Inference of the Magnetic Field in Spicules from Spectro-Polarimetry of He I D₃

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Abstract. Spectro-polarimetric observations of the He I D₃ line in spicules over the solar limb have been analyzed, and the magnetic field direction determined. Up to a 90° ambiguity the field appears to be aligned with the visible spicular structures. The anomalous broadening of the observed line prevents the retrieval of other information at this stage. The only further constraint we were able to place was on the field strength: fields stronger than 40 G must be statistically present in our observations, but not much stronger than that.

1. Resonance Scattering Polarization of He I D₃ in Spicules

In recent years an effort has been made to once again measure the magnetic fields in prominences using the He D₃ line, and, to the extent to which this is possible, to also improve the techniques employed to achieve this goal. In the 1980's, Leroy and his group (Leroy, Bommier, & Sahal-Bréchot 1983; Bommier et al. 1994) developed this technique with great success. In López Ariste & Casini (2002) we built over that experience, and showed how the new instruments and data analysis tools that have appeared in the meantime now allow us to scan full prominences and map their vector magnetic field (see, e.g., Casini et al. 2003).

However, prominences are not the only solar structures that show a non-negligible signal in the He I D₃ line. This line is in fact observed in emission also in spicules, and under conditions that are not very different from those found in prominences. Having developed the tools and the expertise to observe and analyze the polarization data of this line in prominences, it only appeared natural to try to do the same in spicules.

On May 28, 2002, we took 30 images, approximately 5′′ off the solar limb, using the Advanced Stokes Polarimeter (Elmore et al. 1992). The slit was fixed and placed parallel to the limb. The distance from the solar limb was chosen sufficiently large to avoid the accidental input of disk light into the spectrograph because of seeing-induced image motion. The image quality was not good enough to see separate spicules (we observed the forest as a whole), but from the Hα slit-jaw image it is clear that the observed spicules had a common inclination across the slit (roughly 45° from the solar radial direction), displaying the typical wheat-field pattern. The observed region was close to the eastern solar equator.
and a magnetically active region can be seen near the spicules over the disk in Hα (see the background image of Fig. 2).

The first unexpected finding was the anomalous broadening of the line, which was obviously of non-thermal origin. We decided to adopt a semi-empirical model to treat it, and assumed that it was due to a (symmetrical) distribution of line-of-sight velocities. The PDF of such distribution was assumed to be a Gaussian, and we used the observed intensity profiles to measure its FWHM. Figure 1 shows the results of those measurements. A FWHM of 50 km/s appeared as the median value of the PDF. This is a high value, although not impossible in a coronal environment like the one in which spicules evolve. It suggests that a velocity convolution is not the only contribution to the observed anomalous broadening. However, the intensity profiles were nicely fit with this convolution model, so we retained it as a working hypothesis.

A second hypothesis was that the polarization profiles were the convolution of non-broadened profiles with the Gaussian PDF of velocities. This is equivalent to assuming that the polarization emitted is independent of the plasma dynamics, which may be unrealistic in a low-β plasma, where the dynamics is primarily driven by the magnetic field.

With these two working hypotheses, we synthesized a database of anomalously broadened profiles for known magnetic fields and fixed temperature of $10^4$ K (no microturbulence). To this synthetic dataset we applied the inversion algorithm developed for the He i D$_3$ line in prominences (López Ariste & Casini 2002). The question we wanted to address was whether, despite the anomalous broadening, there still was information in the profiles about the vector magnetic field. The comparison between the inverted values of the vector magnetic field and the values used for the synthesis showed us that the information on the inclination of the field with respect to the line-of-sight was completely lost because of the broadening of the profiles. We found similar results for the field strength. In contrast, the position angle of the field projection on the plane-of-the-sky (POS) could be retrieved with an acceptable error of about 20°.
Magnetic Fields in Spicules

Figure 2. Magnetic-field projection on the POS for each pixel along the slit. The background image is a slit-jaw image in Hα of the observed spicule region. The horizontal black line is the spectrograph slit, while the two vertical ones are the hairlines limiting the field. The magnetic-field projections are seen to be roughly aligned with the visible spicules, organized in a characteristic wheat-field pattern.

