Bull. Astr. Soc. India (1999) **27**, 383-389

Evershed velocities in bipolar sunspots

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Received 27 September 1998; accepted 16 December 1998

Abstract. Spectra taken at the solar telescope-spectrograph, Kodaikanal, are analysed to find the sight-line velocity values in the regions between the opposite polarity sunspots. Velocities in opposite directions in the range 1 – 2.5 km per second are obtained in the cases of δ - type sunspots (spots having common penumbra), whereas opposite polarity sunspots having separate structures do not show any appreciable velocity in the regions between them. The velocities in the sunspots are restricted to the penumbral boundaries.

Key words. Evershed velocity - bipolar sunspots - flares

1. Introduction

Though Evershed effect has been studied elaborately, many questions concerning the material motion in sunspots are still unresolved. The fact that the Evershed velocities disappear when the spot is close to the disc centre, and steadily grow as the spot approaches the solar limb, suggests that the flows are nearly parallel to the solar surface. All the observations of the Evershed effect show only a horizontal flow pattern with the velocity maximum occurring in regions where the magnetic field is almost horizontal in both the photosphere and chromosphere.

The Evershed effect that is associated with the sunspot is certainly the result of magnetic field organization. The fine structures seen in white light and in Hα pictures have been known for centuries, but the relations of Evershed flow and the magnetic field of the penumbral fine structures are still under constant debate. It is uncertain whether the flow predominantly occurs in the bright or dark lanes and how the magnetic field fluctuations correlate with these structures. The magnetic field of the bright filaments is found to be strongly inclined to the surface, whereas that of the dark filaments is nearly horizontal (Beckers and Schröter 1969, Wiehr et al, 1984) but the magnetic field strengths show very little difference between the dark and bright filaments (Rimmele 1995). Most high resolution observations indicate that the

Evershed flow is confined to dark filaments where the field is nearly horizontal (Bones and Maltby 1978, Beckers 1981, Wiehr et al 1984, Küveler and Wiehr 1985, Title et al, 1993, Degenhardt and Lites 1994). However, the spectroscopic observations of Wiehr and Stellmacher (1989), Lites et al (1990) do not show this correlation.

Another point of interest and controversial discussion is the extension of the Evershed effect beyond the penumbral boundary. Very highly resolved white light pictures of the sunspots show an extremely sharp outer edge where granulation abruptly replaces the penumbral filaments. The fact that radial flow of matter disappears near the sunspot border (Evershed 1910, St. John 1913, Abetti 1932, Maltby 1964, Beckers 1968) gives an impression that the Evershed effect is exclusively a sunspot phenomenon. However, spectroscopic observations yield conflicting results as to whether the Evershed flow is confined to the sunspots alone. Some of the results show the Evershed flow stopping at the penumbral boundary (Brekke and Maltby 1963, Kawakami 1983, Wiehr et al, 1986, Wiehr and Degenhardt 1992) whereas a flow beyond the sunspot penumbra has also been measured (Kinman 1952, Küveler and Wiehr 1985, Börner and Kneer 1992, Solanki et al, 1994). Filtergrams which have better resolution show the flow beyond the penumbral boundary (Dialetis et al, 1985, Alissandrakis et al, 1988, Dere et al, 1990, Muller 1992). However Title et al (1993) find a sudden drop of the Evershed shift at the visible penumbral boundary from filtergrams. Rimmele (1995), from high quality velocity maps, and Ichimoto (1987) show the evidence for foot points and elevated flow channels within the penumbra where the Evershed flow is confined to dark elevated filaments. However, Rimmele's (1994) earlier observations showed Evershed velocities extending beyond the penumbral boundary, but it was not clear how far in the adjoining regions the Evershed arches reach. It is also now known that much of the magnetic flux in the penumbra continues radially outward beyond the penumbral boundary in the form of a magnetic canopy elevated above the surrounding photosphere (Giovanelli and Jones 1982, Solanki et al, 1992) and such sunspot canopies are known to host line of sight velocities up to 2 km per second (Wiehr and Balthasar 1989, Solanki et al. 1994, Westendorp Plaza et al, 1997). These conflicting results on whether the Evershed flow stops at the penumbral border is a hindrance for a better understanding of the correlation that may exist between magnetic and velocity field in sunspots.

Recent observations have provided increasing evidence that the Evershed flow can be traced along individual magnetic channels which end in intense magnetic features of opposite polarity outside the sunspot (Börner and Kneer 1992, Rimmele 1995, Stanchfield et al, 1997, Montesinos and Thomas 1997) or which dive below the visible surface within the penumbra itself (Sundara Raman 1997, Westendorp et al, 1997). The observations of Westendorp et al indeed show both of these configurations where the Evershed flow is connected in patches of opposite magnetic polarity near the outer edge of the sunspot.

