

Exploring the Magnetic Fields of Solar Prominences and Spicules via He I D₃ Spectropolarimetry

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Abstract. Over the last few years a large set of spectropolarimetric observations of prominences and spicules in the He I D₃ multiplet have been collected at the observatory of the Istituto Ricerche Solari Locarno (IRSOL), using increasingly improved versions of the ZIMPOL polarimeter. The novel HAZEL inversion code of Stokes profiles generated by the joint action of the Hanle and Zeeman effects is being applied to this set of data, in order to infer the strength and geometry of the magnetic field present in these structures. This paper presents a brief overview of the most recent observations and inversions.

1. Introduction

The best available technique we have at our disposal for determining the magnetic field vector that confines and/or channels the plasma of prominences and spicules is based on the measurement and interpretation of spectropolarimetric observations in the He I 10830 Å and/or D₃ multiplets (e.g., see Trujillo Bueno (2010), for a recent review). In such weakly magnetized plasma structures the linear polarization is dominated by atomic level alignment and its modification by the Hanle effect. The longitudinal Zeeman effect is usually at the origin of the observed circular polarization, although for the He I D₃ multiplet atomic level orientation can also play a significant role. Examples of recent spectropolarimetric observations in the D₃ multiplet are those of Paletou et al. (2001); Casini et al. (2003); López Ariste & Casini (2005), while He I 10830 Å investigations can be found in Trujillo Bueno et al. (2002, 2005); Merenda et al. (2006); Centeno et al. (2010)

Since 2003 a large set of high quality spectropolarimetric observations in the He I D₃ multiplet have been collected also at the IRSOL observatory. A first set of data has already been presented at SPW4 (Ramelli et al. 2006a,b). Additional observations have been obtained after significant improvements in the instrumentation.

Recently, a powerful spectral synthesis and inversion code called HAZEL (from HANle and ZEeman Light) has been made available to the astrophysical community

(Asensio Ramos et al. 2008). It allows an efficient synthesis of theoretical Stokes profiles of lines of neutral helium as well as the inversion of spectropolarimetric observations taking into account the joint action of atomic level polarization and the Hanle and Zeeman effects (with the wavelength positions and strengths of the σ and π components calculated within the framework of the Paschen-Back effect theory). The code is also able to take into account the effects of radiative transfer on the emergent Stokes profiles by using the constant-property slab model (Trujillo Bueno et al. 2005).

We present here some of the new observations collected at IRSOL along with the preliminary results obtained by applying the HAZEL inversion code.

2. Observations

Since 2003 about 50 observations of prominences and 70 of spicules were collected at IRSOL. The basic observation technique has already been described in Ramelli et al. (2005, 2006b). Care needs to be taken in the data reduction of these off-limb observations. In particular the effects of stray-light (instrumental + atmospheric aureole) and the instrumental polarization (IP) needs to be correctly accounted for. The stray-light correction is made more difficult by the presence of several telluric blend lines, one of them very near to the intensity maximum of the He I D₃ emission profile.

The observations take advantage of the high polarimetric sensitivity of the ZIMPOL polarimeter (Gandorfer et al. 2004; Ramelli et al. 2010a) and of the characteristics of the Gregory-Coudé telescope (GCT) at IRSOL (Bianda et al. 2009). The field stop (diameter ca. 200 arcsec), placed at the primary focus, strongly reduces the amount of stray light. The IP is easy to correct for through calibration, since it basically depends on declination only and can be assumed constant during one observing day. The main sources of IP are two folding mirrors whose effect cancels out when observing near the celestial equator.

The observing technique has been improved through the years. The most relevant instrumental developments since the presentation of the papers about this project at SPW4 (Ramelli et al. 2006a,b) are the installation of cylindrical micro-lenses on the ZIMPOL sensor (end 2006), the installation of a new slit-jaw camera (2009), the use of a high transmission pre-filter (2009) and the use of the adaptive optics system for the limb tracking (Ramelli et al. 2010b). In addition, we are currently starting to use an improved and more efficient ZIMPOL camera (ZIMPOL-III) (Ramelli et al. 2010a).

