of such magnitude (0.5 – 1 km/s) and direction were not previously observed. Cauzzi et al. (1996) found similarly (directioned) flows in three emerging active regions, although the amplitude of flows was significantly smaller. Finally, NOAA AR 9244 provides example of asymmetric flows changing with time as the active region grows. First, we observed strong, compact downflow in the leading polarity spot and weaker more dispersed upflow in the following polarity just below it (lower-left from downflow). The direction of flows corresponds to following-to-leading polarity asymmetric flow. About six

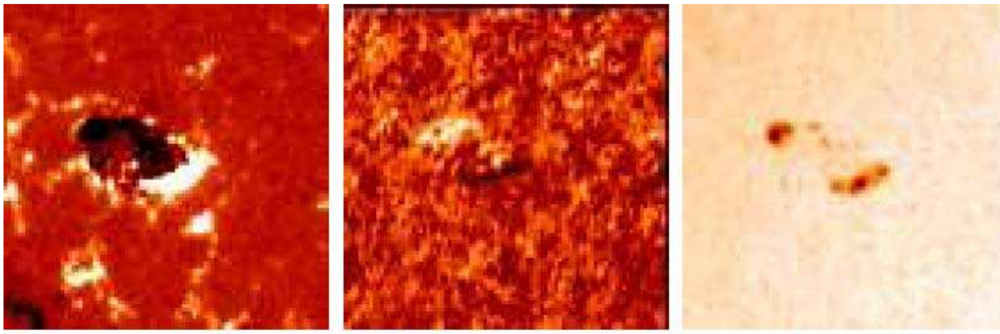

Figure 2. Early emergence of NOAA Active Region (AR) 8699: longitudinal magnetogram (left, white/dark is positive/negative polarity), Dopplerogram (middle, white/dark corresponds to downflow/upflow), and white-light image (right). Doppler velocities were scaled between $\pm$ 1 km/s.

hours later, the flows had changed. One can still see a strong, compact downflow associated with the leading polarity spot. However, the previously described upflow in the following polarity disappears, and a new upflow develops in other area of negative polarity that shows a growth (far left from leading polarity downflows).

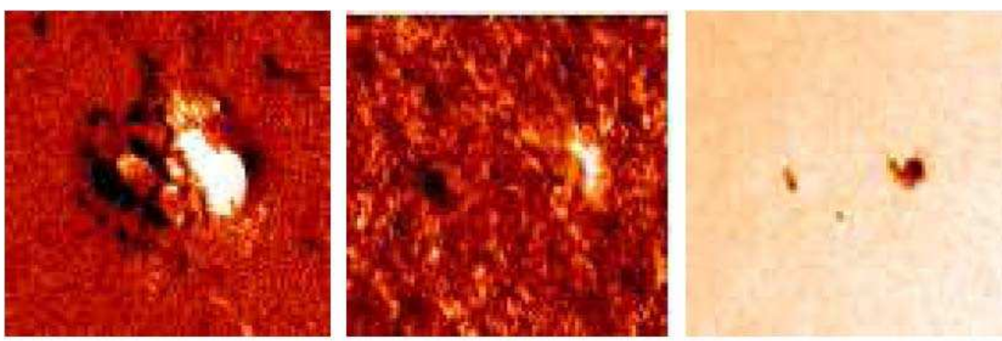

Figure 3. Magnetic field and flows in emerging region NOAA AR 8617. For description of individual panels see Figure 1.

4. Flows Prior to Flux Emergence

Figure 4 (lower panel) suggests that a systematic flow (in this case, upflow) develops sometime after the magnetic flux reaches a certain degree of development. The upper panel of Figure 4 (compare with lower panel) shows no systematic (up- or down-) flows in the area of negative and positive polarity that would support the notion that the flows in developing sunspots might precede the

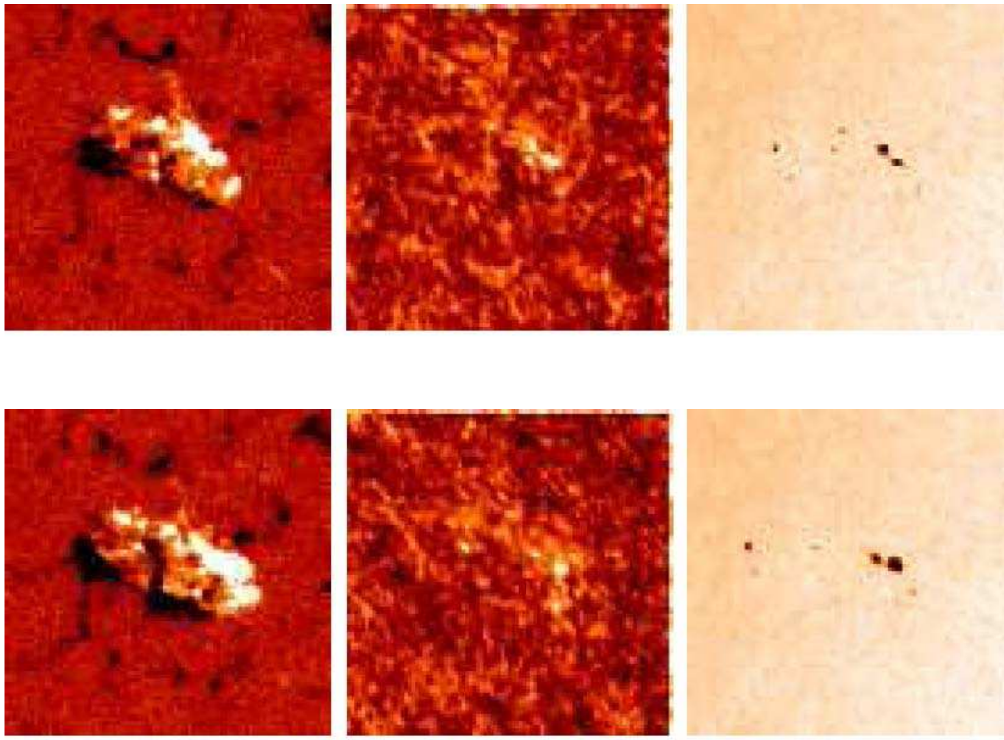

Figure 4. Asymmetric flows in NOAA AR 9244. Notice change in location of area of upflows (dark halftones) as the region evolves.

