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The Evershed flow from simultaneous chromospheric and photospheric observations(*)

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Summary. — We study the Evershed flow in the photosphere and the reverse Evershed flow in the chromosphere giving emphasis to the temporal evolution of the phenomenon. Our results verify that the velocity of the Evershed flow has a maximum above the penumbra in the photosphere and well outside the penumbra in the chromosphere. We found a quasi-periodic behavior of the reverse Evershed flow in the chromosphere with period between 10–15 min. We were not able to identify an obvious repetitive behavior in the photosphere, except from the propagation of the slow photospheric waves.

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PACS 95.75.Mn – Image processing (including source extraction).
PACS 01.30.Cc – Conference proceedings.

1. – Introduction

A large-scale flow pattern, called Evershed flow, is associated with sunspots. At photospheric levels the flow pattern consists of a radial horizontal outflow from the sunspot to the surroundings, while at chromospheric levels the direction is reversed and material flows into the sunspot umbra. Rimmele [1] and Shine *et al.* [2] found that Evershed velocities are non-stationary. They observed velocity packets propagating radially outward, towards the penumbral boundary and into the adjacent quiet photosphere. The average propagation speed was about 3.2 km s^{-1}, subsequent velocity packets were separated in space by 2000–3000 km and the pattern repeated in a quasi-periodic way on a time scale of the order of 15 min. The velocity packets were travelling in Evershed channels. Rimmele [1] noticed that the period matches with the long-term oscillations observed in

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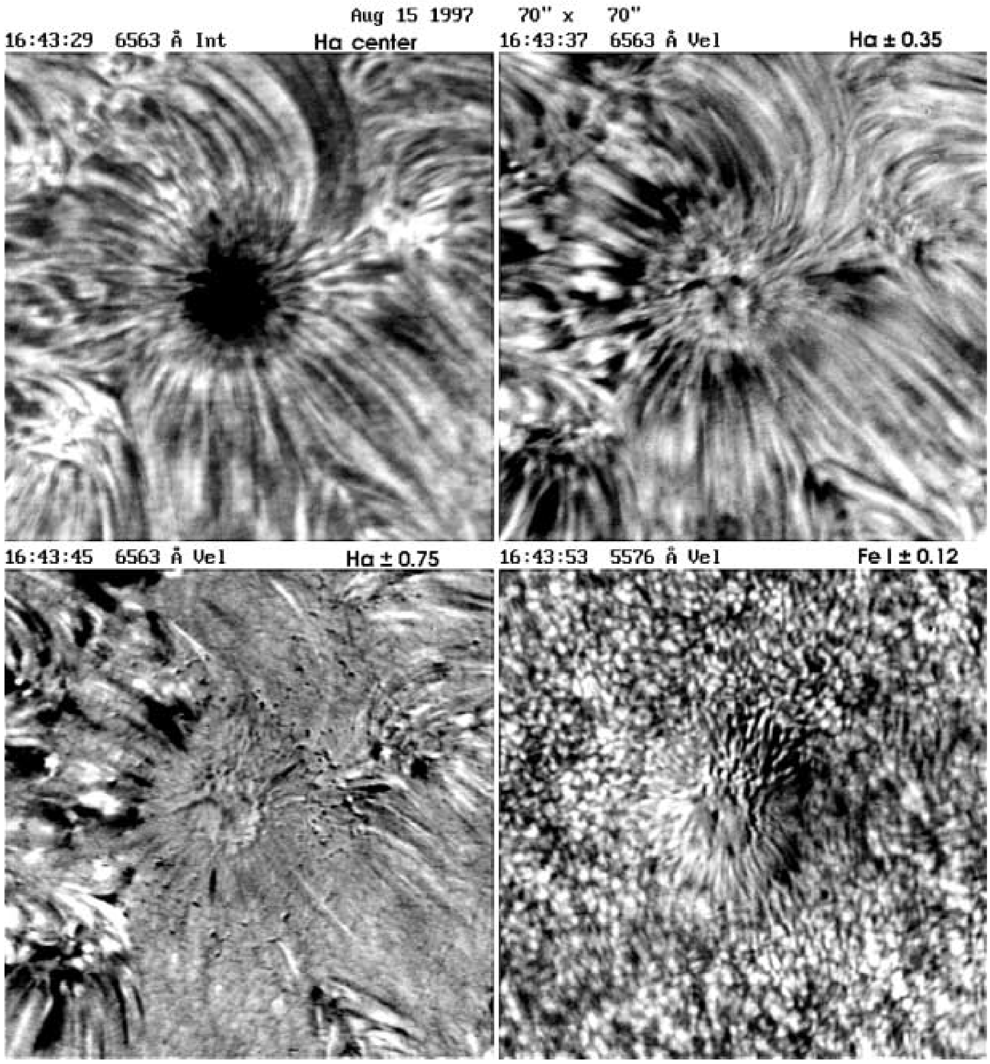

