PRECURSOR OF SUNSPOT PENUMBRAL FORMATION DISCOVERED WITH HINODE SOLAR OPTICAL TELESCOPE OBSERVATIONS

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ABSTRACT

We present observations of a precursory signature that would be helpful for understanding the formation process of sunspot penumbras. The Hinode Solar Optical Telescope successfully captured the entire evolution of a sunspot from the pore to a large well-developed sunspot with penumbra in an emerging flux region appearing in NOAA Active Region 11039. We found an annular zone (width 3″–5″) surrounding the umbra (pore) in Ca ii H images before the penumbra formed around the umbra. The penumbra developed as if to fill the annular zone. The annular zone shows weak magnetogram signals, meaning less magnetic flux or highly inclined fields there. Pre-existing ambient magnetic field islands were distributed at the outer edge of the annular zone and did not come into the zone. There are no strong systematic flow patterns in the zone, but we occasionally observed small magnetic flux patches streaming out. The observations indicate that the annular zone is different from the sunspot moat flow region and that it represents the structure in the chromosphere. We conclude that the annular zone reflects the formation of a magnetic canopy overlying the region surrounding the umbra at the chromospheric level, long before the formation of the penumbra at the photospheric level. The magnetic field structure in the chromosphere needs to be considered in the formation process of the penumbral.

Key words: Sun: chromosphere – Sun: magnetic topology – Sun: photosphere – sunspots

Online-only material: animation, color figures

1. INTRODUCTION

Sunspots are dark patches on the solar surface and the most readily visible manifestations of magnetic flux concentrations (Solanki 2003; Thomas & Weiss 2008). A well-developed sunspot typically consists of a dark central region called the umbra which is surrounded by a less dark annular region called the penumbra. Sunspots appear with successive series of magnetic flux emergence, in which magnetic flux rises through the convection zone to the solar surface and penetrates into the upper atmosphere. Pores, which are essentially small sunspots without penumbra or are naked umbrae, are first formed at both edges of emerging flux regions. Pores develop to become large sunspots with penumbra through the coalescence of pores and smaller magnetic flux tubes into a single, growing pore. When the pore has grown to sufficient total magnetic flux \( (1–1.5) \times 10^{20} \text{ Mx} \), it forms a penumbra in sectors (Leka & Skumanich 1998). The formation of a penumbra is a sudden event, generally within 20–30 minutes, and the Evershed flows are observed without delay after the penumbral formation (Leka & Skumanich 1998; Yang et al. 2003). Recently, Schlichenmaier et al. (2010b) showed that the size of the umbral area is unchanged during the growth of the penumbra in about 4 hr, and concluded that the umbra has reached an upper size limit (about 4 Mm in diameter) and that any newly emerging magnetic flux that joins the spot is linked to the process of penumbral formation.

However, the formation process of a sunspot penumbra is difficult to catch observationally, especially with high spatial resolution. Because of this, we understand poorly the formation process and have not yet answered fundamental questions, such as why do sunspots have penumbrae and what causes their rapid formation. Here, we present a unique data set from high-cadence filtergraph observations of the Hinode Solar Optical Telescope (SOT), which successfully captured the entire evolution of a leading sunspot from the pore to a well-developed sunspot with penumbra (Section 2). We discover an annular zone surrounding the umbra in Ca ii H before the penumbra is formed around the umbra (Section 3), and discuss what the annular structure is in Section 4.

