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LETTER

Letter to the Editor

Infrared lines as probes of solar magnetic features

XV. Evershed flow in cool, weak penumbral fields

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Abstract. Observations of Ti I lines at 2.2 μm show that the Evershed flow takes place in cool, almost horizontal channels with a low magnetic field strength ($\approx$ 500–900 G) that does not appear to change significantly across the penumbra. This property might allow an outward directed siphon flow to exist along such cool flux tubes.

Key words: Sun: activity – Sun: infrared – Sun: magnetic fields – Sun: photosphere – Sun: sunspots

1. Introduction

The Evershed effect seen in sunspot penumbrae is characterized by spectral line shifts whose sign is compatible with a material outflow. The magnitude of these shifts, obtained using visible lines, range between 1–2 km s^{-1} at low spatial resolution and 6 km s^{-1} at high spatial resolution. The flow seems to be concentrated in the dark penumbral filaments. For more information on the Evershed effect we refer to the reviews by Thomas (1994), Martínez Pillet (1997) and Solanki (1997).

The Evershed effect is usually explained by means of the siphon flow mechanism which was originally proposed by Meyer and Schmidt (1968). In their model the gas pressure difference between the two footpoints of the loop is due to the difference in field strength between these footpoints (the flow is directed from the footpoint with weaker field to that with stronger field). Originally it was thought that the flow starts inside the penumbra and ends in strong-field flux-tubes outside the sunspot. Recently, however, Westendorp Plaza et al. (1997) presented new observations which indicate that *most* of the flow returns into the solar interior in the penumbra, in agreement with the mass-balance arguments of Solanki et al. (1994, 1999). These observations, coupled with the fact that the field strength decreases from the inner penumbra to the outer boundary of the sunspot, place severe constraints on a possible siphon flow of the type proposed by Meyer & Schmidt (1968). Thus, although Thomas & Montesinos (1993) and Montesinos & Thomas (1997) could reproduce certain features of the observations with flows starting and ending in the penumbra or ending in the field-free surrounding, they had to assume that the background penumbral field is independent of the radial distance from the sunspot centre. They analysed the case of a magnetic flux tube embedded in a magnetic environment (corresponding more closely to penumbral conditions).

In this paper we address this problem on the basis of observations at 1.56 μm and 2.2 μm (Rüedi et al. 1998). We also discuss the implications of these observations for the model proposed by Schlichenmaier et al. (1998) in which the flow is accelerated locally in the penumbra through the interchange instability and does not require strong magnetic field concentrations at the downstream footpoints to accelerate it.

2. Observational results

2.1. The observations

The observations on which we base our analysis have been described in detail by Rüedi et al. (1998). Here, we recall only their most important characteristics.

The slit was placed in the heliocentric E-W direction through the center of a sunspot located on the limbward side of active region NOAA 7958 on April 21 1996 ($\mu = \cos\theta = 0.43$). The full Stokes vectors of the extremely magnetically sensitive Ti I lines at 2.2310 μm ($g = 2.5$) and 2.2211 μm ($g_{\rm eff} = 2.0$) were observed using the NIM (Near Infrared Magnetograph, Rabin 1994). These lines are also very temperature sensitive and are present only in cool regions such as sunspot umbrae (Hall 1974, Rüedi et al. 1995). Similar observations of this sunspot were obtained a few hours earlier in the Fe I 1.5648 and 1.5652 μm lines using the same apparatus and at approximately the same slit location.

Fig. 1 shows the most important parameters obtained from the analysis of the Ti I observations (carried out using an improved version of the inversion code of Solanki et al. 1992):