Fig. 1. – Images of a large isolated sunspot observed near disk center on August 15, 1997 in Hα center (a) and line-of-sight Doppler velocity images in Hα $\pm$0.35 Å (b), Hα $\pm$0.75 Å (c), and Fe I 5576 $\pm$0.12 Å (d). Note the Ellerman bombs in the Hα $\pm$0.75 Å velocity image appearing as dark dots (blue wing excess) indicating the quality of our observations.

the penumbra. In this work we study the temporal behavior of the Evershed flow from simultaneous photospheric and chromospheric observations.

2. – Observations and image processing

Observations were obtained at the R. B. Dunn telescope of the Sacramento Peak Observatory with a 512 by 512 pixel CCD camera and the UBF filter. The pixel spatial resolution was 0.26 arc seconds. A large isolated sunspot was observed at N14.7, E26.0 on August 15, 1997. The duration of our observations was 116 minutes; images were

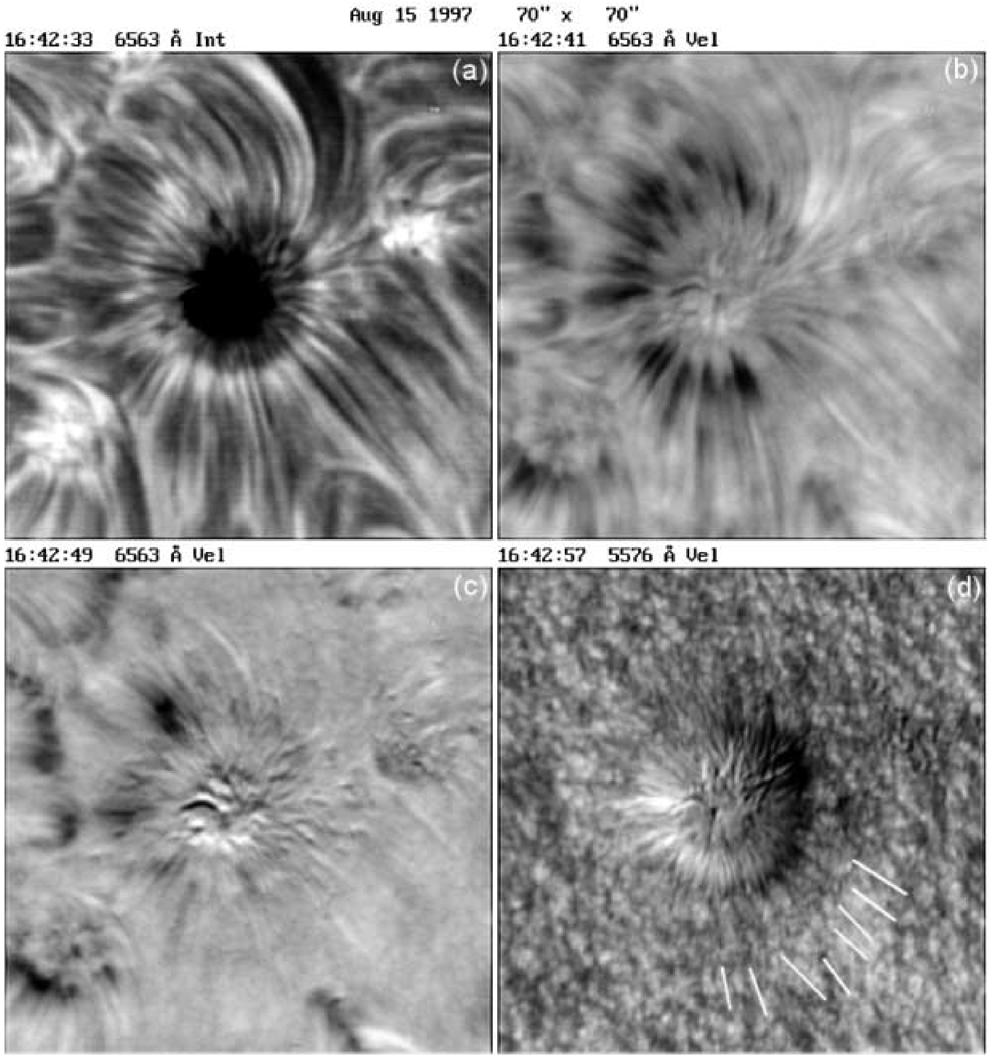

Fig. 2. – Time average sunspot images (over 70 min) in Hα center (a), and line-of-sight Doppler velocity images in Hα ± 0.35 Å (b), Hα ± 0.75 Å (c), and Fe I 5576 ± 0.12 Å (d). The reverse of the flow in the chromosphere is obvious. We have marked in (d) velocity channels that extend well beyond the outer boundary of the penumbra in the photosphere.