2. OBSERVATIONS AND DATA ANALYSIS

The observations were carried out by SOT (Tsuneta et al. 2008; Suematsu et al. 2008; Shimizu et al. 2008; Ichimoto et al. 2008) on board Hinode (Kosugi et al. 2007). The SOT continuously monitored NOAA Active Region 11039 from 2009 December 29 to 2010 January 2 with some short interruptions for X-Ray Telescope (XRT) synoptic observations. In the SOT field of view (FOV), a large emerging flux region appeared from December 30 to 31 and we completely captured the overall evolution from the birth of the pore to the development of the large sunspot at the leading area. The region was located at S28 W07 on December 30 and at S27 W22 on December 31. The Broadband Filter Imager took Ca ii H (3968 Å, bandwidth: 3 Å) images every 3 minutes and G-band (4305 Å, bandwidth: 8 Å) images every 2 hr with \( 2 \times 2 \) pixel summation (0′′10896). The Narrowband Filter Imager acquired longitudinal magnetograms (0′′160 pixel\(^{-1}\)) in Na i D (5896 Å) every 3 minutes. The spectral bandwidth of the Lyot filter is 90 mÅ. The magnetograms were derived with the observable MG4 VI (ObsID 85), in which a pair of \( I+V \) and \( I−V \) was measured at +140 mÅ off-position four times and \( I/V \) was calculated on board after accumulating the four pairs for better signal-to-noise ratio. No spectro-polarimeter
Figure 1. Evolution of the sunspot seen in the G band and Ca ii H about every 4 hr. North is up and east is to the left. The field of view is 32.7′ × 32.7′ (300 × 300 pixels). The horizontal line in the Ca ii H images indicates the position of the slit center for generating the time-slice maps in Figures 2 and 3. The arrows are pointing to the disk center and the dotted line is the umbral edge. (A color version of this figure is available in the online journal.)

The time series of SOT images were aligned with respect to the solar rotation, which was followed by the spacecraft altitude pointing with a tracking curve (rotation rate is 0.00014805 deg s⁻¹; Shimizu et al. 2007). A cross-correlation method was applied with a large FOV to obtain the series of aligned images. In addition, G-band images acquired by XRT (Golub et al. 2007; Kano et al. 2008) were used to remove small gradual FOV drifts in the time series due to proper motion of the solar features and intensity gradient in the FOV (Shimizu et al. 2008). The magnetogram conversion to the flux density (Gauss or Mx cm⁻²) is determined by comparing the magnetogram to the magnetic flux density map derived from SP data taken at 13:44–14:05 UT on December 31 for the region outside the sunspot.

3. RESULTS

Figure 1 is the temporal evolution of the sunspot seen in the G band and Ca ii H every about 2 hr. Frequent appearance of emerging magnetic patches was observed at the east side of the spot. The penumbra formed in sectors; the penumbra developed at the north side, and then it formed at the west and south. Note that remarkable chromospheric dynamics associated with the elongated structure formed in the umbra is beyond the scope of this Letter and will be discussed in a separate paper. Figure 2 is the time slice of Ca ii H images for the slit located across the sunspot. The slit center is shown in Ca ii H images in Figure 1 and the average intensity in the width of ±7 pixels from the slit center is given in the time slice. The umbra drifted toward the west with a speed of 0.22 km s⁻¹. On the slit, the development of the penumbra was observed from 6 UT to 8 UT on December 31. We can easily see a zone between the umbra and ambient bright features before the penumbral formation. This zone appeared soon after the pore formation and was seen for about 10 hr until the penumbral formation. The zone is annular with the width of 3″–5″ in Ca ii H images. In the Ca ii H image at the left of Figure 1, the zone exists at the outer side of the umbral edge (indicated by the dotted contour) on almost all locations excepting the east side of the spot. Its brightness is almost similar to that inside the network cells far from the sunspot. The penumbra was developed as if to fill the annular zone. The zone became very dark after the penumbral formation and its brightness is 58%–73% of the brightness in the quiet-Sun network cells.

