The Spatial Structure of the Evershed Effect

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ABSTRACT

Aims. The spatial disappearance of the line asymmetry from the Evershed effect near the boundary of the white-light penumbra is investigated.

Methods. The neighboring lines Ni I 5435.9 (g=0.5) and Fe I 5434.5 (g=0; formed about 300 km higher) are observed in a sunspot penumbra at \( \vartheta = 65^\circ \).

Results. Immediately beyond the ends of the dark penumbral continuum structures, both lines simultaneously lose their asymmetry. The spatial distance of their disappearance of maximally 500 km is too short for a ‘disappearance with height’ as is suggested by models of a penumbral ‘canopy’. Instead, the data favor a rather flat orientation of the Evershed flow with an abrupt disappearance. It is suggested that this location marks the sharp threshold of the equipartition between kinetic and magnetic energy density at the outer penumbral border.

Key words. Sun - Sunspot Penumbra - Evershed effect - Line asymmetry - Fine-structure - 'Canopy'

1. Introduction

The characteristic signature of the Evershed effect is a line profile asymmetry which often occurs as a pronounced line ‘kink’ (Maltby 1964) and can not be explained by a velocity gradient with depth (Stellmacher & Wiehr 1980). Instead, one has to consider that the observed line profiles represent superpositions of spatially unresolved penumbral structures: a stronger ‘main component’ originating from the bright structures superposed by a Doppler-shifted and weaker line ‘satellite’ from the dark structures (Stellmacher & Wiehr 1971). This is supported by the finding that pronounced line ‘kinks’ only occur if the (dark) penumbral structures are oriented almost along the line-of-sight, i.e. in center-side penumbrae of spots very close to the limb (Wiehr 1995).

Observed differences between the Evershed effect in center- and limb-side penumbrae suggest angles of inclination to the solar surface between 6° (Maltby 1964) and 15° (Schröter 1965). Such flat structures cannot gradually ‘disappear with height’ as is to be expected for a penumbral ‘canopy’ (cf. Solanki et al. 1992). In that picture the profile asymmetry of FeI5434Å (formed about 500 km above the continuum level), should ‘disappear’ over a horizontal distance of several arcsec beyond the white-light penumbral border. This, however, disagrees with the results of Wiehr & Degenhardt (1992,1994).

On the other hand, the chromospheric Hα superpenumbra extends far beyond the edge of the continuum penumbra. But the opposite sign of the chromospheric Evershed effect (e.g. Maltby 1975) indicates that it cannot represent a continuation of the photospheric Evershed effect at higher levels. Hence, a possible extension of structures, flow, and magnetic field beyond the white-light penumbra needs further study. The present paper investigates an upper limit for the abrupt disappearance and its physical reason.

2. Observations

On October 22, 1994, the neighboring lines FeI5434.5 (g=0) and NiI5435.9 (g=0.5) were observed with the Gregory telescope on Tenerife (Wiehr 1986) in a sunspot at a heliocentric angle of \( \vartheta = 65^\circ \) with a 1024 x 1024 pixel CCD at an exposure time of 0.1 seconds. In order to avoid the use of an image rotator, the time of observation was chosen such that the Coudé rotation of the solar image yields an almost parallel orientation of the slit to the limb nearest the spot. During the two hours of observation the image rotation increased the angle between slit and limb from \(-15^\circ\) to \(+15^\circ\) with respect to the exactly parallel orientation.

An accurate pointing of the 40 µm slit at very small distances from the outer penumbral edge (e.g. \( \Delta < 0.5\) arcsec) is difficult, since the slit occurs as a 1/3 arcsec wide dark streak on the slit-jaw image just at the location under study. However, if the telescope’s guiding automat is switched off, a slow image drift of about 0.5 arcsec/min occurs, which affects a kind of automatic scanning if a large number of CCD-spectra is taken at a short time cadence. This yields spectra at a variety of slit distances including such of few 100 km inside or outside the penumbral edge. Since the image rotation slowly varies the slit orientation on the sun, a repetition of such a series of ‘drifted spectra’ gives slit orientations of different azimuth angles with the spot border, thus covering large parts of the limb- and of the center-side penumbral boundaries. In the best spectra, a spatial resolution near 0.5 arcsec is achieved. Two examples are shown in figure 1.
Fig. 1. CCD spectra of Fe I 5434.5 (left) and Ni I 5435.9 (right) a) immediately inside the center-side, (b) just outside the limb-side penumbral border; the spatial extension of each spectrum covers 50 arcsec. The black dot marks a profile asymmetry not related to the Evershed effect.

3. Results

The numerous spectra obtained from slit positions in the immediate vicinity of the penumbral border confirm (e.g. Wiehr & Degenhardt 1994) that line asymmetries occur exclusively at locations of pronounced continuum depressions produced by dark penumbral structures (solid line in Fig. 2a). In the neighboring bright structures, both line profiles are symmetric (dotted lines in Fig. 2). Immediately outside the penumbra, where the slit just ‘missed’ the outer ends of the dark structures, the line profile asymmetries disappear simultaneously for both lines.