obtained in Hα center, Hα ± 0.35 Å, Hα ± 0.75 Å and in the magnetically non-sensitive line Fe I 5576 ± 0.12 Å. Note that the precision of the UBF filter is of the order of 1 mÅ, while the FWHM is about 240 mÅ near Hα and about 120 mÅ near Fe I 5576 Å. The time interval between successive images of the same wavelength was 28 seconds, while the time difference between opposite Hα and Fe I wings was 4 seconds. We computed Dopplergrams in Hα ± 0.35 Å Hα ± 0.75 Å as well as in Fe I 5576 ± 0.12 Å by red blue wing subtraction. We used the Doppler images as qualitative maps of the line-of-sight velocity. We used an image segmentation procedure based on a histogram technique in order to produce segmented images in which the umbra, penumbra or superpenumbra

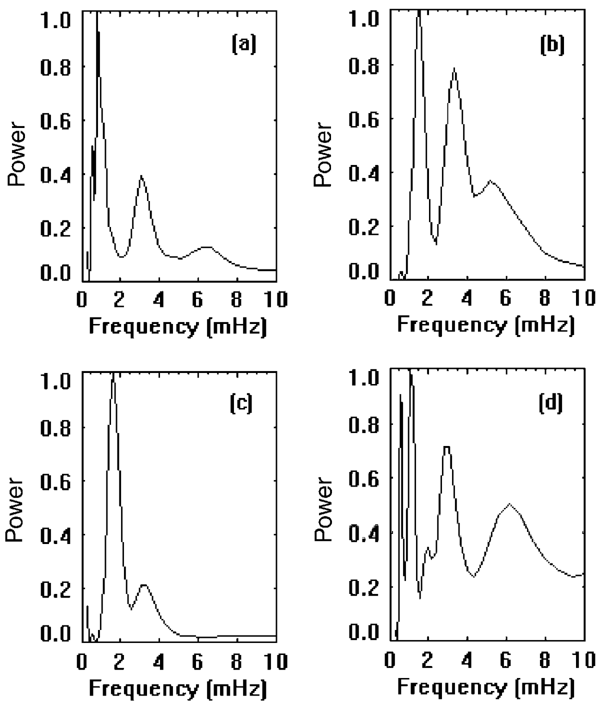

Fig. 3. – Average power spectra of the penumbral and superpenumbral points for Hα center (a), and for Doppler velocity in H$\alpha \pm 0.35$ Å (b) and Hα ±0.75 Å (c); average power spectra of the penumbral points for Doppler velocity in Fe I 5576 ±0.12 Å (d).

pixels conserved their original intensity and the background was set to zero. Following a method first introduced by Kinman [3] and assuming an axial symmetry of the sunspot and that the line is formed at the same height over the entire region, we computed the components of the velocity vector as a function of distance from the center of the spot. Figure 1 shows images of the sunspot in Hα center image (a), and line-of-sight Doppler velocity images in Hα ±0.35 Å (b), Hα ±0.75 Å (c), and Fe I 5576 ±0.12 Å (d).

