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Letter to the Editor

Infrared lines as probes of solar magnetic features

IV. Discovery of a siphon flow

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Abstract. Spectra of two neighbouring infrared lines, Fe I 15648.5 Å ($g = 3$) and Fe I 15652.9 Å ($g_{\rm eff} = 1.53$) are analysed. The spectra were obtained with an infrared array detector in active region plages with the entrance slit of the spectrograph placed across the polarity-inversion (neutral) line. Near the neutral line the positive polarity field is weaker ($B(z = 0) \approx$ 1200 G) and shows an upflow of up to 2 km s^{-1}, while the negative polarity field is stronger ($B(z = 0) \approx 1500$ G) and exhibits a downflow of up to 1 km s^{-1}. This configuration corresponds to the expected signature of a siphon flow along a loop connecting flux tubes across the neutral line.

Key words: Solar magnetic fields – Solar active regions – Flux tubes – Siphon flows – Infrared polarimetry

1. Introduction

The physical description of siphon flows in loop-shaped solar magnetic flux tubes has been well studied (e.g. Meyer & Schmidt 1968, Cargill & Priest 1980, 1982, Thomas 1988, Montesinos & Thomas 1989, Thomas & Montesinos 1990, 1991 and Degenhardt 1989, 1991), but their observational confirmation has so far remained elusive. It has been suggested that the Evershed effect seen in sunspots is due to a siphon flow (e.g. Meyer & Schmidt 1968, Spruit 1981). However, the absence of systematic flows in small-scale magnetic features located in solar plages, which must form the other photospheric footpoint of the loop containing the flow, casts some doubt on this idea (cf. Solanki et al. 1992b, Paper V). In the present paper we discuss measurements – magnetic field and line-of-sight velocity in a plage area – that are most naturally interpreted as a siphon flow between regions of stronger and weaker magnetic field.

The present paper extends the current series of paper on infrared lines and magnetic fields in a natural manner. Paper I (Muglach & Solanki 1992) presents a many-line analysis of a Fourier transform spectrometer (FTS) Stokes I and V spectrum of a solar network region, Paper II (Solanki et al. 1992a) explores in detail the diagnostic potential of the Fe I 15648.5 Å and Fe I 15652.9 Å lines and Paper III (Rüedi et al. 1992) applies the diagnostics developed in Paper II to observations of these two lines in solar plages. The new feature of the observations analyzed here — spatial extension afforded by the use of an infrared array detector — is essential for detecting a siphon flow.

2. Observations and modelling techniques

The observations were obtained in active region NOAA 5900 on 27 January with the 0.8 m east auxiliary of the McMath telescope, the 13.7 m vertical grating spectrograph and a 58 × 62 pixel InSb array which operates in the 1–5 μm range. The active region was located very close to the centre of the solar disk ($\mu = \cos\theta = 0.998$). The slit was oriented approximately E-W and crossed the polarity-inversion or neutral line. Stokes $I \pm V$ spectra of Fe I 15648.5 Å, a pure Zeeman triplet with a Landé factor $g = 3$, and Fe I 15652.9 Å, with an effective Landé factor $g_{\rm eff}$=1.53, were obtained, from which Stokes V (net circular polarization) was extracted. Stokes I (intensity) is sacrificed in order to interface the slow infrared array with the relatively fast polarisation modulation (30 Hz). This is not a crucial sacrifice, since Stokes V contains information on the magnetic features in purer form than Stokes I. The angular and spectral scales per pixel were 0.85″ and 0.176Å. More information on the data and their reduction is given by Rabin (1991).

Because the actual spatial resolution, as dictated by seeing at the time of the observations, was approximately 2″–3″, we have co-added 3 consecutive spectra to improve the S/N ratio. This produces 21 spatially independent spectra. The spectral resolving power is estimated to be 45000. This low spectral resolution, dictated by the small format of the array, reduces the sensitivity of the measured Stokes V profiles to the magnetic field strength (see Fig. 8 of Paper III). The absence of Stokes I rules out the determination of Stokes V shifts relative to Stokes I. On the other hand, the array spectra provide at least limited spatial information. This allows us to recognise spatially localized shifts of the V profiles by comparing their wavelengths with those of simultaneously measured profiles at

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other spatial positions. As we shall see this capability is crucial for the identification of a siphon flow. Also, all the points in the present data set are measured simultaneously. Thus we remove one of the main uncertainties haunting the data analysed in Paper III. The anomalous shape of some of the V profiles in the present data (see Fig. 1a) confirms the reality of such profiles in data obtained with a single detector, which were analysed in detail in Paper III.

