FULL TITLE
ASP Conference Series, Vol. **VOLUME**, **YEAR OF PUBLICATION**
NAMES OF EDITORS

The Hanle and Zeeman Effects in Solar Spicules

R. Ramelli, M. Bianda

Istituto Ricerche Solari Locarno, CH-6605 Locarno Monti, Switzerland

L. Merenda, J. Trujillo Bueno

Instituto de Astrofísica de Canarias, E-38205 La Laguna, Tenerife, Spain

Abstract. A large set of high precision full-Stokes spectropolarimetric observations of the He-D_3 line in spicules has been recorded with the ZIMPOL polarimeter at the Gregory-Coudé Telescope in Locarno. The observational technique allow us to obtain measurements free from seeing induced spurious effects. The instrumental polarization is well under control and taken into account in the data analysis. The observed Stokes profiles are interpreted according to the quantum theory of the Hanle and Zeeman effects with the aim of obtaining information on the magnetic field vector. To this end, we make use of a suitable Stokes inversion technique. The results are presented giving emphasis on a few particularly interesting measurements which show clearly the operation of the Hanle and Zeeman effects in solar chromospheric spicules.

1. Introduction

The mechanism governing the formation of spicules is still uncertain. None of the theoretical models proposed until now (see e.g. the review by Sterling 2000) is able to explain in a satisfactory way all observational facts including ubiquity, evolution, energetics and periodicity (De Pontieu 2004) and also the magnetic fields, whose presence in spicules is required by all theoretical models. Investigations of such magnetic fields through spectropolarimetric observation were reported recently (Trujillo Bueno et al. 2005; López Ariste & Casini 2005; Ramelli et al. 2005). Together with a suitable inversion technique, which takes into account the joint action of the Hanle and Zeeman effects, full-Stokes polarimetry is in fact a powerful diagnostic tool to obtain information about the three-dimensional geometry of the magnetic fields that channel the spicular motion. In particular the Helium multiplets at 5876 and 10830 Å are very useful spectral lines for that purpose.

In the past year an ambitious observational project of spicules in the Helium D_3 multiplet has been stared at the Istituto Ricerche Solari Locarno (IRSOL) taking advantage of the good performances of the Zurich Imaging Polarimeter (ZIMPOL) (Gandorfer et al. 2004). A preliminary physical interpretation of our observations based on suitable inversion techniques has been applied in order to obtain information on the magnetic field vectors involved.

With the same technique we have additionally obtained several prominence observations, which are described also in these proceedings (Ramelli et al. 2006).

2. The Observations

The observations of spicules were performed with the Gregory-Coudé Telescope (GCT) at IRSOL, whose aperture is 45 cm. The ZIMPOL polarimeter (Gandorfer et al. 2004) allowed precise measurements free from seeing induced spurious effects (modulation at 42 kHz). The solar image was rotated with a Dove prism set after the polarization analyzer in order to keep the limb parallel to the spectrograph slit. A limb tracker was used to maintain the distance from the limb constant. 53 spicules measurements were obtained at different latitudes and limb distances during 15 days in the period between November 2004 and June 2005. The total exposure time for each measurement ranged from 10 minutes to about 1 hour. Every 2 minutes simultaneous measurements of Stokes I, V/I and one linear polarization component (alternatively Q/I and U/I) was stored allowing to observe the time evolution. Despite of the fact that the dynamic jets that we call spicules have a lifetime of 5-10 minutes, the general structures of the obtained Stokes images remained almost similar even during the long measurements.

Calibrations observations were performed regularly. These included polarimetric efficiency measurements, dark current, flat field and measurements of the instrumental polarization.

The instrumental polarization could be carefully corrected for, taking advantage of the fact that in a GCT the instrumental polarization for a given wavelength is a function of declination and stays therefore almost constant over one day. The crosstalks $I \rightarrow Q$, $I \rightarrow U$ and $I \rightarrow V$ were determined through the measurements performed in quiet regions near the solar disk center. The crosstalks $Q \rightarrow V$ and $U \rightarrow V$ were determined applying a linear polarization filter at different positions before the entrance window of the telescope. The results as a function of the declination are shown in Fig. 1. The $V \rightarrow Q$ and $V \rightarrow U$ crosstalks were extracted from the $Q \rightarrow V$ and $U \rightarrow V$ crosstalk mea-