3. – Results

Figure 2 shows a time average over 70 min of the sunspot in Ha center (a), and line-of-sight Doppler velocity images at Hα ±0.35 Å (b), Hα ±0.75 Å (c), and Fe I 5576 ±0.12 Å (d). From the Doppler velocity images it is verified that the Evershed effect is confined to channels that in some cases extend well beyond the outer boundary of the penumbra in the photosphere (see Rimmele [1]). We further observe that the velocity pattern in Hα ±0.75 Å is much more smooth than in Hα ±0.35 Å indicating lower velocities.

Figure 3 shows average power spectra of the penumbral and superpenumbral points for Hα center (a) and for Doppler velocity images in Hα ±0.35 Å (b) and Hα ±0.75 Å (c), as well as of penumbral points for Doppler velocity images in Fe I 5576 ±0.12 Å (d). The spectra were calculated using wavelet analysis in order to achieve higher resolution at low frequencies. In Hα center and Doppler velocities we observe significant power around 5 min, which is related with running penumbral waves. In Fe I 5576 ±0.12 Å

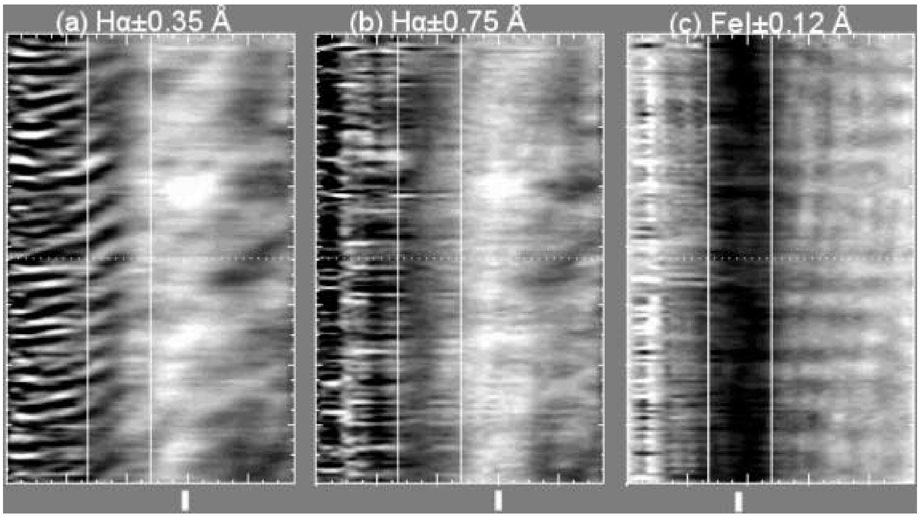

Fig. 4. – Space/time images showing the temporal evolution of the radial component of the velocity as a function of distance from the center of the spot, computed from Doppler velocity images in Hα $\pm$0.35 Å (a), Hα $\pm$0.75 Å (b), and Fe I 5576 $\pm$0.12 Å (c). Each image has a vertical temporal axis and a horizontal spatial axis. Tick marks in the x-axis correspond to 1.3$''$ and tick marks in the y-axis to 140 s. The extend of the photospheric umbra and penumbra is shown by the two vertical lines. The magnitude of the velocity has a maximum above the penumbra in the photosphere and well outside the penumbra in the chromosphere (marked by thick white lines).