The 21 averaged Stokes V spectra in the analysed frame are plotted in Fig. 1a. They have been vertically shifted for clarity. Spectra are numbered at the left of the frame. Each spectrum is offset by 2.55″ on the solar surface with respect to its neighbour. The data analysis and modelling are very similar to that in Paper III (cf. Paper II). The V profiles of both lines are numerically calculated in a thin–tube magnetic model along multiple rays (so–called 1.5–D radiative transfer). Before comparison with the observed spectra, the synthetic V profiles are spatially averaged to the angular resolution of the observations and spectrally convolved with a Gaussian profile having a Doppler width of approximately 6 km s^{-1} to account for both instrumental smearing and macroturbulent velocity (e.g. Papers I and III). All magnetic components of the atmosphere are described by the OS2 model (Obridko & Staude 1986), the non–magnetic part by the HSRASP (Gingerich et al. 1971, but see also Paper II). For the magnetic component(s) this choice gives the best fit to the amplitude ratios of the two, relatively temperature insensitive, lines. The derived field strengths and flow velocities are relatively insensitive to the choice of model (Paper II).

3. Results

The location of the neutral line close to the position of profile No. 8 in Fig. 1a, coupled with the limited spatial resolution of the observations, leads to the anomalously shaped Stokes V profiles in spectra No. 6–10. The anomaly is most pronounced in the $g = 3$ line (15648 Å), while the $g_{\rm eff} = 1.53$ line almost disappears near the inversion line.

The fits of the synthetic to the observed V profiles of both lines yield the field strengths B at the height $z = 0$ (corresponding to $\tau_{5000} = 1$ in the quiet sun) and velocity shifts shown in Figs 1b and 1c, respectively. The $B(z = 0)$ and velocity values derived for each spectrum are plotted at the same level as the zero–level of that spectrum in Fig. 1a. Due to the low spectral resolution the field strength is only reliable to within 50–100 G and the synthetic profiles used for the fit have only been calculated in steps of 50 G. Positive polarity fields are plotted dashed in Fig. 1b; negative polarity fields are plotted solid. Positive velocities in Fig. 1c are directed away from the observer, i.e. mainly downwards in the solar atmosphere (only the line–of–sight velocity component is measured). The origin of the velocity scale is determined by requiring that the velocity must disappear far from the neutral line, in accordance with older Stokes observations (e.g. Stenflo & Harvey 1985, Solanki 1986, Paper I) and with other infrared spectra obtained away from the neutral line in the active region under investigation (cf. Rabin 1991). The latter show no significant shift of one V profile relative to another.

A good fit to most of the spectra is obtained employing only one magnetic flux–tube component. However, near the neutral line two flux–tube components are necessary to reproduce individual observed profiles. The profiles composed of two magnetic components (Nos. 6–10) are plotted again in Fig. 2. Figure 2a shows the observed (solid) and synthetic (dashed) Stokes V profiles of the $g = 3$ line, while Fig. 2b exhibits the synthetic V profiles of the individual magnetic components. Note how subtle differences in the fractional contribution to the flux by the two polarities (which have different field strengths) and in their relative wavelength shift can substantially change the form of the composite profile (see also Skumanich & Lites 1991). The compound profiles can only be reproduced if the profiles of the individual magnetic components are shifted relative to each other. We have also examined the original, unaveraged spectra in the vicinity of the neutral line. They are somewhat noisier but lead to the same conclusion.

Comparing Fig. 1b with Fig. 1c we see the following behaviour near the neutral line: the weaker-field (negative polarity) component exhibits an apparent upflow, while the stronger-field (positive polarity) component shows a downflow. Before interpreting these as material flows, however, we must consider the effects of instrumental Stokes crosstalk.