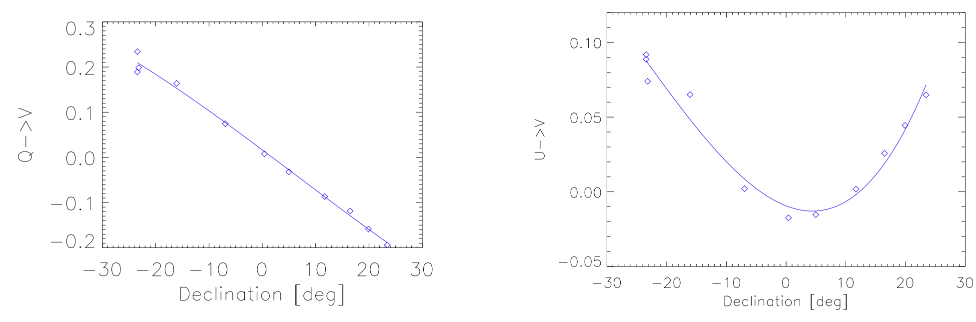

Figure 1. Measurement of linear to circular crosstalks as a function of declination for He-D_3. *Left:* $Q \rightarrow V$ crosstalk. To obtain this measurement a linear polarizer is placed before the entrance window of the telescope with the polarization axis parallel to the geographic equator, which is our choice here for the positive direction of Stokes Q. *Right:* $U \rightarrow V$ crosstalk. To obtain this measurement the linear polarizer is rotated by 45° with respect to the previous measurement.

surements taking into account the symmetries of the theoretical Müller matrix of a GCT (see Sánchez Almeida et al. 1991).

3. Inference of the magnetic field from the He-D_3 profiles

A database containing the theoretical Stokes profiles for different limb distances, magnetic field orientations and strengths has been created, with the theoretical Stokes profiles calculated via the application of the quantum theory of the Hanle and Zeeman effects (see, e.g., Landi Degl'Innocenti & Landolfi 2004) Spicules are assumed to be optically thin. The theoretical profiles that better fit the measured profiles are carefully searched in the database, in order to infer the magnetic field vector.

Future planed improvements in our analysis will include the introduction of non-thermal motions to better fit the intensity profiles and a detailed study of the so-called Van Vleck ambiguity which may occur in addition to the well known 180° ambiguity. We will eventually evaluate the opportunity to account for radiative transfer effects (see Trujillo Bueno et al. 2005), although they are usually small for the He-D_3 line.

4. Results

A preliminary analysis of our observations in quiet regions shows that generally the measured He-D_3 Stokes profiles are compatible with a magnetic field strength of approximately 10 gauss (see examples in Fig. 2, 3 and 4), which is in good agreement with the results obtained from the He I 10830 Å multiplet by Trujillo Bueno et al. (2005). The Stokes V profiles are usually dominated by the symmetric signature due to the alignment-to-orientation transfer mechanism discussed by Kemp et al. (1984) and Landi Degl'Innocenti & Landolfi (2004).

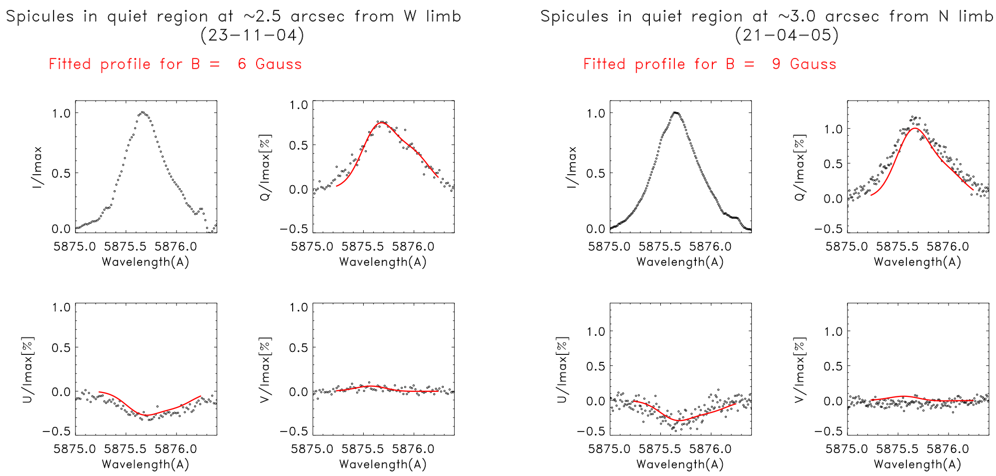

Figure 2. Examples of Stokes profiles observed in a quiet region obtained after integrating 60 arcseconds along the direction specified by the spectrograph slit. The solid lines show the corresponding theoretical fits.

