Temporal Relation between the Disappearance of Penumbral Fine-Scale Structure and Evershed Flow

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Sunspot penumbrae consist of many fine-scale radial filaments. Their fine-scale structures reflect complex magnetic field structures in penumbrae: azimuthal fluctuations of the penumbral magnetic field inclination and field strength are well observed at the scale of the intensity fluctuations. A systematic outward flow called Evershed flow is closely related to the formation of penumbral fine-scale magnetic field structures. Evershed flows are radial outward flows propagating along the penumbral horizontal magnetic fields, and their origin is rising hot gas well observed in the inner penumbra.

We investigate the temporal relation between the Evershed flow, dot-like bright features (penumbral grain), the complex magnetic field structure, and dark cores along bright filaments in a sunspot penumbra. We use the dark core in order to trace the center of the bright filament (Figure 1). It is believed that a pile-up of hot plasma along the center of the bright penumbral filament pushes up the $\tau = 1$ surface into the upper layer, where the temperature is lower. As a result, a dark lane (dark core) is observed along the top of the cusp of the $\tau = 1$ surface.

This study confirms that the appearance and disappearance of the Evershed flow and penumbra grains occur at nearly the same time and are associated with changes of the inclination angle of the magnetic field from vertical to more horizontal (Figure 2)[1]. This suggests that both convection (penumbral grains) and horizontal fields in the penumbra are necessary for (or caused by) the formation of the Evershed flow. The close correlation between the Evershed flow, convection, and more horizontal fields supports recent models wherein the Evershed flows are convective flows in the inclined magnetic field lines in the penumbra.

The dark core of the bright filament also appears coincidental with the Evershed flow. However, we find that the dark-cored bright filament survives at least for 10–20 minutes after the disappearance of the Evershed flow. If the Evershed flow only caused a pile-up of hot plasma along the bright filament, the dark core should disappear within a cooling timescale after the end of the Evershed flow. However, the dark core is continuously observed without the Evershed flow for a period much longer than a cooling timescale in the photosphere. This suggests that local heating along the bright filament of the penumbra is important for maintaining its brightness, in addition to heat transfer by the Evershed flow.

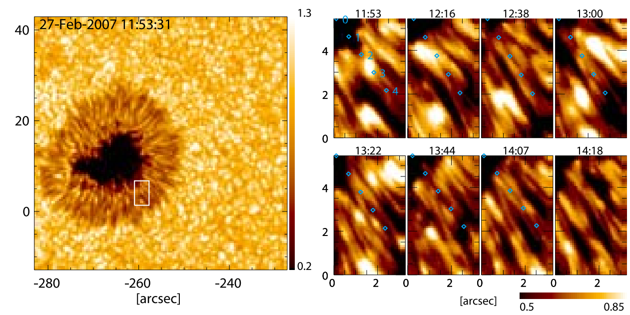

Figure 1: *left*: G-band intensity image obtained with the Solar Optical Telescope aboard *Hinode*. The intensity is normalized to the mean intensity of the quiet area outside the sunspot. The axes represent the positions with respect to the disk center. *right*: Time series of G-band images in the white box of the left panel. The dots with intervals of 1″ are linearly aligned on a dark core in the bright penumbral filament. Note that the dark core disappears at 14:18 UT.

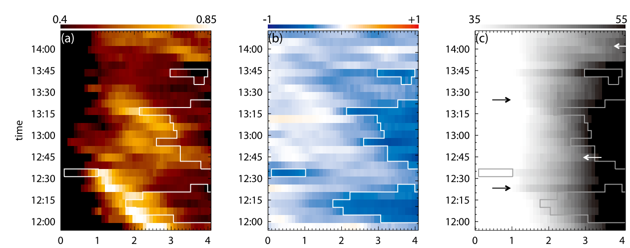

Figure 2: Space vs. time plots along the dotted lines in Figure 1 for (a) G-band intensity, (b) Doppler velocity, and (c) magnetic field inclination. The contours represent the Doppler velocity of $-0.4\,\mathrm{km\,s^{-1}}$. The positive (negative) Doppler velocities indicate a redshift (blueshift) in units of $\mathrm{km\,s^{-1}}$. The magnetic field with the line-of-sight direction is represented by the inclination angle of 0 degree.

Reference

[1] Kubo, M., et al.: 2011, *ApJ*, **731**, 84.