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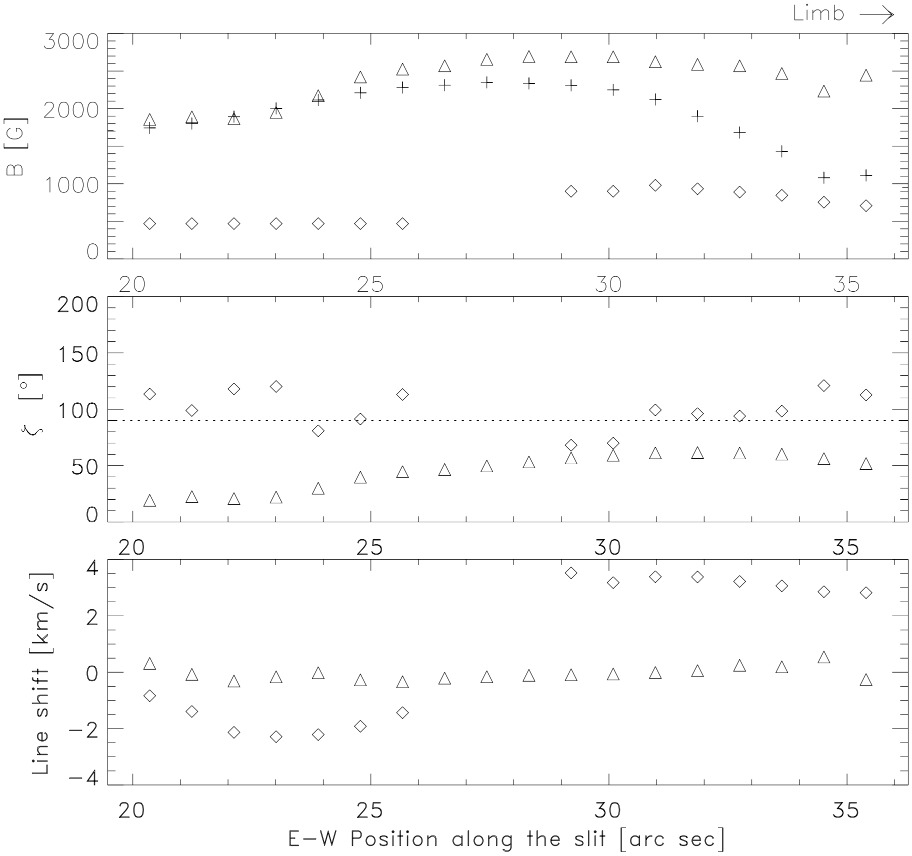

Fig. 1. Parameters obtained from the inversion of NIM spectra. The spectrograph slit, oriented in the heliocentric E-W direction, runs through the centre of the umbra. The x-axis gives the projected position along the slit. The triangles and diamonds respectively represent the strong and weak magnetic field component observed in the Ti I line at 2.2 μm. The "+"-signs represent the values obtained from the Fe I lines at 1.56 μm. *Top:* the magnetic field strength, B, *Middle:* the inclination angle to the solar surface normal, ζ (zenith angle), *Bottom:* the Doppler shift along the line of sight. The zero velocity level was set by requiring that the more vertical umbral field component is unshifted. More details on the Ti I observations are given by Rüedi et al. (1998).

the magnetic field strength, B, the inclination angle of the magnetic vector to the vertical, ζ, and the Doppler velocity. In most cases two magnetic components, with very different characteristics were necessary to satisfactorily reproduce the Ti I-line profiles. The triangles represent the component with larger magnetic field strength, which is fairly vertical and shows no significant Doppler shift, while the diamonds represent the weaker field component, which is closer to the horizontal and shows a strong signature of the Evershed effect, even at the moderate spatial resolution of these observations of about $3''$. Each of the two distinct cool magnetic components shows surprisingly homogeneous parameter values (a cut through the same sunspot in the perpendicular direction gave similar results, Rüedi et al. 1998). Due to the weakness of the signals produced by the magnetic component with low field strength, we can only trust it to be horizontal to within roughly 20°. The parameters of the strong magnetic component are more accurate.

2.2. Comparison with other observations

Visible lines, as well as the Fe I lines at 1.56 μm, invariably gives a much smoother picture of the magnetic structure of sunspots at similar spatial resolution: a continuous decrease of the field strength from the sunspot centre towards its boundary, with no sudden jumps in the field strength and inclination angle. Also, they do not suggest the presence of 2 distinct magnetic components within the sunspot.

Observations carried out earlier in the day in the same sunspot, with the Fe I lines at 1.56 μm confirm this standard picture (as shown by the "+"-signs in Fig. 1). Hence the strange behaviour exhibited by the Ti I lines is not due to a peculiarity of this sunspot or problems with the observations. We show here that it is rather due to the unique combination of the strong sensitivity of the Ti I lines to cool features and their large Zeeman sensitivity.