After performing these tests, we knew that we could apply our inversion algorithm to the real data, and, imposing the validity of our working hypotheses, expect to infer the direction of the field in the POS. Figure 2 shows the results of the inversion code. The white segments represent the projection of the field vector on the POS. In the background a slit-jaw image in Hα shows the spicules with the slit (horizontal) superimposed. Our main result is obvious from this figure: the retrieved orientation of the magnetic field in the POS coincides with the observed inclination of the visible spicule. Because of the 180° ambiguity affecting the inclination, we cannot know the orientation of the field. Furthermore, our inversion revealed the presence of an additional 90° ambiguity, so that actually we cannot tell if the magnetic field is truly aligned with the spicule structure (as shown in Fig. 2) or rather it is perpendicular to it. Because current models of spicules support the “aligned field” picture, we also show this solution here. But from He i D3 spectro-polarimetry alone we cannot rule out the “perpendicular field” solution.

This 90° ambiguity in the position angle of the field in the POS is well known in the context of coronal magnetometry (e.g., Casini & Judge 1999; Casini, Bevilacqua, & López Ariste 2005). The linear polarization tangent to the solar limb can be approximated, for strong fields, by the expression

$$Q \sim (3 \cos^2 \vartheta_B - 1) \sin^2 \vartheta_B \cos 2\Phi_B ,$$

where $\vartheta_B$ is the inclination of the field with respect to the local vertical, and $\Phi_B$ is the position angle of the field in the POS. The factor 2 in front of $\Phi_B$ is
responsible for the well-known 180° ambiguity. A change of 90° in $\Phi_B$ would lead to a change of sign of $\cos 2\Phi_B$, and therefore of $Q$, unless the term in parentheses also changes sign while preserving its modulus. In this case, one would get two 90°ambiguous solutions. The He I D$_3$ line is not very sensitive to the 90° ambiguity (Casini et al. 2005) for essentially two reasons: i) Stokes V carries information also on $\Phi_B$, and ii) for field strengths below 100 G, typical of prominences, Eq. (1) is not a good approximation for this particular line, as further terms need to be taken into account, which usually break the symmetry responsible for the 90° ambiguity.

Our results thus show that the anomalous broadening of the polarization profiles not only deleted part of the information on the vector magnetic field, but also made the 90° ambiguity more general than could have been anticipated. In fact, the information in the observed $Q$ was so scarce that the inversion algorithm could find acceptable fits even if the conditions for the 90° ambiguity deduced from Eq. (1) were not exactly matched.

The determination of the field direction in the POS, despite the 90° ambiguity, is already a good result. But we also wanted to determine at least a constraint to the field strength. We were able to do so after we realized that, in our tests with synthetic profiles, the inversion error on the field strength and the field strength itself are not uncorrelated. In fact, we found that the error increases with the field strength, as shown in Fig. 3. Thus, a field of 10 G is affected by an error bar of 10 G, and a field of 60 G by an error bar of 60 G. This means that, statistically, the measurement of a 60 G field cannot be obtained for a true field of 20 G, whereas a measurement of 20 G can occur pretty much regardless of the true field strength. In Fig. 3 we also show the histogram of the field strengths inferred from the observations. It is clear that there is a non-negligible amount of results
above 50 G. Statistically, the presence of these solutions can only be due to the presence of true fields above at least 40 G. We do not expect them to be much stronger than that, since above 100 G we would expect the longitudinal Zeeman effect to be responsible for signals above the observed Stokes $V$ amplitudes, but nevertheless we can conclude positively on the presence of fields stronger than 40 G.

2. Conclusions

We applied inversion tools that were developed for the diagnostics of vector magnetic fields in prominences—based on spectro-polarimetry of the He I D$_3$ line—to spicules. The observations of spicules made with the ASP show anomalously broadened profiles for which we lack an appropriate modeling. We therefore adopted an empirical explanation in terms of the convolution of the polarization profiles with a Gaussian velocity distribution with a FWHM of 50 km/s. Under this assumption, and with the further hypothesis that the polarization signals are independent of the velocity distribution, we found that the inversion code was able to retrieve the position angle of the magnetic field on the POS, and place some constraints on the field strength.

When we applied our inversion code to the real data, we retrieved magnetic fields approximately aligned with the visible spicules. An additional 90° ambiguity forced us to accept also the possibility of magnetic fields perpendicular to the spicule. Our analysis also indicate the presence of fields stronger than 40 G, but not much stronger than that. These field strengths are much smaller than those requested by some current models of spicule formation (James, Erdélyi, & De Pontieu 2003; De Pontieu, Erdélyi, & James 2004).

References

De Pontieu, B., Erdélyi R., & James, S. P. 2004, Nat, 430, 536