magnetic field development. Figure 5 gives another example of a quiet Sun area about one day prior to a new active region development. A weak positive magnetic flux observed in the area corresponds to small magnetic concentrations commonly present in "quiet Sun" areas. This weak magnetic flux is unrelated to the emerging region. Doppler velocity maps show no systematic flows in the region.

Analysis of all fifteen regions revealed that in some cases weak upflows and downflows were present in areas of future new flux emergence. However, we found no systematic pattern (up- or down-) in these flows, and in some cases upflows changed to downflows (or *vice versa*) within a one-day time period. The lack of regularity suggests that (up-/down-) flows that we observed at the site of future active region development are probably unrelated to the flux emergence.

After the magnetic flux begins to emerge, the Dopplergrams show the presence of downflows in the general area of flux emergence. These downflows usually encompass the entire area of an active region. They represent a well-known effect of material draining down from the apex of a rising loop to its footpoints. Figure 6 shows an example of this downflow.

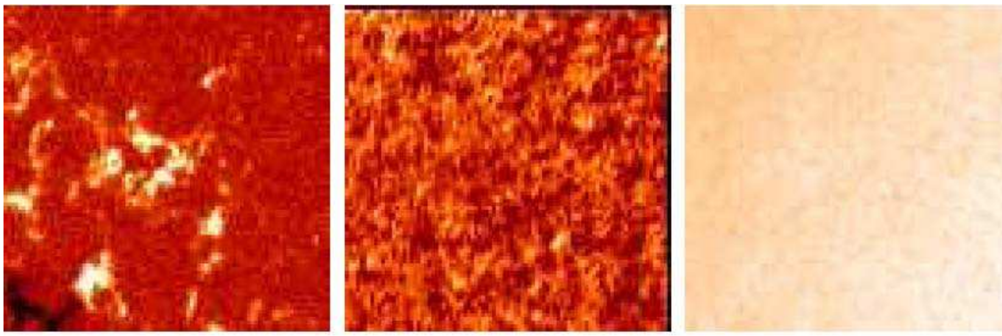

Figure 5. Flows in area of emerging region prior to flux emergence.

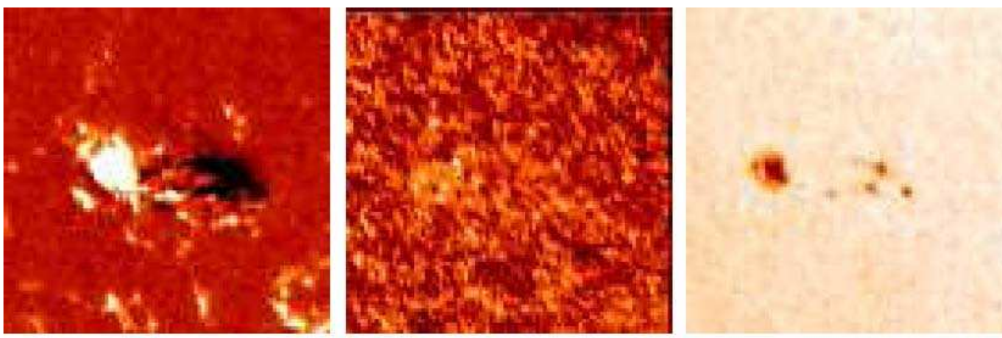

Figure 6. Flows in active region after the flux emergence.

5. Timing of Evershed Flow and Sunspot Penumbra Development

The time-cadence, observing sequences, and spatial resolution of MDI data (white light, Dopplergrams, and line-of-sight magnetic flux) restricted our study of the relative timing of formation of Evershed flow and sunspot penumbra. The penumbra forms when sunspots are still very small in size, and often the observations were inconclusive with respect to the presence or absence of penumbrae. Only in one case was the sunspot large enough to allow us to detect a rudimentary penumbra at the time when Dopplergrams showed only general downflows, but no classical pattern of the Evershed flow. Although this single observation is insufficient to make any definite conclusions, it still suggests that at least rudimentary penumbra may form prior to the development of the Evershed flow circulation.

6. Discussion

We have presented pictorial results of our study of different types of flows in/around emerging active regions. Asymmetric flows were found in a small minority of sunspots. These flows seem to be present at the very early stages of flux emergence. The direction of these flows is not systematic with respect to leading-to-following or following-to-leading polarity pattern, which might indicate that the direction of flow is determined by an imbalance of field strength at flux tube footpoints, not mutual orientation of magnetic polarities. The fact that the majority of regions in our data set do not show any indication of such asymmetric flows may be due to limitations of our present data set.

Our analysis does not support the presence of systematic up- or down- flows in quiet Sun areas prior to active region development. Such flows are necessary for "local sunspot dynamo" models.

We described a single case of the formation of sunspot penumbra prior to development of Evershed flow. This timing suggests that perhaps Evershed flow is the consequence of the penumbra formation. This relationship between two major sunspot features may be important in understanding and modeling the sunspots as the phenomena.

The limitations of our dataset do not allow us to make definite conclusions with respect to all three aspects of our study. Still, these pictorial results pose important questions that should be answered with better data.

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