Penumbral Stokes-V Asymmetries of Fe I 1564.8 nm

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Abstract. Stokes profiles of sunspot penumbral show distinct asymmetries, which indicate strong gradients in the magnetic field and in the velocity field. Measurements of Stokes profiles with high spatial resolution and high polarimetric accuracy are crucial for an understanding of the penumbra and offer a diagnostic tool to test theoretical models. We have measured the polarized light of the infrared iron line \((g=3, \text{ triplet})\) at 1564.8 nm. We present intriguing characteristics of penumbral Stokes-V profiles: 1) The amplitude asymmetry of the Stokes-V profile on the center-side of the penumbra is significant: It depends on the radial distance from spot center while it only varies slightly with azimuth. It shows a sign reversal in the mid penumbra (in inner and outer penumbra it assumes values of different signs). 2) In the vicinity of the magnetic neutral line (on the limb side of the penumbra), we observe abnormal Stokes-V profiles, which exhibit four lobes. We will give qualitative explanations on how these observations can be reconciled within the concept of the moving tube model.

1. Spatial maps of observed sunspot

We have measured the Stokes parameters of the infrared iron line \((g=3, \text{ triplet})\) at 1564.8 nm, using the Tenerife Infrared Polarimeter (TIP) (Collados 1999; Martínez Pillet et al. 1999) at the German vacuum tower telescope at the Observatorio del Teide (Tenerife). Using a correlation tracker and a scanning unit, we obtained maps of all Stokes parameters of a sunspot. We achieve a spatial resolution of about 700 km, with a polarimetric accuracy of better than \(10^{-3}\) and a spectral resolution of 6 pm. The chosen line forms in the deeper part of the photosphere. The line depression contribution function of the line core peaks around \(\log \tau = -1\) for a quiet sun atmosphere, and originates significantly deeper than e.g. the iron line at 630.25 nm (above \(\log \tau = -2\)). Therefore the IR line is better suited for a comparison of observations with predictions of the moving tube model (Schlichenmaier, Jahn, & Schmidt 1998). The observed sunspot (AR 8755 on Nov 9 1999) was located at a heliocentric angle of \(\theta = 30^\circ\). Spatial maps were obtained by scanning the solar image (150 steps at a spacing
Figure 1. Spatial maps of Stokes parameters $\log(\int |I| d\lambda)$ and correspondingly for $V/I$, $Q/I$, and $U/I$, and maps of the Doppler shift, the total polarization, the amplitude asymmetry, $\delta A \equiv \frac{|A_b| - |A_r|}{|A_b| + |A_r|}$, $A_b$ ($A_r$) being the amplitude of blue (red) V-lobe, and the amplitude difference, $dA \equiv \max(V/I) + \min(V/I)$. The latter gives the absolute difference of $V/I$ of the two most extreme V-lobes in units of percent.
of 0.4"", corresponding to 43.5 Mm on the sun, and a slit width of 0.5"") across the slit (with a length of 24 Mm on the sun). The arrow drawn in the umbra of the intensity map in Fig. 1 points toward disk center.

2. Abnormal Stokes-V profiles in penumbra

2.1. Amplitude asymmetry on disk center side of penumbra

Considering the center-side-penumbra (upper part of penumbra), it is seen in both maps of the lowest panel in Fig. 1 that the amplitude asymmetry varies from positive to negative values with increasing distance from spot center. In Fig. 2 we have displayed the V-profiles along a slice from the inner to the outer center-side-penumbra. The arrows to the right denote sign and magnitude of the amplitude asymmetry as it is defined in the text of Fig. 1. The amplitude asymmetry, dA, has a minimum in the outer penumbra (dA = −2.4%) and a maximum in the inner penumbra (dA = 2.2%).

Possibly, the penumbral fine structure in form of up- and outflows in magnetic flux tubes is responsible for this finding: in the inner penumbra the upflows dominate, whereas in the outer penumbra, the horizontal outflows dominate. We speculate that upflows embedded in a steep background magnetic field generate an amplitude asymmetry of a different sign than horizontal outflows.

Comparison with synthetic lines: In order to elaborate on our speculation, we calculate synthetic Stokes-V profiles. We use a penumbral model atmosphere from Kjeldseth Moe & Maltby (1969) in which we place a flow channel at a specified depth range. This is a geometric configuration which is motivated by the moving tube model and which is in many respects similar to models used by Solanki & Montavon (1993) and Martínez Pillet (2000), e.g. we also use a decrease of the magnetic field strength with optical depth, τ, according to $B(\tau) = 1300 + 50 \cdot \log \tau$. With such a model geometry, the asymmetries are caused by discontinuities that arise when the line-of-sight (LOS) crosses the flow channel. We consider discontinuities in the inclination and/or the strength of the magnetic field and discontinuities that are due to a different flow velocity within the tube. In this preliminary step, we do not consider changes of the temperature and pressure stratification due to the flow channel. For simplicity, and since we are only interested in reproducing the observed peculiarities qualitatively, we limit ourself to one single ray, i.e. we do not mix several components. The synthetic lines are obtained by solving the Unno-Rachkovsky equation (Grossmann-Doerrth 1994). Atomic data for Fe I 1564.8 nm are taken from Zayer, Solanki, & Stenflo (1989). To account for macroturbulence and instrumental broadening of the line profile we convoluted the line profile with a gaussian having a width corresponding to 1.5 km/s (8 pm).

