A New View of Fine Scale Dynamics and Magnetism of Sunspots Revealed by Hinode/SOT

K. Ichimoto,1 Y. Suematsu,2 Y. Katsukawa,2 S. Tsuneta,2 M. Shimojo,2 T. Shimizu,3 R. A. Shine,4 T. D. Tarbell,4 T. Berger,4 A. M. Title,4 B. W. Lites,5 M. Kubo,5 T. Yokoyama,6 and S. Nagata1

Abstract. The Solar Optical Telescope on-board Hinode is providing a new view of the fine scale dynamics in sunspots with its high spatial resolution and unprecedented image stability. We present three features related to the Evershed flow each of which raises a new puzzle in sunspot dynamics; i.e., twisting appearance of penumbral filaments, the source and sink of individual Evershed flow channels, and the net circular polarization in penumbrae with its spatial relation to the Evershed flow channels.

1. Introduction

The origin of the fine scale structure of sunspot penumbrae has been one of the central topics in the research of the solar magneto-hydrodynamics. The Evershed flow, the most distinctive property of sunspot penumbrae, is closely related to the filamentary structure of penumbrae (for review, see Solanki 2003; Thomas & Weiss 2004; Bellot Rubio 2007). The uncombed structure of penumbrae is generally accepted, in which the inclination of the magnetic field vector fluctuates in azimuthal direction and the flow takes place in radial filaments that have nearly horizontal magnetic fields (Degenhardt & Wiehr 1991; Schmidt et al. 1992; Title et al. 1993). The embedded flux tube model was proposed to account for such geometry (Solanki & Montavon 1993), i.e., nearly horizontal magnetic flux tubes carrying the Evershed flow are embedded in more inclined background magnetic fields of the penumbra (Schlichenmaier et al. 1998). The source of the Evershed flow (foot points of the flux tube) was identified by Rimmele & Marino (2006) as bright penumbral grains associated with an upflow.

In spite of the remarkable progress of recent high resolution observations of sunspots (e.g., Bellot Rubio, Schlichenmaier, & Tritschler 2006; Sánchez...
Almeida et al. 2007), a number of issues remain unsolved; An argument was raised that the penumbral bright filaments are better explained by protrusions of non-magnetized, convecting hot gas into the background oblique magnetic fields of the penumbra (Spruit & Scharmer 2006; Scharmer et al. 2007). There is still no consensus on the origin of the penumbral fine structure. The mass and energy budgets of the Evershed flow are still important issues. The nature of the dark core of penumbral filaments (Scharmer et al. 2002) is a mystery. Line asymmetry or the net circular polarization (NCP) in sunspot may provide an important information on the depth structure of the line forming layer, but its fine scale distribution and relation to the Evershed flow is not known.

The Solar Optical Telescope (SOT, Tsuneta et al. 2008; Suematsu et al. 2008; Tarbell et al. 2008; Kosugi et al. 2007) aboard Hinode provides us new opportunities to settle those fundamental questions on the fine scale structure of penumbrae with the unprecedentedly stable time series of images. This paper is devoted to demonstrate new features in fine scale dynamics of the sunspot penumbrae revealed by the SOT with an attention on the aspects that raise new puzzles in sunspot physics.

2. New Features found in Sunspot Penumbra

To study the fine scale dynamics in sunspots, we used time series of the blue continuum images taken by the Broadband Filter Imager (BFI) and normal scan maps of the Spectropolarimeter (SP). The BFI images have a pixel scale of 0.054 arcsec/pix and time cadence of 20-30 sec. The SP took full Stokes profiles of the pair of Fe lines at 6301.5 and 6302.5 Å with a photometric accuracy of 0.1% and a pixel resolution of 0.16 arcsec/pix.

2.1. Twisting Appearance of Penumbral Filaments

One obvious feature immediately found in movies of the continuum images of sunspots taken by the BFI is the evidence of outward motions of material along penumbral filaments. The outward motions start from the innermost edge of bright filaments, which reinforces the finding that the penumbral bright grains are the footpoints or sources of the Evershed flow (Rimmele & Marino 2006). Another noticeable feature is that some bright filaments reveal internal intensity fluctuations moving laterally across the filaments, giving rise to a strong impression of twisting motions of individual filaments (Fig. 1).

The apparent twisting motions of penumbral filaments are observed only in restricted sections of the sunspot, i.e., they are found in the penumbra located in the direction perpendicular to the line connecting the sunspot center and the solar disk center, and hardly seen in the limb-side and disk-center-side penumbra. Also found is that the direction of the twist of the filaments belonging to the same section of the penumbra is the same and the lateral motions of intensity fluctuation in the filaments are always from the limb side toward the disk center side. This feature was confirmed to be a common rule for several sunspots located at different positions on the solar disk. Thus the “twists” observed in penumbral filaments are neither an actual twist nor a helical motion of individual filaments, but rather are a manifestation of their dynamical nature such that their appearance depends on the viewing angle. The locations
where the ‘twisting’ filaments are observed are complementary to those of the dark cored filaments which are preferentially observed in limb-side and disk-center-side penumbrae (Sutterlin et al. 2004). The mechanism that produces the apparent twisting motions is not well understood (Ichimoto et al. 2007a).

2.2. Vertical Motions in Evershed Flow Channels

To understand the continuities of mass and energy flux associated with the Evershed flow, the vertical component of motions in the penumbra was examined for a simple sunspot located near the disk center (heliocentric angle $\sim 1^\circ$) on 28 February 2007. As reported by Ichimoto et al. (2007b), a number of tiny, blue shifted regions are found over the penumbra in Dopplergrams made from the bisector position of the line wing of Fe I 6301.5 Å. Also found are a number of red shifted patches that have opposite magnetic field polarity to the sunspot and are preferentially located near and around the outer border of the penumbra.