A low field strength and a low temperature are both drawbacks to unambiguously detecting an *unresolved* magnetic component using standard visible lines, and even using the Fe I lines at 1.56 μm. Let us illustrate this by assuming that the penumbra is composed of 2 magnetic components whose properties are taken to be compatible with those derived from the Ti I lines: a hotter plasma with strong magnetic field which is fairly vertical and a cooler component with almost horizontal, weak magnetic field. Each component covers half of the resolution element. They have the following parameters: $T_{\rm eff}(1) = 5250\,$K, $B(1) =$ 1800 G, $\zeta(1) = 30^\circ$ and $T_{\rm eff}(2) = 4250$ K, $B(2) = 700$ G, $\zeta(2) = 75^\circ$. The Stokes V profiles due to each component are plotted in Fig. 2 for the Ti I 2.2310 μm and Fe I 1.5648 μm lines (dotted (1) and dashed (2) lines). They have been broadened by a macroturbulent velocity of 2 km s^{-1}. The solid lines denote the composite profiles.

The Ti I 2.2310 μm line unambiguously shows the presence of 2 components, with the cool low-field-strength component dominating the profile shape. In contrast, the Fe I 1.5648 μm

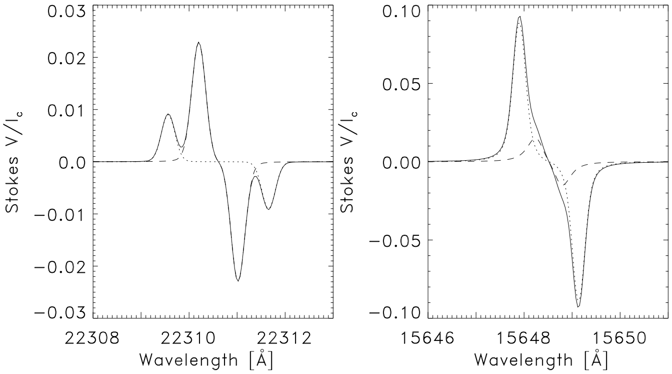

Fig. 2. Composite Stokes V profiles (solid lines) of the Ti I 2.2310 μm and Fe I 1.5648 μm lines resulting in the presence of two components (dotted and dashed lines), each covering half of the resolution element and having the parameters given in the text.

line profile is only slightly affected by this component. Lines in the visible are found to behave in a manner similar to the 1.56 μm lines. Consequently, in order to be detected using visible lines or the 1.56 μm lines, a sufficiently cool, weak-field component needs to cover *most* of the resolution element. These calculations demonstrate that the anomalous results obtained with the Ti I lines are compatible with the Fe I 1.56 μm lines and with earlier observations.

It is widely accepted that the Evershed effect is concentrated into dark channels of almost horizontal field (e.g. Title et al. 1992, Hofmann et al. 1994). Our Ti I observations show that these channels are indeed cool and that the field-strength in these channels is very low and nearly constant throughout the sunspot penumbra, at least wherever the gas is sufficiently cool to harbour a significant amount of neutral Ti. This suggests that sunspots harbour two quite distinct cool components, with an additional hotter component in the penumbra (revealed by the 1.56 μm lines) having stronger and more vertical magnetic field than the cool penumbral component. Since the spatial resolution of our observations was limited by the moderate seeing conditions, we cannot rule out that the cool horizontal fields seen in Ti I are restricted to the outer penumbra. For the same reason we cannot decide if the more vertical cool component is restricted to the umbra or also extends into the penumbra (cf. Lites et al. 1993).

3. Standard siphon flow models

In traditional siphon flow models, such as that of Montesinos & Thomas (1997), the magnetic field strength of the inner footpoint is slightly lower than that of the outer footpoint at equal gravitational potential. However, all observations, with the exception of the 2.2 μm Ti I lines, show that B decreases steadily outwards in a sunspot, which is incompatible with the requirements of the standard siphon flow model if both legs of the loop lie within the penumbra (as is suggested by the observations of Westendorp Plaza et al. 1997). It is usually argued that the different heights of formation of the spectral line at both footpoints may lead to a match with the observations. For this explanation to work the background field strength at a given geometrical height would have to be roughly constant in the penumbra (as is indeed assumed by Montesinos & Thomas 1997). This can be tested by considering, e.g., the model of Jahn (1989) or of Jahn & Schmidt (1994). These models reproduce a number of observations, including the radial dependence of B and ζ, as well as the distribution of the continuum intensity, which is very sensitive to the magnetic field structure (Pizzo 1986). In these models the magnetic field strength at a given geometrical height definitely decreases outward. This suggests that the problem associated with siphon flows is not solved just by invoking a different height of formation of spectral lines in different parts of the penumbra.