Under these circumstances, we have attempted to determine the sight line component of the Evershed velocities in the regions between the opposite polarity sunspots. The δ- type sunspots shows velocities in opposite directions in the regions between the opposite nuclei. It would also be interesting to know the velocity values in the case of bipolar sunspots of leading and following types, as the nearby opposite magnetic structure may influence the flow well outside the penumbral border, but the results do not show any appreciable velocity in the regions between them. Our data once again establishes the identity of the Evershed velocity as a sunspot phenomena as the observed velocities are within the penumbral border.

2. Observation

Spectra of the bipolar sunspots were obtained at the solar tower telescope-spectrograph. A precise determination of the velocity field in sunspots is greatly facilitated if the influence of the Zeeman effect is eliminated. In principle, a symmetrical Zeeman broadened line will not affect the velocity measures. But due to instrumental polarization, a partial suppression of one of the σ - components can occur. Oblique reflections at aluminized mirrors certainly introduces instrumental polarization. To avoid completely the influence of the magnetic field, the line λ 4912 Å Ni I, which is insensitive to the Zeeman effect (g=0), is chosen for velocity measurements. This line is also blend free. The formation level of the spectral line core λ 4912 Å is 300 km in the photosphere above sunspots and for the line wing, the height is 150 km calculated from the contribution function to the line depression (Degenhardt and Wiehr 1994). The spectra were observed in the fifth order where the dispersion at λ 4912 Å is 8.1 mm per Å. We used Kodak 103 aE high resolution astronomical emulsion. The slit width corresponded to 0.55 arcsec and the exposure time was of the order of 2-3 seconds. Spectra were obtained at the best seeing conditions of the order of 1-2 arcsec. The sunspots were located at the heliocentric angles between $\theta = 30°$ to $\theta = 50°$.

It is also important to know precisely the coordinates of the points where the displacements were measured on the spectra. To achieve this, the orientation of the slit and the disc position of the spot were precisely determined. A thin wire of about 0.2 mm thickness was stretched over the slit jaws. This wire casts shadows on the spectrum and serves as the fiduciary marks on the emulsion. The spot spectra was taken after bringing the desired portion of the spot below this wire. A recording of the position of the wire, the slit position and the spot were made immediately on the termination of the exposure. These sunspot maps with the wires, and the slit position marked, were later used during the measurement of the spectra. The coordinates of the points where the velocity measures are made, can be determined by using these sunspot maps and white light photoheliogram taken at Kodaikanal around the time of the spot exposures.

3. Data reduction

The analysis of the spectra were carried out using a positional densitometer system (PDS) with a sampling interval corresponding to 50μ (0.275 arcsec) along the direction of the slit (X-direction). Several microphotometer scans over the spots at intervals of 0.2 mm (1.1 arcsec) parallel to the dispersion (Y-direction) were obtained. For the dispersion of 8.1 mm per Å at λ 4912 Å in the fifth order, the Doppler shift corresponding to one pixel difference is 0.006 Å or a velocity of 377 m s^{-1}. Smoothing of the spectrum is needed as a compromise between resolution and stability and a five point equally weighted average is done for all the scans. On such high dispersion solar spectra of the kind used in this study, it is very difficult to measure precisely the small Doppler displacements. Since the Fraunhofer lines are broad

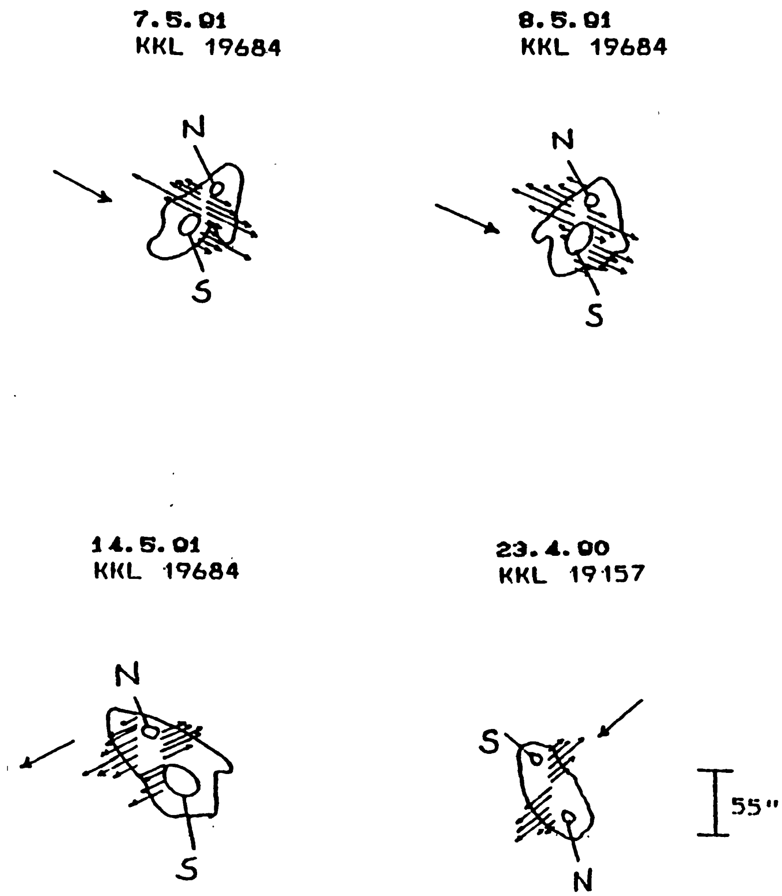

Figure 1. Evershed velocities in bipolar sunspots (δ-type) with the image scale marked. The day of observation and the kodaikanal sunspot number are marked above the sunspots. A single arrow in the region away from the spot shows the direction of the disk centre. The cluster of arrows shown within the spot and also close to it give the sight line velocities.