The cylindrical micro-lenses array on the ZIMPOL sensor allow to concentrate the light on the unmasked pixel rows. Since for the ZIMPOL demodulation technique 3 out of 4 pixel rows of the CCD sensor need to be masked, with this improvement we obtain an increased light collection efficiency of about a factor 4. The high transmission interference pre-filter used instead of the monochromator allows a further efficiency improvement. The new slit-jaw CCD camera (Baumer) allows on one side to better document our observations (e.g. Fig. 1) and on the other side a much better limb distance determination, which is an important input parameter for the HAZEL inversion. An automatic limb recognition and fitting procedure has been built for a quick and automatic determination of the limb position with respect to the spectrograph slit on the slit jaw images (see Fig. 2).

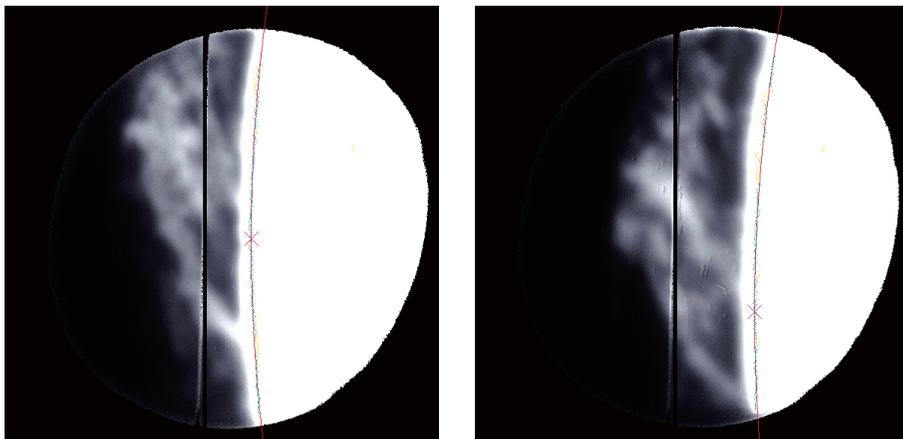


Figure 1. Slit-jaw H_{α} images showing the spectrograph's slit positions of the prominence observations taken on 16 March 2010. The red arc shows the fitted limb position, considered to be located where the intensity gradient reaches the maximum. Note that the flat field correction is not perfect near the spectrograph slit. The limb - spectrograph slit distance is shown in Fig. 2

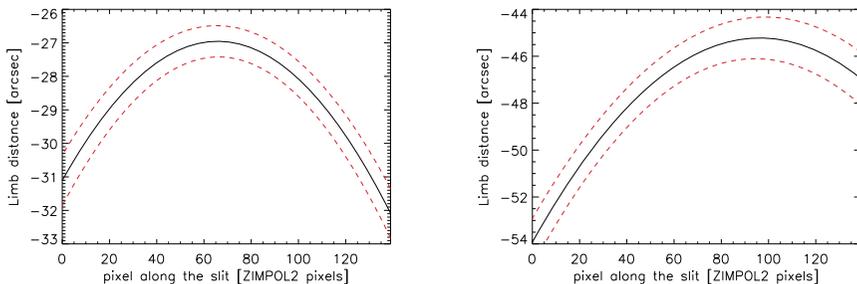


Figure 2. Limb distance as a function of the spectrograph slit position, determined processing several slit-jaw images taken during the 16 March 2010 prominence observations (see Fig. 1). The red lines show the RMS interval of the image motion.

In this SPW6 presentation we decided to focus our attention on the few observations obtained near to the spring equinox of this year, taking advantage of the improved instrumentation. On 16 March 2010, we observed a prominence positioned on the NW limb (Fig. 1), while on April 14th 2010 we observed spicules at different positions (South, $\text{lat}=-90^{\circ}$; East, $\text{lat}=-10^{\circ}$; West, $\text{lat}=+10^{\circ}$ at two different limb distances). The typical integration time for each observation was about 5 to 10 minutes.

3. Inversion of prominence observations

3.1. Spatial variation

The Stokes images from the spectropolarimetric observations of prominences we obtained on 16 March 2010 are shown in Fig. 3.