The spatial distance between adjacent positions of the slit is partly determined by slow image drift and mainly by the image motion. The latter can be expected to be slightly smaller than the 0.5 arcsec spatial resolution in the spectra, which are additionally degraded by the spectrograph optics. Assuming a spatial distance of the order of the slit width of 1/3 arcsec and correcting this value for the geometric foreshortening at \( \theta = 65^\circ \), one obtains a horizontal distance of maximally 500 km over which the line profile asymmetries disappear simultaneously for the two lines, which formed at a vertical distance of about 300 km.

Among the numerous spectra showing a strictly simultaneous disappearance of the asymmetry of both lines, only one location is found (dot in Fig. 1b) which exhibits a line asymmetry of Fe I 5434 but not of Ni I 5435 (see Fig. 2b). However, this structure shows no continuum depression and is thus not a dark penumbral filament. It is located between a bright continuum streak from a facula and another streak with opposite line asymmetry (cf. Fig. 1b) thus indicating a disturbed region at the penumbral border (possibly an Ellerman bomb).

Fig. 2. Fe I 5434.5 and Ni I 5435.9 with profile asymmetry at a location of a continuum depression produced by the end of a dark penumbral structure (solid line in the upper panel) in comparison with a location immediately outside the penumbra (dotted line). Lower panel: profile asymmetry only for Fe I 5434.5 and not related with a continuum depression (solid line), originating from a high velocity region (dot in Fig. 1b) outside the spot.

4. Discussion

The simultaneous disappearance of the profile asymmetry of both lines together with the continuum depressions supports the idea that the profile asymmetries are due to superposed line satellites from spatially unresolved dark penumbral structures (Wiehr 1995). These line ‘satellites’ disappear in photospheric layers together with the dark structures where they are formed. If a ‘canopy’ existed, one
would expect the asymmetry of FeI 5434, (a line formed near the temperature minimum; see e.g. Degenhardt & Wiehr 1994)) to disappear further away from the penumbral continuum border than that of NiI 5436 (formed about 300 km higher). In the 'canopy' scenario, the simultaneous disappearance over a horizontal distance of less than 500 km would require a steep inclination of the flow (and thus of the magnetic field) of at least 60°, which severely conflicts with the values observed by Maltby (1964) and by Schröter (1965).

The present observations, however, strongly suggest a nearly horizontal orientation of the Evershed flow (and thus also of the magnetic field in the dark penumbral structures) with an abrupt disappearance at the very border of the white-light penumbra. A plausible explanation for such a sharp end is the equipartition between the magnetic and kinetic energy densities: For a photospheric density value of \( \rho = 5 \times 10^{-7} \) g/cm\(^2\), a granular velocity of 3 km/s balances 740 Gs, which is close to values observed at the penumbral edge. If the magnetic field varies radially with \( B \sim r^{-2} \) (cf. Wittmann 1974), the magnetic energy density \( B^2/8\pi \) decreases with \( r^{-4} \). This results in a sharp threshold for an equipartition with the kinetic energy density of the neighboring granules. Flow and field will then (vertically) sink at the very penumbral border. [Such a 'disappearance' of the flow may conflict with the siphon model (Meyer & Schmidt 1968) but hardly with the idea of 'turbulent pumping' (Parker 1974).]

A 'canopy' formed by such an extension of the bright penumbral structures does not contradict Rüedi et al. (1995) who deduced significantly steeper inclinations from the HeI line at 10830Å than expected from a neighboring SiI line. The latter, however, is formed in deep layers which are dominated by flat dark structures. The helium line, instead, originates from high layers, which are dominated by the steep bright structures.

**References**

Beckers I.M., Schröter E.H., 1969, Solar Phys. 10, 384
Börner P., Kneer E., 1992, A&A 255, 307
Degenhardt D., Wiehr E., 1991, A&A 252, 821
Degenhardt D., Wiehe E., 1994, A&A 287, 620
Maltby P., 1964, Astron. Norweg. 8, 205
Maltby P., 1975, Solar Phys. 43, 91
Meyer E., Schmidt H.U., 1968, Z. angew. Mathematik & Mchanik 48, 218
Parker E.N., 1974, ApJ 189, 563
Rimmele T., 1994, A&A 290, 972
Rüedi I., Keller C.U., Solanki S.K., 1995, Sol. Phys. 164, 265
Schmidt W., Hofmann A., Balthasar H., Tarbell T.D., Frank Z.A., 1992, A&A 264, L-27
Schöter E.H., 1965, Z. Astrophys. 62, 228
Solanki S.K., Rüedi I., Livingston W., 1992, A&A 263, 339
Solanki S.K., Montavon C.A.P., Livingston W., 1994, A&A 283, 221
Stellmacher G., Wiehr E., 1971, Solar Phys. 17, 21
Stellmacher G., Wiehr E., 1980, A&A 82, 157
Wiehr E., Stellmacher G., Knöker M., Grosser H., 1986, A&A 155, 402
Wiehr E., Degenhardt D., 1992, A&A 259, 313
Wiehr E., Degenhardt D., 1994, A&A 287, 625
Wiehe E., 1986, in 'The role of fine-scale magnetic fields on the structure of the solar photosphere', E.H. Schröter, M. Vazquez, A.A. Wyller (eds.), Cambridge, p. 162
Wiehr E., 1995, A&A 298, L-17
Wittmann A., 1974, Solar Phys. 36, 29

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