The corresponding time slice of Na I D magnetograms is shown in Figure 3. The annular zone shows weak signals; the magnetic flux there is weak or highly inclined. The existence of positive-polarity (the same polarity as the sunspot) magnetic flux islands concentrated at the outer edge of the zone is remarkable. These are pre-existing flux patches and may be observed as bright features in Ca ii H (Figure 2). The sunspot developed in the region where the dominant magnetic flux polarity is the same as that of the sunspot. The pre-existing flux patches that come to the outer edge of the zone moved west in response to the motion of the sunspot, and they did not come inside the zone. The total ambient flux located at the west side of the sunspot is almost constant (2.5 × 10²⁰ Mx) within ±15% in between before and after the penumbral formation. Note that we measured the total flux of ambient magnetic patches existing in the zone within ±13.6 arcsec from the position of the slit center outside the annular zone or penumbra. The total magnetic flux of the sunspot monotonically increased with time and was 5 × 10²⁰ Mx at 3 UT and 7 × 10²⁰ Mx at 6 UT on December 31.
Figure 2. Time slice of Ca\textsc{ii} H images for the slit located across the sunspot. The slit center is shown on Ca\textsc{ii} H images in Figure 1. The larger values in the slit position are toward the west. The black stripes are data gaps.

(A color version of this figure is available in the online journal.)

Figure 3. Time slice of Na\textsc{i} D magnetograms. See Figure 2 for details. Note that the data are clipped as given in the scale bar.

Gas flow patterns inside the zone before the penumbral formation were examined with 3 minute cadence time series of Na\textsc{i} D magnetograms (see Figure 4 and the online animation). We observed some flux patches that flowed out from the edge of the spot and moved outward. Cellular patterns, in which most of the flux is distributed at the cellular edge, formed in between the spot and the ambient field (arrows in Figure 4). The cellular patterns gradually evolved to an annular structure. There were no strong systematic flow patterns in the annular zone, which is quite different from the moat region, but a limited number of outward moving patches were observed, as shown in Figures 4(a) and (b). The speed of these moving patches is 1–2 km s\(^{-1}\). In the zone, no magnetic patches were observed that showed inward motion toward the umbra. Note that the flux patches moving toward the umbra were frequently observed on the east side of the spot where flux emergence actively took place (Schlichenmaier et al. 2010a). After the penumbral formation, we observed that small magnetic patches frequently flowed out from around the penumbral edge.

4. DISCUSSION AND CONCLUSIONS

Ca\textsc{ii} H images newly revealed that an annular zone surrounding the pore existed before the formation of penumbra. Here, we discuss the physical nature of the annular zone.

First, the annular zone structure is different from the sunspot moat region. The moat region is an annular region outside the penumbra with a persistent large-scale radial outflow (moat flows) and frequent appearances of moving magnetic features (Sheeley 1969; Harvey & Harvey 1973). Since the penumbra is developed as if to fill the pre-existing annular zone and a systematic moat-flow-like outflow is not observed in the annular zone, we can conclude that the annular zone represents a structure different from the moat. Second, the annular zone has
Hurlburt & Rucklidge (2000) conducted numerical simulations of the formation of the penumbra at the photospheric level (Figure 5). Overlying the region surrounding the umbra, long before the penumbral formation, the magnetic fields at the edge of the umbra extend to the chromosphere and corona. The magnetic field structures created in the chromosphere may influence the field inclination at the photosphere. According to recent numerical simulations of sunspot models, the development of pre-existing flux elements cannot move inside the annular zone.

Figure 5. Magnetic field structure before the penumbral formation. The nearly horizontal dashed line indicates the photospheric (τ = 1) level. The dotted lines with the arrow head are large-scale gas flows in the subsurface layer.

A possible interpretation is that the annular zone may reflect the formation of a magnetic canopy at the chromospheric level overlying the region surrounding the umbra, long before the formation of the penumbra at the photospheric level (Figure 5). Hurlburt & Rucklidge (2000) conducted numerical simulations on axisymmetric flux tubes in a compressible convecting atmosphere and showed how the magnetic field configuration changes as a function of magnetic flux, i.e., from a small pore to a well-developed sunspot. The potential magnetic field is used in the atmosphere above the photospheric layer. Because of the pressure balance with surrounding gas that has a decreasing pressure at higher atmosphere, the flux tube forms a canopy configuration in the layer above the photosphere. They showed that the size of the canopy structure is almost independent of the total flux content of the flux tube, which is in good agreement with the almost constant width of the annular zone (3′′–5′′) in the entire period from pore formation to penumbral formation. Because of the magnetic pressure of the canopy fields, ambient pre-existing magnetic flux elements cannot move inside the annular zone.