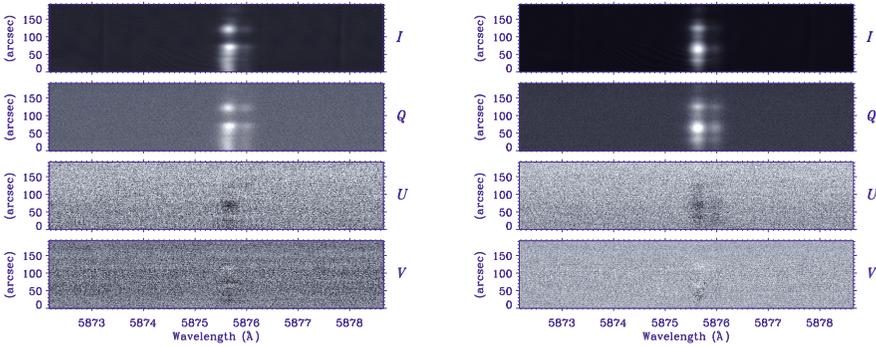


Figure 3. Stokes images of the spectropolarimetric observations of prominences obtained on 16 March 2010. The left panel images correspond to the observation with the smallest limb distance.

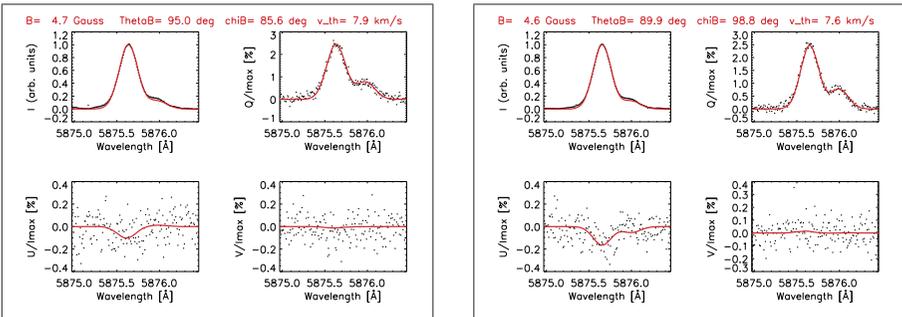


Figure 4. Examples of Stokes profiles from the prominence observations obtained on 16 March 2010. In red the corresponding theoretical profile obtained by the HAZEL inversion.

The spectrograph slit has been divided into about 35 overlapping intervals of 7 arcsec length each (corresponding to 5 pixels on the ZIMPOL images). For each interval we obtained the corresponding 4 Stokes profiles on which the HAZEL inversion has been applied (examples in Fig. 4). The resulting Stokes profiles at all positions along the spectrograph's slit look quite similar. The Stokes V profiles are almost flat. The inversion of all profiles gives a horizontal magnetic field vector close to the plane of the sky and with small variations of direction. The absence of a clear signal in Stokes

V in this field geometry makes the determination of the field strength more difficult. A theoretical synthesis of Stokes Q profiles for this geometry shows that there is a clear reduction of the maximum value of the profile (depolarization) when going from zero to a few gauss. Then, for larger field strengths, the maximum value of Q stays almost constant with small oscillations. For field strengths of 5 G or 25 G the maximum amplitude of the Stokes Q profile is almost the same. A difference is indeed seen in the weak red component of the D_3 multiplet. At 25 G the expected depolarization in this component is clearly larger than observed (see example in Fig. 5). Thus, in this preliminary analysis we would be inclined to favor the weak field solution shown in Fig. 4.

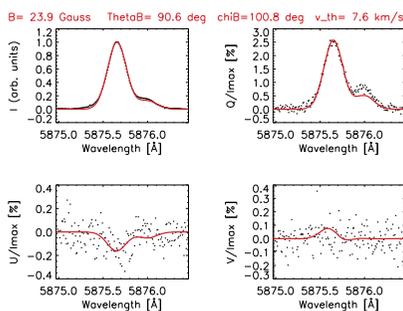


Figure 5. Results of the inversion of the profiles shown in the right panel of Fig. 4, after forcing the field strength to be in the 20-40 G interval. Note that the faint red component of the D_3 multiplet is not well fitted in the Stokes- Q profile.

3.2. Temporal variation

In order to investigate if there are significant temporal variations of the magnetic field we studied also the temporal evolution of the Stokes profiles corresponding to the region along the spectrograph's slit (length ca. 30 arcsec) where the maximum intensity in the D_3 emission is reached. No significant variations in the magnetic field are observed. The only clear variations obtained from the inversions are oscillations in the Doppler width and Doppler global shifts. These kind of variations are seen both spatially and temporally.