For modelling the observed negative amplitude asymmetry in the outer penumbra, we assume a nearly horizontal, deep lying flow channel ($-0.5 \geq \log \tau \geq -1.0$) which carries a flow of 14 km/s (Fig. 3). Viewing the disk-center-side penumbra at a heliocentric angle of 30°, we obtain a synthetic V-profile that shows a negative amplitude asymmetry of $dA = -1.8\%$, similar to the observed values, which have a slightly larger modulus.
Stokes V profiles along trace from inner (bottom) to outer (top) penumbra.

Units of y-axis: V/I in %.

Values of amplitude asymmetry dA are given next to each profile. The arrow heads indicate magnitude and sign of dA.

Figure 2. Amplitude Asymmetries of Stokes-V changes sign along a radial trace from inner (bottom) to outer (top) center-side-penumbra.
Figure 3. The sketched configuration (left panel) yields a synthetic V-Profile (right panel) with an amplitude asymmetry of $dA = -1.8\%$. The absolute flow velocity within the tube is 14 km/s, resulting in a LOS component of the velocity of about 9 km/s.

Figure 4. The sketched configuration (left panel) yields a synthetic V-Profile (right panel) with an amplitude asymmetry of $dA = 2.1\%$. 

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In the inner penumbra hot, optically thick, upflows with a velocity of at least 3 km/s and with a substantially reduced magnetic field strength are predicted by the moving tube model. We describe these upflows by placing the flow channel in the deepest layers \((2 \geq \log \tau \geq -0.5)\) along the LOS, and assume a magnetic field strength of 1000 Gauss and a flow velocity of 3 km/s within the tube (Fig. 4). The resulting synthetic V-profile has a positive amplitude asymmetry, \(dA = 2.1\%\), i.e. the observed sign reversal from the inner to outer center-side-penumbra of the amplitude asymmetry can qualitatively be reproduced within the framework of the moving tube model.

We note that our model is very simple and that more sophisticated line profile calculations within the concept of the moving tube model are needed. We also like to mention that the amplitude asymmetry is also present in the outermost part of the limb-side penumbra. There, the profile has the other polarity with the red wing being broader than the blue one. On both sides, the amplitude asymmetry decreases towards the penumbral edge. This might be connected to the finding that the absolute flow velocity also decreases in the outermost penumbra (e.g. Schlichenmaier & Schmidt 2000).

2.2. 4-lobe-V-profile in vicinity of magnetic neutral line

On the limb-side penumbra, the appearance of V-profiles is completely different from profiles on the center-side. The most intriguing observational phenomenon is the magnetic neutral line, which indicates that the mean magnetic field is viewed perpendicular to the LOS. The magnetic neutral line is visible in Fig. 1 as the black semi-circle in the limb-side penumbra, where the V-signal is at a minimum. What remains from the V-profiles is expected to stem mainly from the penumbral fine structure. In Fig. 5 we show the V-profiles along a slice from the outer to the inner limb-side penumbra. In the middle penumbra, i.e. in the vicinity of the magnetic neutral line, we observe 4-lobe-V-profiles. Such profiles can in principle be explained by magnetic components of different signs which are superimposed in the line profile (Rüedi et al. 1992), either by actually having two components within the resolution element, or by having two components in different layers.

Being lead by the moving tube model, we assume a horizontal channel (with horizontal magnetic field) in a deep layer \((-0.5 \geq \log \tau \geq -1.0)\) and a steep magnetic field inclination elsewhere. The horizontal tube has a magnetic field component pointing away from the observer, whereas the steep component is not quite perpendicular to the LOS, but is inclined by 80° to the LOS (i.e. 50° to the surface normal) and has a magnetic field component pointing towards the observer. Such a configuration yields a synthetic 4-lobe-V-profile which is similar to the observed profile. Interestingly, we obtain the 4-lobe-profile by considering only one ray and by changing only the inclination the magnetic field within the channel (no velocity gradients are prescribed). This again demonstrates that the moving tube model naturally generates “abnormal” V-profiles.

3. Summary

We have presented intriguing asymmetries of penumbral V-profiles. As a first step we have concentrated on the amplitude asymmetries in the disk-center-side
Stokes V profiles along trace from outer (bottom) to inner (top) penumbra. Unit of y-axis: V/I in %.

Zeeman splitting corresponds to $\sim$1950 Gauss.

4-lobe-V-profile in vicinity of neutral line.

Strong amplitude asymmetry in outer part of limb side penumbra.

Figure 5. Stokes-V profiles along trace from outer (bottom) to inner (top) center-side-penumbra. In the vicinity of the magnetic neutral line on the the limb side penumbra, 4-lobe-V-profiles are present, hinting at two magnetic components of different sign.
of the penumbra, and on 4-lobe-profiles in the vicinity of the magnetic neutral line on the limb side of the penumbra. Previously, Sanchez Almeida & Lites (1992) have performed a similar investigation using the iron line at 630.25 nm. To some extend our result confirm their analysis, however, they do not find the sign reversal of the amplitude asymmetry on the disk-center-side penumbra. There they find profiles that correspond to profiles in the outer penumbra in our data set. We surmise that their line originates too high in the atmosphere to sense the upflows in the deep photosphere, which are responsible for the sign reversal of the amplitude asymmetry.

Obviously, these asymmetries are caused by the penumbral fine structure. The moving tube model is successful in reproducing many features of the penumbral fine structure. From predictions of this model, we have constructed simplified model atmospheres in order to synthesize V-profiles. They can, in principle, reproduce the behaviour of the observed V-profiles.

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