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Spectropolarimetric inversions of the He I 10830 multiplet in an active region filament

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Abstract. Full-Stokes spectropolarimetric data (in the 10830 Å region) of an active region filament were obtained in July 2005 using the Tenerife Infrared Polarimeter instrument. The polarization profiles in the filament show Zeeman-like signatures. Milne-Eddington inversions were performed to infer the chromospheric magnetic field, inclination, azimuth, velocity and Doppler width from the He I 10830 Å multiplet. Field strengths of the order of 600-800 G were found in the filament. Strong transverse fields at chromospheric levels were detected near the polarity inversion line. To our knowledge, these are the highest field strengths reliably measured in these structures. Our findings suggest the possible presence of a flux rope.

Key words. Techniques: polarimetric – Sun: chromosphere – Sun: filaments – Sun: magnetic fields – Sun: photosphere

1. Introduction

Filaments can be seen as long and dark structures in Hα observations on the solar disk and they are formed of denser and cooler plasma than their surroundings. We can distinguish between two types of filaments: active region (AR) and quiescent filaments. They are located along polarity inversion lines (PILs) and their exact height is not easily inferred from on-disk data. From observations and three-dimensional models it has been shown that AR filaments are stronger and lie lower in the atmosphere than their quiescent counterparts (see Aulanier & Démoulin 2003, and references therein).

Partly due to the limited availability of spectropolarimetric data, there are very few studies of magnetic field strengths in AR filaments. Wiehr & Stellmacher (1991) inferred the longitudinal magnetic field in an AR prominence using the Stokes *V* spectra of the Ca II 8542 Å line. Values between 75 and 180 G were found. Furthermore, by analyzing the full Stokes vector of the He I 10830 Å multiplet of a multi-component flaring active region, Sasso et al. (2007) have inferred magnetic field strengths around 380 G.

This paper will focus on the full-Stokes inversion of the He I 10830 Å multiplet mea-

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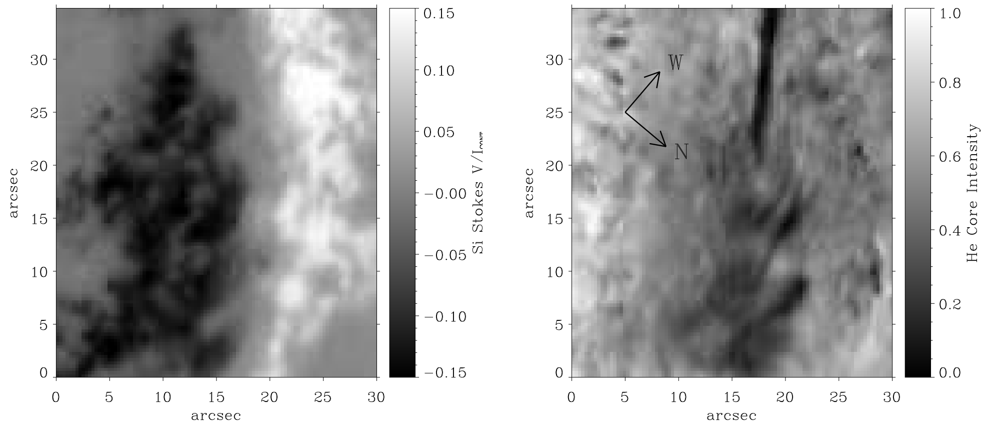

Fig. 1. *Left*: Si I Stokes *V* map normalized to the continuum intensity. *Right*: He I "red" core intensity map reconstructed from the slit scan positions. The arrows indicate Solar West and North.

sured in an AR filament near the solar disk center. Section 2 begins by laying out the observations, Sect. 3 describes the spectropolarimetric inversions and results, which are then discussed in the last section .

2. Observations

The analyzed data were acquired on 2005 July 5, with the Tenerife Infrared Polarimeter (TIP-II, Collados et al. 2007) at the German Vacuum Tower Telescope (VTT, Tenerife, Spain). The active region NOAA 10781 was localized near the disk center at N13 W29 (μ = 0.92). The filament was lying above a compact active-region neutral line.

Various spatial scans, using in addition the KAOS adaptive optics system (von der Luehe et al. 2003), were taken along the AR with the slit parallel to the polarity inversion line, covering an area of 35″ × 30″. Moreover, one time series was acquired with the slit fixed at the PIL. The spectral range covered the chromospheric He I 10830 Å multiplet, the photospheric Si I 10827.1 Å line, and at least one telluric line, with a spectral sampling of ~ 11.1 mÅ px^{-1}. The data reduction, as well as the polarimetric calibration (Collados 1999, 2003), were performed for all the data sets. In order to improve the signal-to-noise ratio a 3 pixel binning in the spectral domain and a 6 pixel binning in the spatial direction were applied to the data. For a more detailed description of the observations see Kuckein et al. (2009).