3.3. Previous data

We have applied the HAZEL inversion code also to the set of data collected before 2006. For each observation we selected manually few regions where the emission intensity is large enough, taking care that in the selected interval any strong variation in the polarization signature is seen. Our preliminary analysis confirms that the magnetic field is predominantly horizontal with varying azimuth values. The field strength shows some variability from few gauss to few tens of gauss. However, a deeper analysis of the data is needed prior to making more definitive conclusions on the field strength.

4. Inversion of spicules observations

An example of a spectropolarimetric observation of spicules obtained on 14 April 2010 is shown in Fig. 6. From the observations we extracted several Stokes profiles corresponding to 7 arcsec intervals along the spectrograph slit. For the HAZEL inversion we imposed a field inclination smaller than 50 degrees with respect to the vertical in order to get rid of the Van Vleck ambiguity.

We could find theoretical Stokes profiles (resulting from the inversions) nicely fitting the observations (e.g. Fig. 7). However, in some cases we experienced some more difficulty trying to find good fitting theoretical profiles. This preliminary analysis seems to indicate that the inversion of the spicules profiles we have observed tend to be a little bit more difficult than is the case for prominences.

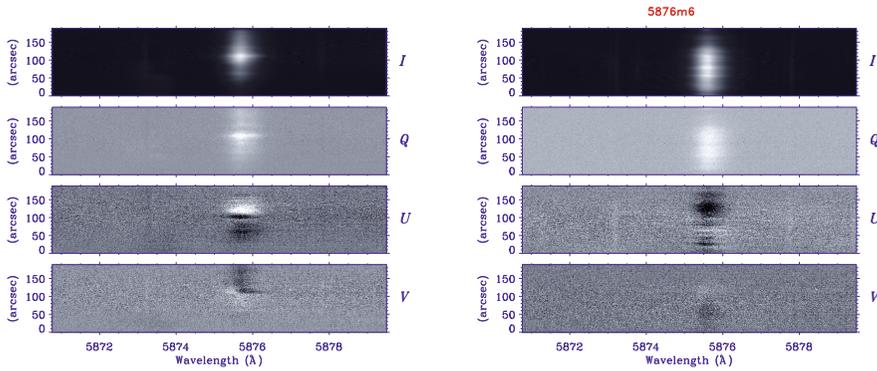


Figure 6. Stokes images of spectropolarimetric spicules observations obtained on April 14th 2010 near the West limb (at $+10^\circ$ latitude).

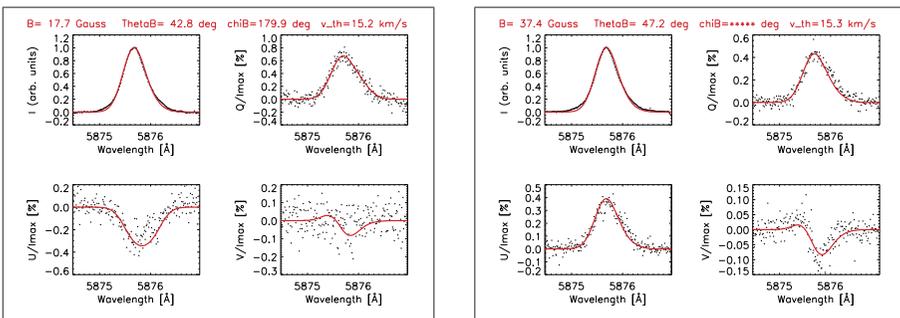


Figure 7. Examples of Stokes profiles from the spicules observation of April 14th 2010 shown on the left panel of Fig. 6. In red the corresponding theoretical profile obtained by the HAZEL inversion.

5. Conclusion

The preliminary results reported here look promising. With HAZEL we have a powerful tool to interpret our spectropolarimetric observations in order to improve our empirical knowledge on the magnetism of solar prominences and spicules.

The instrumental improvements (AO, ZIMPOL with micro-lenses, etc.) achieved in the recent years at the IRSOL observatory, thanks to the collaboration with the University of Applied Sciences and Arts of Southern Switzerland (SUPSI) and the former group of solar physics at ETH-Zurich, have facilitated further improvements in the quality of our observations.

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