Fig. 2b shows a map of magnetic field inclination obtained from the Milne-Eddington fitting to the SP data overlaid with the contours showing the up-flow (blue or black) and down-flow (red or gray) regions. Filamentary structure is noticeable in the inclination map; the penumbra consists of radial filaments which alternatively have nearly horizontal and more inclined magnetic fields showing the uncombed structure. Upflow regions are located in the umbral side of the horizontal field channels, while the downflow regions tend to exist at the outer end of the horizontal field channels. Since the Evershed flow is associated with the horizontal field channels, the up-flow and down-flow regions
are convincingly regarded as the source and sink of the Evershed flow, and we are resolving the individual Evershed flow channels.

Fig. 2a shows a continuum intensity map overlayed by the contours showing the up-flow and down-flow regions. A close correlation between the up-flow and bright grains is obvious, which strongly suggests that the energy for maintaining the penumbral brightness is carried by the up-flows (e.g., Schlichenmaier & Solanki 2003). Note that, however, there is no significant statistical difference in the continuum intensity (or temperature) between the up-flow in penumbra and the down-flow around the outer boundary. The energy budget of the Evershed flow as the source of the penumbral brightness is still not understood.

2.3. Net Circular Polarization in Penumbrae

Net circular polarization (NCP) defined as the integrated Stokes-V over spectral lines is generated by combinations of velocity gradient with the gradient of magnetic fields along the line-of-sight (LOS) (Landolfi & Landi Degl’Innocenti 1996). Distribution of NCP in sunspots from earlier observations in visible spectral lines is summarized as follows (e.g. Martinez Pillet 2000): For positive polarity sunspots, 1) the limb-side penumbra has a positive NCP, 2) the disk-center-side penumbra has a negative and weaker NCP, 3) penumbrae of sunspots at disk center has a positive NCP. The negative polarity sunspots have opposite sign of NCP. Tritschler et al. (2007) demonstrated the filamentary structure of NCP in high resolution observations, though the spatial correlation with the Evershed flow is not conclusive. The most successful scenario that accounts for the NCP of sunspots today is based on the $\Delta \gamma$-effect, i.e., the gradient (or discontinuity) of the magnetic field inclination ($\gamma$) along LOS, takes a crucial role for creating the NCP together with the horizontal Evershed flow in deep photospheric layer (Sánchez Almeida & Lites 1992). Such geometry of penumbrae
Figure 3. NCP of the same sunspot at disk center (a) and at the heliocentric angle of 17.2° (b). (a) is overlaid with the same contours as Fig. 2 and (b) with Doppler shifts of -1.5 (blue or black), 0.3 (pink or light gray) and 1.2 km/s (red or gray).

and the distribution of NCP in sunspots are explained by the embedded flux tube model (Solanki & Montavon 1993; Martinez Pillet 2000; Schlichenmaier & Collados 2002; Müller et al. 2002, 2006; Borrero, Bellot Rubio, & Müller 2007). To account for the NCP of disk center sunspots, upflows are assumed in the background magnetic field in Martinez Pillet (2000).

Fig. 3 shows the NCP maps of the same (positive polarity) sunspot as in Fig. 2 when it was located near the disk center and at the heliocentric angle of 17.2°. The radially elongated filamentary structures of NCP are noticeable. In the disk center sunspot, the positive NCP in the penumbra is closely related to the blue-shifted and red-shifted regions, i.e., upflow and downflow in deep layer are the source of the positive NCP. In the sunspot at heliocentric angle of 17.2°, the limb-side penumbra shows that the positive NCP is associated with the Evershed flow channels (red shift) as expected. Both positive and negative NCP structures are equally present in the disk center-side penumbra, and remarkably the positive NCP is again correlated with the Evershed flow channels (blue shift). Thus the negative NCP spatially averaged in the disk-center-side penumbra is attributed to the inter-Evershed flow channels rather than the Evershed flow.

These results are contradictory to the current pictures accounting for the sunspot’s NCP and it can be shown that the $\Delta B$-effect, i.e., a positive spatial correlation between the magnetic field strength and the flow velocity may serve as a more natural interpretation than the $\Delta \gamma$-effect as the cause of the sunspot’s NCP (Ichimoto et al. 2008). Further studies with more realistic models are obviously required.

3. Summary: New Puzzles on the Penumbral Dynamics

The Hinode/SOT revealed a new view on the fine scale dynamics in sunspots and we are resolving individual Evershed flow channels in spectropolarimetric
observation. At the same time, however, these results raised new questions and puzzles as summarized below:
- What is the cause of the apparent twisting motion of penumbral filaments?
- What is the energy budget associated with the Evershed flow to account for the penumbral brightness?
- How the NCP in penumbra can be explained?
- What is the nature of the material motions in inter-Evershed-flow channels?

Acknowledgments. Hinode is a Japanese mission developed and launched by ISAS/JAXA, with NAOJ as domestic partner and NASA and STFC (UK) as international partners. It is operated by these agencies in co-operation with ESA and NSC (Norway).

References

Bellot Rubio, L. R. 2007, in Highlights of Spanish Astrophysics IV, ed. F. Figueras, J. M. Girart, M. Hernanz & C. Jordi (Dordrecht: Springer), 271