2.1. Description

The slit-reconstructed image of the He I "red" component at ~ 10830.3 Å is shown in the right panel of Fig. 1 shows a dense concentration of plasma above the PIL. Highly twisted structures can be identified in the lower part of the map. On the contrary, in the upper part these dark structures seem to align with the PIL. These findings could suggest the presence of a flux rope. One question that needs to be asked, however, is whether we are seeing the dips or the tops of that flux rope. An exhaustive study of the vector magnetic field must be carried out to obtain this information. This is future work that will be presented in a following paper.

The Stokes profiles of He I 10830 Å obtained in this campaign (see Fig. 1 of Kuckein et al. 2009) indicate a strong predominance of Zeeman-like signatures in the AR filament, characteristically with three-lobe profiles in Stokes Q and U. Observations of quiescent filaments using the same He I multiplet have shown that the polarization is dominated by atomic level polarization and its modification through the Hanle effect (see Trujillo Bueno et al. 2002).

3. Spectropolarimetric inversions

Three methods were used to invert the Stokes profiles: magnetograph analysis, Milne-Eddington (ME) inversions and principal component analysis (PCA), the latter taking into account the physics of atomic level polarization and the Hanle effect (see López Ariste & Casini 2002, for a review of this code). The magnetograph analysis, based on the weak-field approximation, gives us a first approach of the vector magnetic field. Furthermore, these results were compared with more accurately ME and PCA-based inversions. Kuckein et al. (2009) concluded that the magnetic field strengths inferred with the magnetograph analysis are under-estimated by around 100–150 G, while the inclinations and azimuths are in very good agreement.

The time series were inverted using the ME and the PCA-based inversion codes. Kuckein et al. (2009) presented, for both inversion codes, the best fits for the Stokes profiles of two selected points of the data set and found that both techniques yielded almost the same magnetic field strengths, inclinations and azimuths. The Stokes profiles have Zeeman-like shapes and atomic polarization is almost absent at the filament.

This paper will focus on the results achieved with the ME inversion code for the entire map of the AR filament.

3.1. Milne-Eddington inversions

The He I Stokes profiles were inverted using MELANIE (Socas-Navarro 2001). This inversion code computes the Zeeman-induced Stokes spectra, in the incomplete Paschen-Back effect regime (Socas-Navarro et al. 2004), that emerge from a model atmosphere described by the Milne-Eddington approximation. A set of eleven parameters of the model atmosphere are modified by the inversion code to obtain the best fits to the observed Stokes profiles. We performed several inversions for the same point changing the initial model atmosphere configuration in order to obtain the best fit.

Figure 2 presents the magnetic field (B), LOS velocity (v), inclination (θ) and azimuth (ϕ) with respect to the line-of-sight (LOS)and the Doppler width obtained from the ME inversions. A He I slit-reconstructed image, centered at the red core, is also shown to identify the filament. On average, the magnetic field strength inferred from the ME inversions in the filament is around 600–800 G. Moreover, high inclination values between 80° and 100° with respect to the LOS are found at the PIL, indicating predominantly transverse fields.

The azimuth origin is referenced to the Earth's North-South direction. From the lower right map of Fig. 2 it appears that the azimuth is aligned with the dark structures of the filament. Nevertheless, these results must be interpreted with caution because the 180 degree ambiguity is not yet resolved. This is an important issue for future work.

As can be seen from Fig. 2, the Doppler width is around 210–220 mÅ in the filament, smaller than its surroundings and it seems to shape the surface form of the filament.

The LOS velocities were not calibrated for the orbital motions which contribute to the wavelength shifts. Instead, we calculated the mean velocity from different areas of the map outside the filament and subtracted it from the velocity of every pixel. Consequently, this map gives us some hint whether the plasma is moving upward (negative v) or downward (positive v). If we only take into account the velocities which correspond to Doppler widths below 220 mÅ, the filament is rising with respect to its surroundings with a mean speed as large as 2.2 km s^{-1}.

4. Discussion

We have presented Milne-Eddington inversions using the MELANIE code for an active region filament lying near the solar disk center. The Stokes profiles in the filament are completely dominated by the Zeeman effect. It is somewhat surprising that no atomic polarization was found. Casini et al. (2009) sug-