In the penumbrae, the average inclination of the magnetic field increases from approximately 40 deg at the umbra–penumbra boundary to about 70 deg at the outer edge of the penumbra (Bellot Rubio et al. 2003). There is no obvious gradual increase in the field inclination during the formation of penumbrae (Leka & Skumanich 1998). Thus, the appearance of a penumbra would be quite sensitive to the field inclination at the edge of the umbra. The magnetic fields at the edge of the umbra extend to the chromosphere and corona. The magnetic field structures created in the chromosphere may influence the field inclination at the photosphere. According to recent numerical simulations of sunspot models, the development of a penumbra appears to be quite sensitive to the magnetic field structure in the chromosphere. Rempel et al. (2009) provided the first MHD simulations of the entire sunspot structure that resolve sunspot fine structures and their dynamics. The vertical domain size of their simulations is still small and the top boundary condition is located only about 700 km above the quiet-Sun τ = 1 level. With a different boundary condition at the top, the numerical runs result in a different penumbral structure of the simulated sunspot, including no penumbral formation (M. Rempel 2011, private communication). Rapid penumbral decay is also observed in conjunction with major flares, suggesting that the penumbral structure at the photospheric level can be significantly influenced by magnetic field topology in the corona (Wang et al. 2004; Deng et al. 2005).

It was observed that a limited number of small magnetic flux patches stream out at the photosphere below the chromospheric canopy structure. The frequency of the outgoing patches tells us that the emergence from below the photosphere in the annular zone is not the origin of the penumbral magnetic features. Earlier observations showed that motions toward the pore dominate in the 1′′–2′′ zone around the pore boundary and their average speed is 0.3–0.5 km s\(^{-1}\), while at larger distances the granules move away from the pore with speeds much slower than 1 km s\(^{-1}\) (Keil et al. 1999; Sobotka et al. 1999). Bipolar moving magnetic features were observed to stream out from a pore (Zuccarello et al. 2009). Recently, Rempel (2011) ran a simulation to explore the subsurface field and flow structure around the spot without a penumbra and compared it with the structure in the run with a penumbra. Even in the absence of a penumbra, the simulation shows a large-scale
radial outflow surrounding the sunspots everywhere in the photosphere, in addition to a converging flow in the proximity of sunspots.

Our observations suggest that the canopy structure is formed in the upper atmosphere, i.e., the chromosphere. When unknown conditions set in, the chromospheric canopy fields may have evolved to the highly inclined penumbral fields at the photospheric level. Rezaei et al. (2012) found that, at the early stage of penumbral formation, the magnetic area of the umbra extends over the visible limits of the penumbra at the photospheric level. There, the field strength is fairly high and the field has large inclinations. This is consistent with a forming canopy. Thus, the observed annular zone structure can be interpreted as the precursor of penumbral formation. The chromospheric structure surrounding the umbra can depend on the spatial distribution of pre-existing magnetic flux elements surrounding the umbra and their magnetic polarity. In the case presented in this Letter, the pre-existing flux is the same as the umbra’s, and therefore an annular canopy structure is formed in the area between the flux-concentrated umbra and ambient flux patches, as illustrated in Figure 5. The existence of ambient flux patches may keep the canopy fields from going down to the photospheric level. If the ambient field has the opposite sign, an annular canopy structure may not be well developed around the umbra, because magnetic reconnection can easily take place in between the umbra’s and ambient field. Thus, we point out the possibility that different developmental paths of chromospheric structures around the umbra may lead to different developmental paths of penumbrae, which should be studied observationally with more examples in the future.

We conclude that the annular feature in Ca\textsc{ii} H reflects the formation of a magnetic canopy overlying the region surrounding the umbra at the chromosphere and that the canopy structure may play an important role in the formation of penumbrae. Further investigations in the magnetic structures at both the chromosphere and the photosphere are urgently needed in coming years.

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