The 2.2 μm Ti I observations reveal a nearly constant field strength along the cool horizontal component of the field harbouring (at least a part of) the Evershed flow. This is consistent with siphon-flow models, since our observations are not accurate enough to detect the small horizontal gradients of the field strength required by such models. Hence the Ti I lines resolve the problem posed by the observations of Westendorp Plaza et al. (1997). The height-of-formation explanation, whose adequacy has never been demonstrated for a realistic background penumbral field, need no longer be invoked in the light of our observations.

These may also help to solve another problem faced by siphon flow models. Degenhardt (1991) mentions that his model photospheric loops are normally too short to reproduce penumbral filaments. However he points out that longer filaments are obtained when reducing the magnetic field strength of the arch to approximately 400 G in the upstream penumbral footpoint (for a flux-tube embedded in a field-free atmosphere). Such a low field strength is plausible in view of the weak horizontal magnetic component we observe. According to Thomas & Montesinos (1993) the addition of a surrounding magnetic field also produces an increase of the length of the filaments.

Our observations lead us to propose that siphon-flow calculations be carried out along loops with field strengths in both footpoints of around 500 G. They should be embedded in a background magnetic field which corresponds roughly to the model of Jahn (1989).

4. Evershed flow in interchange flux tubes

In the model of Schlichenmaier et al. (1998) the gas flows along horizontal flux tubes which owe their inclination and position to the interchange instability. The flow is not driven by the magnetic gradient between the footpoints of these arched flux tubes and consequently does not constrain the field strength of the downflowing footpoint. Rather, the process appears to be more akin to convection, with the field lines acting as a guiding funnel.

In the upflowing footpoint of their model, the flux tube has a lower field strength than the surroundings, but is hotter. Further out in the penumbra, the horizontal tube cools to the surrounding temperature and its field strength and velocity shift increase.

A major discrepancy between this model and our observations arises from the fact that it does not predict that cooler gas has lower magnetic field strength. The model can be reconciled with the observations if the low-field strength component seen in Ti I is only restricted to near the outer penumbral edge, where the field of the ambient hotter medium has become weaker. As pointed out in Sect. 3, due to the seeing our observations are indeed compatible with a confinement of the cool horizontal field component to the outer part of the penumbra. The fact that the outflowing gas near the upflow footpoint is hot in this model does not necessarily contradict the observations, since, firstly, lines formed at higher temperatures than the infrared Ti I lines also show the Evershed effect, although less strongly. Secondly, the larger opacity of the hot gas at the upflow footpoint raises the height of formation of continuum and line radiation, so that the spectral lines sample less of the hot, flowing gas.

5. Discussion and conclusions

Westendorp Plaza et al. (1997) claim that *most* of the Evershed flow already returns to the solar interior inside the penumbra. This could explain the sudden disappearance of the Evershed flow at the penumbral boundary reported by many observers. However, it means that the field strength of the upstream footpoint is larger than that of the downstream footpoint, which conflicts with the requirements for a siphon flow. Our data defuse this problem since they show that the cool outflowing gas in the penumbra has the same (low) field strength everywhere. A model of the type proposed by Schlichenmaier et al. (1998) also appears to be compatible with our observations, however.

Our observations suggest that the penumbra is composed of at least two different kinds of flux-tubes: those of one type are cool, almost horizontal and possess a low field strength while the others are hotter and can have a larger range of inclination and field strength. The temperature sensitivity of the Ti I lines enables us to see the cool structures, unaffected by averaging over different spatial structures such as dark and bright filaments or poor seeing. Due to its low magnetic field strength and low temperature this component is difficult to isolate using visible observations.

There remains the problem of force balance between the two components, in particular for the traditional siphon flow models. It could be achieved if the cool gas is denser than the warmer gas, particularly in the inner penumbra. Recall that the plasma β is above unity in the lower photosphere of sunspots (Solanki et al. 1993), so that the density can indeed play a decisive role.

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