Doppler velocities we also observe significant power around 5 min and 3 min as well. We now concentrate our analysis to low frequencies that might be related with the long-term evolution of superpenumbral fibrils and a periodic behavior of the Evershed flow. In the Hα center we see that significant power is concentrated around 16.5 min probably associated with the long-term evolution of superpenumbral fibrils. However a much longer time sequence is required for more definite conclusions; also it is possible the periodicity to be due to another unknown reason related with the observational procedure. In both Hα $\pm$0.35 Å and Hα $\pm$0.75 Å Doppler velocity maps we observe significant power around 11 min. This indicates a long-term temporal behavior of the reverse Evershed effect of the order of 11 min. It further indicates a common behavior of the Evershed effect in the two atmospheric layers defined by the corresponding wavelengths and although as we noticed before the flow velocity appears to be lower in Hα $\pm$0.75 Å. In the photosphere we observe concentration of power at about 16.5 min and also indications of concentration of power at about 33 min. The latter is probably associated to the observational procedure. Higher-frequency resolution and a longer time sequence is required in order to have a more clear picture about a probable periodicity in the photosphere. Nevertheless our results enhance the picture of the periodical nature of the Evershed effect with period of about 15 minutes. However again the oscillating frequency could be related to another cause.

In order to clarify if the oscillations we found are associated with the Evershed flow, we produced space/time images (see [4]) showing the temporal evolution of the radial component of the velocity as a function of distance from the center of the spot, computed

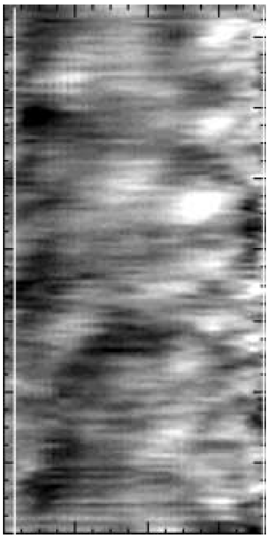

Fig. 5. – "Space/time" image showing the temporal evolution of the line-of-sight Hα ± 0.35 Doppler velocity along the central axis of a superpenumbral fibril. Tick marks in the x-axis correspond to $1.3''$ and tick marks in the y-axis to 140 s.

from Doppler velocity images in Hα ± 0.35 Å (a), Hα ± 0.75 Å (b), and Fe I 5576 ± 0.12 Å (c) (fig. 4). Part of the running penumbral waves is very obvious near the umbra in the "space/time" image computed from Hα ± 0.35 Å Doppler images. This indicates either that the velocity perturbations, associated to the waves, have a significant radial component or that there is an asymmetry in the propagation of the waves. The method for the reconstruction of the velocity vector is less accurate as we approach the center of the spot and the wavelength of running penumbral waves is very short (4–5 Mm). Thus it is difficult to evaluate the above result (and out of the scope of the paper). From fig. 4 it is verified that the radial velocity of the Evershed flow has a maximum above the penumbra in the photosphere and well outside the penumbra in the chromosphere [5]. Our results show variations of the radial velocity of the Evershed flow at the two chromospheric levels with a time scale of the order of 10–15 min. The temporal behavior is similar in both Hα ± 0.35 Å and Hα ± 0.75 Å. However the variations should be characterized as quasi-periodic since they do not seem to have a stable period. Figure 5 presents a "Space/time" image showing the temporal evolution of the line-of-sight Doppler velocity (computed from Hα ± 0.35 Å maps), along the central axis of a superpenumbral fibril; we also observe quasi-periodic variations. This indicates that the variations of the average radial velocity are associated with the variations in individual fibrils or "Evershed channels" and probably depend on the phase coherence of them. We did not find any obvious signature for a repetitive temporal behavior in the radial component of the Evershed flow at the photospheric level except from a signature of the slow photospheric waves [6]. We should note however that the radial velocity, as computed, represents an average and according to Rimmele [1] there is not a significant phase relation linking velocity packets in several adjacent Evershed channels. Further our computations may be influenced by deviations of the sunspot from strict azimuthal symmetry that results in a smoothing of the variation of the radial velocity component. We tried to investigate the temporal behavior of the flow in individual Evershed channels producing "Space/time" images, that show the line-of-sight Doppler velocity along the central axis of the channels. However we could not reach a definite conclusion since the velocity along the channels was influenced by the propagation of the slow photospheric waves described by Georgakilas [6].

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