The area of the positive lobe of Stokes V is larger than the area of the negative lobe, for most of the measured profiles of the $g = 3$ line, as can be seen by comparing the synthetic (with equal positive and negative areas) to the observed profiles in Fig. 2a. In contrast to the usual blue–red asymmetry of Stokes V profiles in solar plages (Stenflo et al. 1984, Solanki & Stenflo 1984, 1985, Paper I), the effect seen here changes with the polarity of the field. Also, the observed $g = 3$ line is more asymmetric than the $g_{\rm eff} = 1.53$ line, which is contrary to the expectations of an asymmetry produced by velocity gradients (Grossman–Doerth et al. 1989, Paper I).[1] Both these findings are suggestive of instrumental cross–talk from Stokes Q or U into V; the asymmetry produced by the cross–talk is expected to be bigger for the $g = 3$ line, since its Q and U amplitudes are bigger (Paper II). To test this hypothesis we have calculated the Mueller–matrix M of the telescope for the setup and time of the observations, assuming freshly coated mirrors. We find

$$\mathrm{M} = \begin{pmatrix} 0.789 & -0.036 & 0.011 & 0.001 \\ -0.036 & 0.786 & -0.013 & 0.072 \\ -0.012 & 0.009 & -0.756 & -0.225 \\ -0.001 & 0.073 & 0.225 & -0.752 \end{pmatrix} .$$

Noteworthy is the large $U \rightarrow V$ term of 0.225.[2]

The asymmetry of the V profile of the $g = 3$ line is observed to increase towards the neutral line, which implies an increase in Stokes Q and U towards the neutral line. This is consistent with the picture that the two polarities are connected by a series of loops, whose field lines in the photosphere become more inclined in the direction of the neutral line as the footpoints approach each other. The cross–talk also induces a wavelength shift in the V profiles (Soltau, private communication). Since the cross–talk is larger in the $g = 3$ line, its

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[1] Due to its smaller observed asymmetry the $g_{\rm eff} = 1.53$ line is generally much better reproduced by the calculations.

[2] The two extra mirrors necessary to feed the vertical spectrograph from the east auxiliary telescope increase the Stokes crosstalk relative to the main McMath telescope, for which, under the same conditions, the largest off-diagonal term ($U \rightarrow V$) would be 0.084 (cf. Harvey 1985). This may explain why little sign of a cross-talk was found in the data analysed in Paper III.

