The Evershed Effect with SOT/Hinode

K. Ichimoto and the SOT/Hinode Team

Abstract The Solar Optical Telescope onboard Hinode revealed the fine-scale structure of the Evershed flow and its relation to the filamentary structures of the sunspot penumbra. The Evershed flow is confined in narrow channels with nearly horizontal magnetic fields embedded in a deep layer of the penumbral atmosphere. It is a dynamic phenomenon with flow velocity close to the photospheric sound speed. Individual flow channels are associated with tiny upflows of hot gas (sources) at the inner end and downflows (sinks) at the outer end. SOT/Hinode also discovered “twisting” motions of penumbral filaments, which may be attributed to the convective nature of the Evershed flow. The Evershed effect may be understood as a natural consequence of thermal convection under a strong, inclined magnetic field. Current penumbral models are discussed in the lights of these new Hinode observations.

1 Introduction

Since its discovery by Evershed (1909), the Evershed effect has been one of the longstanding mysteries in solar physics. It is evident from recent high-resolution observations that the flow is closely related to the small-scale filamentary structures in penumbrae (for reviews see Solanki 2003; Thomas et al. 2004, 2008; Bellot Rubio 2007; Thomas 2010). The inclination of the penumbral magnetic field fluctuates in the azimuthal direction with the spatial scale of the penumbral filaments (interlocking comb structure), whereas the flow takes place in radial filaments, which have nearly horizontal magnetic field (Degenhardt and Wiehr 1991; Schmidt et al. 1992; Title et al. 1993). The flow vector is parallel to the magnetic fields (Bellot Rubio et al. 2004; Borrero et al. 2005).

To account for the filamentary structure of penumbrae, the following models have been proposed, that is, the embedded or rising flux tube model (Solanki and Mondavon 1993; Schlichenmaier et al. 1998) in which the Evershed flow channels
are explained as rising flux tubes embedded in more vertical background magnetic fields in the penumbra, the gappy penumbral model (Spruit and Scharmer 2006; Scharmer and Spruit 2006) in which the bright penumbral filaments are regarded as manifestations of the protrusion of nonmagnetized, convecting hot gas into the oblique background fields of the penumbra, and the downward pumping model (Thomas et al. 2002; Weiss et al. 2004; Brummell et al. 2008) in which the penumbral fine structure is created by localized submergence of penumbral fields that are forced by the photospheric convection around the outer edge of penumbrae. There is still no consensus on the physical nature and origin of the penumbral fine structures.

Using highly stable time sequences of sunspot images and high precision spectropolarimetric data provided by the Solar Optical Telescope (SOT; Tsuneta et al. 2007; Suematsu 2007) onboard Hinode (Kosugi et al. 2007), Ichimoto et al. (2007a) confirmed the interlocking-comb penumbral structure and found that the Evershed flow preferentially takes place in bright filaments in the inner penumbra and in dark filaments in the outer penumbra. They also found the presence of a number of small patches with a vertical velocity component, upward motions distributed over the penumbra, and strong downward motions associated with magnetic polarity opposite to that of the sunspot in the mid and outer penumbra. The vertical motions may be regarded as the sources and sinks of the Evershed flow channels, though unequivocal identification of individual pairs was not reached.

Here we report results on the spatial distribution of vertical motions in penumbrae obtained from further analyses of the sunspot data taken by SOT. The characteristics of the Evershed flow are summarized, and the origin of the flow is discussed within the context of the present penumbral models.

2 Elementary Structure of the Evershed Flow

The spatial distribution of the vertical motions in sunspots were studied using SOT/SP data taken on 1 May 2007. The sunspot was located near disk center, with the viewing angle between the line of sight and the normal to the solar surface $\mu = 5.8^\circ$. Stokes profiles of the pair of Fe I lines at 6,302 Å were fitted using the Milne–Eddington model to obtain vector magnetic fields.

Figure 1 shows the magnetic field inclination overlayed with contours showing the vertical motions. The blue contours show blueshift at $-0.8$ km s$^{-1}$ in the wing of Stokes-$I$ of Fe I 6,301.5 Å and the red contours show $V/I_c = 0.01$ at Fe I 6,302.5 + 0.365 Å, representing strong downflow regions with opposite magnetic polarity to the spot. $V$ and $I_c$ are Stokes-$V$ and the continuum intensity, respectively. Radial penumbral filaments with dark appearance in the inclination map are the channels with nearly horizontal magnetic field. It is remarkable that the upflow and downflow patches are aligned with the horizontal field channels that carry the Evershed flow, and that small-scale upflows are preferentially located near the inner ends, and downflows at the outer ends of the horizontal field channels. Thus, the upflow and downflow patches may be regarded as the sources and sinks of the Evershed