and diffuse at high despersion, profile fitting is required for measuring small displacements. However, this is not done in the present study. The error bar in the calculation of velocity is one pixel and hence it is not possible from our analyses to obtain any velocity less than 377 m s^{-1}. Also the scattered light contribution from the instruments and other seeing effects are not corrected because we are not going to study any velocity fluctuations. Our idea is to simply find out the quantitative measure of the velocities, if any, in the regions between the bipolar sunspots and so these corrections, which may turn out to be very less, are neglected. The bipolar sunspots that were studied are shown in the Figures 1 and 2 with the image scale marked. The day of observation and the Kodaikanal sunspot number are marked above these spots in the figures. A single arrow in the region away from the spot shows the direction of the disc centre. The cluster of arrows seen within the spot and also close to it show the line of sight velocities. The velocity arrow with minimum length shows the minimum velocity and vice versa. Though the velocities were calculated for various slit positions covering the entire spot region, the figures only show selected regions, such as locations between the bipolar spot configuration. The polarities refer to the umbrae of sunspots and were obtained from the bulletin of Russian Geophysical Data.

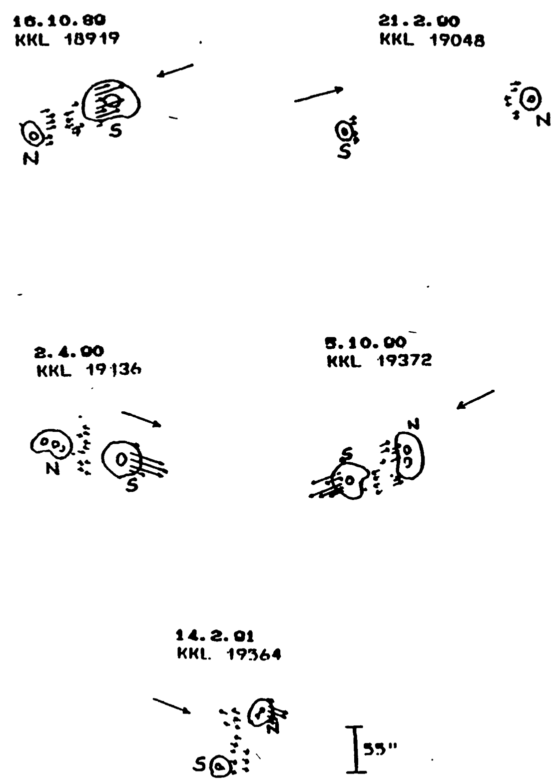

Figure 2. Evershed velocities in bipolar sunspots having separate structures (leading and following types).

4. Results

Our results show velocities of 1 to 2.5 km per second in opposite directions in the regions between opposite polarities umbrae of sunspots with common penumbra (Figure 1.), thus once again confirming the Evershed flow falling back into the sunspot itself. However, in the other category of bipolar sunspots (Figure 2.), we are not able to find any appreciable velocity in the regions between the opposite polarities. The bipolar sunspot KKL 19048 which appeared on 21 February, 1990 during its passage on the third successive solar rotation is separated by a huge margin and here also we are not able to find any velocities in most of the regions between the two polarities (Figure 2.). The material velocities are generally restricted to the penumbral boundary attaining the maximum value near the centre of the penumbra and in general the photospheric non-spot regions do not show any appreciable velocity. Some regions of the penumbra do not show any velocity and these locations may be corresponding to the fine structures in the penumbra. Since the best seeing was 1-2 arcsec, it is not possible to have the direct view of the penumbral fine structure which have sizes less than 0.5 arcsec. It shows that the resolution needed for correlating the material flow with the fine structures of the penumbra is still out of our reach, though it is not impossible. The controversy over the location of magnetic field and Evershed effect within the penumbral structures may be due to the effects of instrumental errors.

Acknowledgements

We are grateful to Prof. K. R. Sivaraman for suggesting this topic. One of us (KSR) is thankful to Dr. R. Kariappa and Dr. K. B. Ramesh for useful suggestions and help while digitizing the data. We thankfully acknowledge the help rendered at the telescope by Mr. P. Devendran and Mr. G. Hariharan. Our sincere thanks are to the unknown referee whose valuable comments improved the presentation of the paper.

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