1992A&A...261L..21R

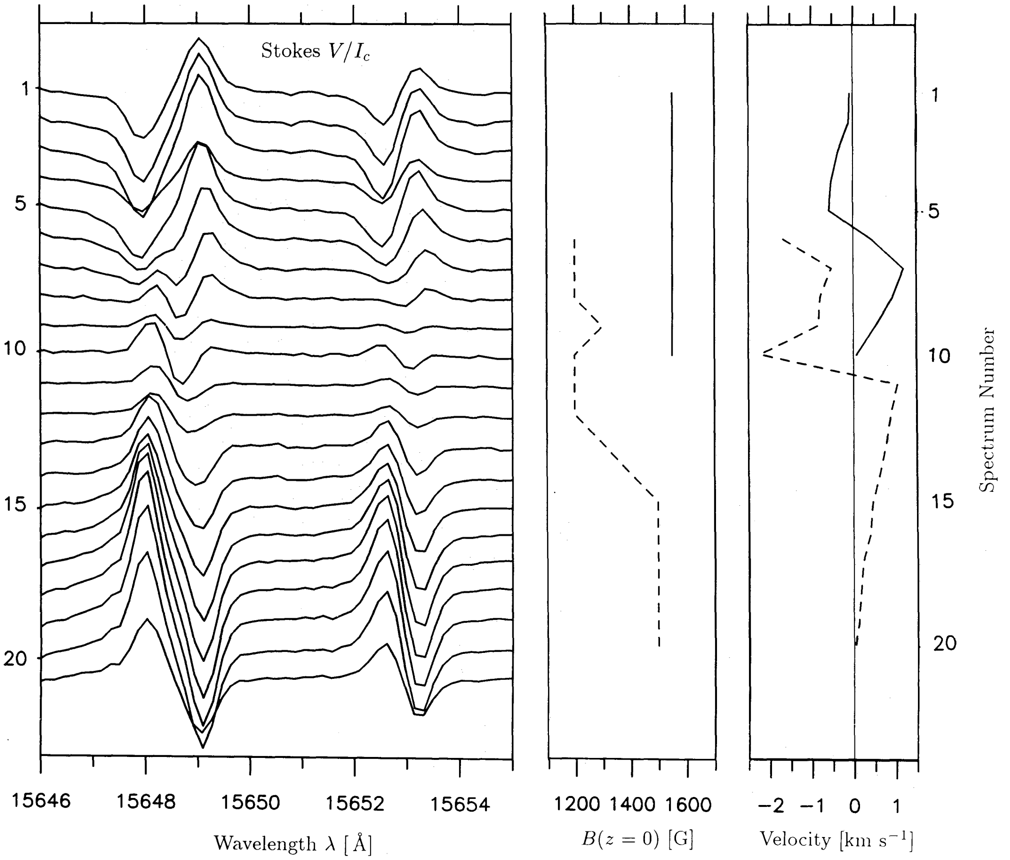

Fig. 1. a. Stokes V/I_c spectra at different positions along the slit; I_c is the local continuum intensity. Each displayed profile is the sum of 3 neighbouring profiles on the original frame. Each spectrum is offset by 2.55″ on the solar surface with respect to its neighbours along the spectrograph slit. The coadded spectra are numbered at the left of the frame. **b.** Variation of the field strength B along the slit. The values plotted at the same vertical position as the zero level of a Stokes V/I_c spectrum in Fig. 1a were derived from that spectrum. The B values at intermediate spatial positions have been linearly interpolated. The fields plotted dashed have positive polarity, those plotted solid have negative polarity. **c.** Line-of-sight flow velocities. Positive velocities are directed downward in the atmosphere.

cross–talk induced shift is expected to be larger. By comparing the measured shifts of the $g = 3$ and $g_{\rm eff} = 1.53$ lines we conclude that the blueshift measured for profiles 1–5 (negative polarity) and the redshift of profiles 11–21 (positive polarity) in Fig. 1c is largely an artifact of the cross–talk. The shifts of the two components forming profiles Nos. 6–10 (mixed polarity), on the other hand, are in the *opposite* sense to that expected from the instrumental cross–talk. These shifts must, therefore, be due to mass flows. If anything, instrumental cross–talk reduces the magnitude of the observed velocities, so that the true flow velocities are probably larger than those shown in Fig 1c. The probable inclination of the field also implies that the true field–aligned velocities are larger than the measured line–of–sight values. Note that instrumental cross–talk does not affect the derived field strengths systematically, although it increases their uncertainty somewhat.

4. Discussion

Now that we have, to the best of our ability, established the reality of the flow in the flux tubes near the neutral line, we can speculate on its physical nature. Matter is flowing downwards in the positive polarity flux tubes with stronger fields and upwards in the weaker fields of the negative polarity flux tubes. Let us make the natural assumption that opposite polarity flux tubes situated so close to the neutral line are connected by magnetic loops, as supported by the increased line asymmetry due to instrumental cross–talk near the neutral line. Because the flux tube obeys lateral pressure balance, the footpoint with weaker field (lower magnetic pressure) has higher gas pressure; the opposite is true for the other footpoint. Thus, the observed flow satisfies the conditions required of a siphon flow: an upflow in the tubes with higher gas pressure (weaker field) and a downflow in tubes of lower gas pressure (stronger field). Our observations correspond to the signature for a siphon flow predicted by Thomas and Montesinos (1991).

Why have siphon flows not been observed before now? A siphon flow can only be identified if the full spectral profiles of Stokes V are measured at different spatial positions spanning a neutral line. Such measurements are rare. A previous observation of Stokes profiles compatible with a siphon flow has been published by Skumanich & Lites (1991), but was not interpreted by them as such. Their fit to a composite profile observed on the neutral line also results in a blueshifted weaker field component (1200G) and a redshifted stronger field component (1500G).