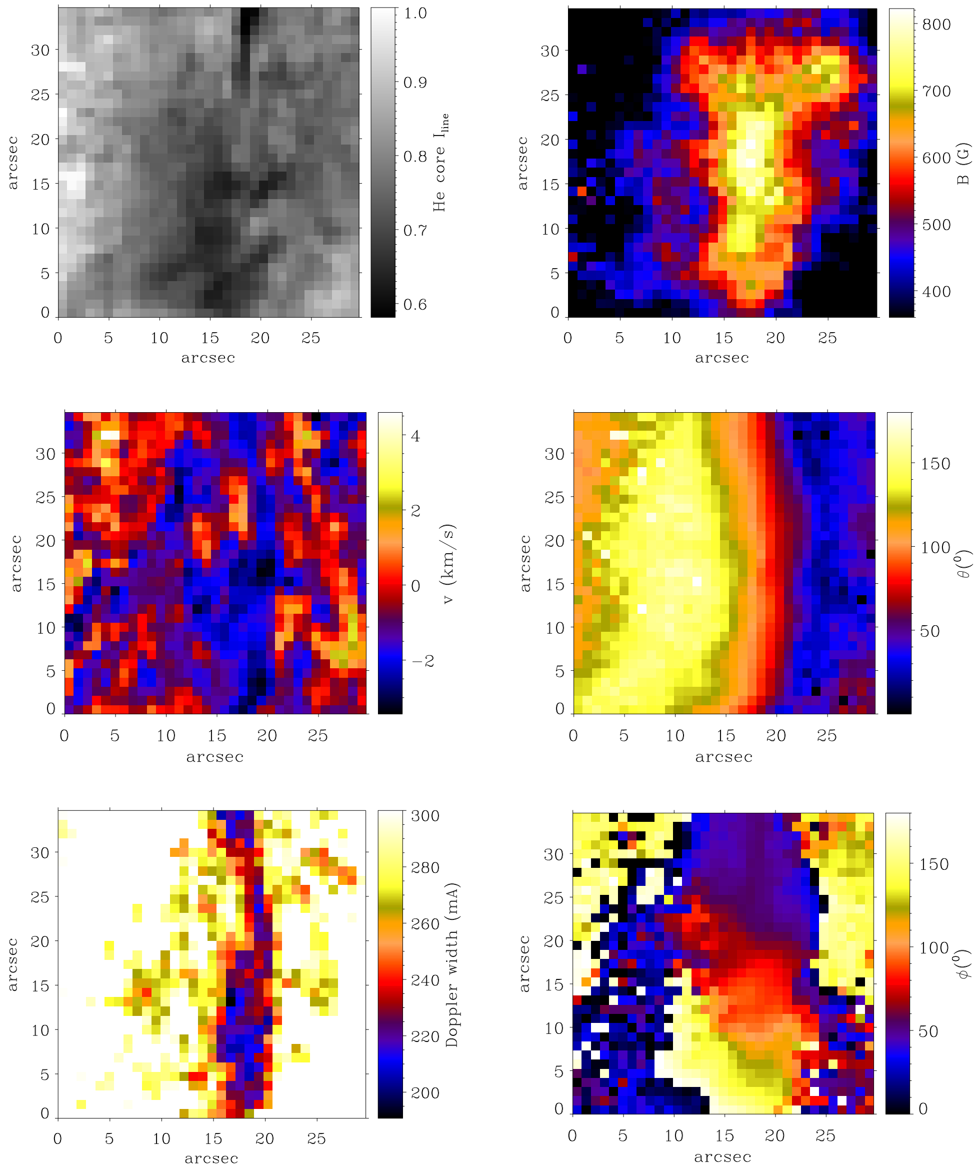

Fig. 2. From *top* to *bottom* and *left* to *right*: He I red-core intensity, magnetic field strength in Gauss units, LOS velocity (see definition in Sect. 3.1), LOS inclination θ in degrees, Doppler width in mÅ and LOS azimuth ϕ in degrees.

gest that the presence of an unresolved magnetic field with a random component could explain the lack of atomic polarization signatures in the Stokes profiles. Another explanation was proposed by Trujillo Bueno & Asensio Ramos (2007), who argue that the radiation field of the optical thick filament itself decreases the anisotropy radiation thus making it negligible.

At the formation height of He I strong transverse magnetic fields of 600–800 G are found of 600–800 G. In reviewing the literature, apart from our study, no observational evidence for such strong magnetic fields in AR filaments at chromospheric levels has been found before. Is this common to all active region filaments? Further spectropolarimetric observations, with high resolution, are needed to answer this question. Recent photospheric observations of an AR filament, like the ones presented by Okamoto et al. (2008), showed horizontal magnetic fields of 650 G on average and evidence of an emerging helical flux rope. If our filament would lay at a very low height then we could expect such strong fields.

The inclination and azimuth maps have shown that the magnetic field vector is highly transversal and in some parts aligned with the dark structures of the filament. This alignment in the lower part of the AR would indicate that the field is inclined $\sim 45^{\circ}$ with respect to the axis of the filament. Since the velocity map of Fig. 2 shows upward motions for the filament, the emerging flux rope scenario (see Lites 2009) might be a valid explanation for this case. Furthermore, Lites (2009) proposes that the flux rope lies at low heights and therefore should become measurable using photospheric spectral lines. Since our spectral window comprises the photospheric Si I 10827.1 Å line, it is mandatory to invert this line in order to retrieve information of its magnetic field vector in the photosphere.

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