Finally, we wish to point out the advantages of observing siphon flows in the infrared. Due to the larger Zeeman sensitivity in the infrared it is easier to determine the field strength in each magnetic component reliably. For spatially unresolved flows the Stokes V profile shape of a strongly split line is more sensitive to the detailed field strengths and flow velocities. For example, compare profile No. 7 of the $g = 3$ line with the profile of the $g_{\rm eff} = 1.53$ line in the same spectrum. The V profile of the former line is clearly more responsive to the differences between the two components. A profile of the Fe I 5250.2 Å ($g = 3$) line calculated using the same model parameters as the two infrared lines of spectrum No. 7 shows no obvious signs of an anomaly. However, both infrared lines appear to possess

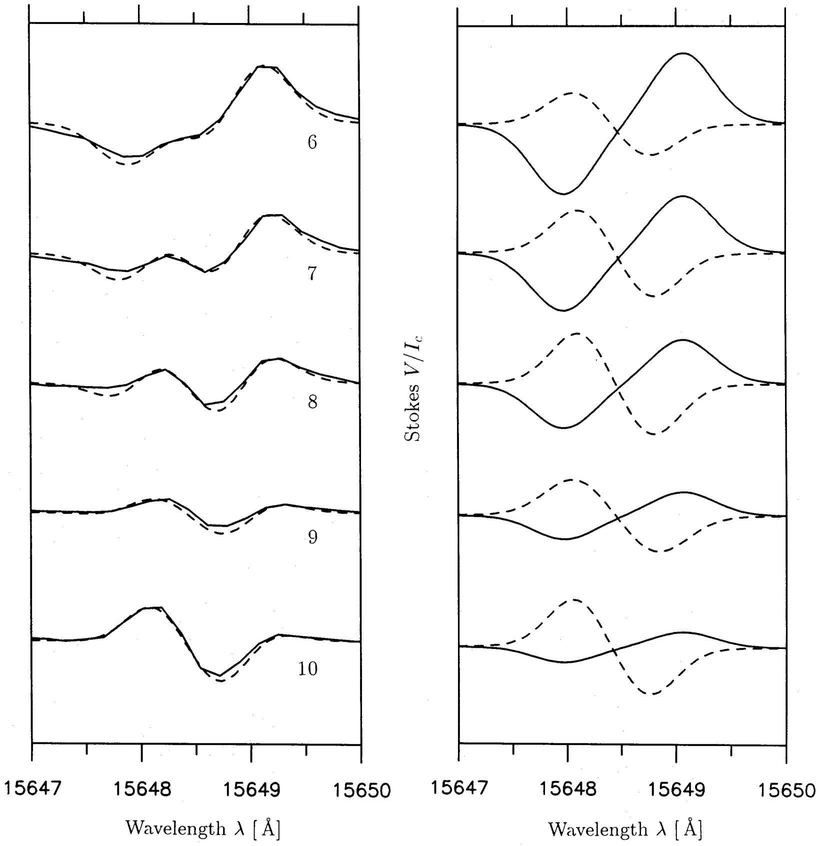

Fig. 2. a. Stokes V/I_c profiles of Fe I 15648.5 Å at the 5 spatial positions requiring two magnetic (and one non–magnetic) components to fit the profiles (top: spectrum No. 6, bottom: spectrum No. 10, spectra are labelled.). Solid curves: measured solar spectra, dashed curves: synthetic profiles fitted such that they reproduce the positive parts of the profiles best. **b.** Synthetic V/I_c profiles of the individual magnetic components forming the composite synthetic profiles shown in Fig. 2a. Top: spectrum No. 6, bottom: spectrum No. 10.

equally anomalous profiles for some combinations of parameters, particularly when a larger fraction of the unsigned magnetic flux resides in the weaker field component (cf. spectrum No. 9). This point is supported by the anomalous appearance of Fe I 5250.2 Å calculated with the model parameters best reproducing spectrum No. 9.

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