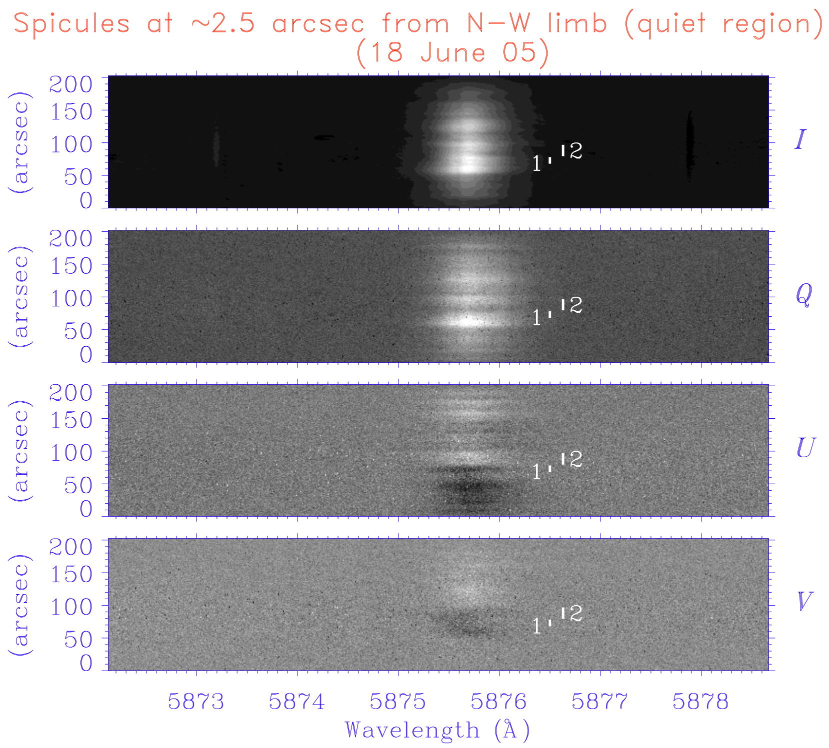

Figure 3. A measurement of spicules in a quiet region. Note that the V-profile is dominated by the alignment-to-orientation conversion mechanism explained in Kemp et al. (1984) and Landi Degl'Innocenti & Landolfi (2004). Two regions marked with "1" and "2" are selected for inversions, which are shown in the next figure.

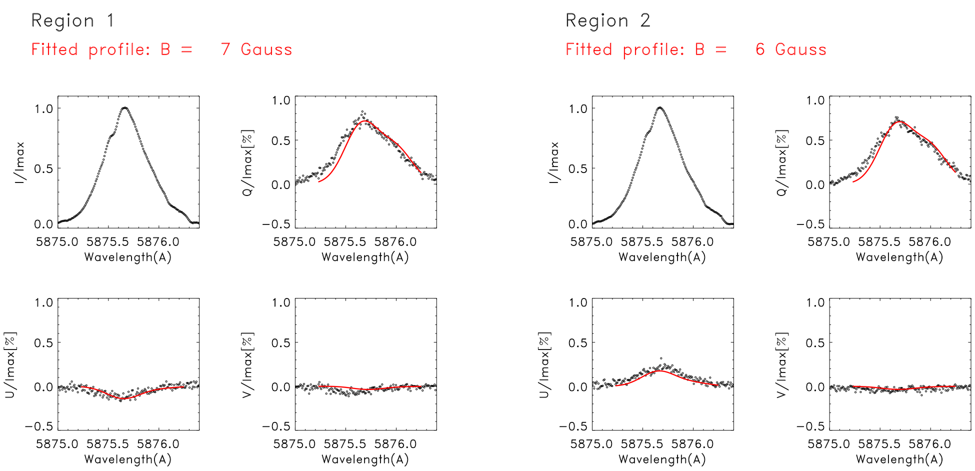

Figure 4. Stokes profiles corresponding to the two regions selected in Figure 3 with the ensuing theoretical fits (continuous lines)

Only in one measurement the Stokes profiles indicate magnetic field strengths as high as 50-60 gauss (Figs. 5 and 6). In this particular case the Stokes V profile shows a typical Zeeman-like antisymmetric shape. Note that Stokes Q is affected by a strong depolarization. It is very important to point out that this measurement was obtained near the equator in the proximity of an active region (AR 10776, 18 June 2005).

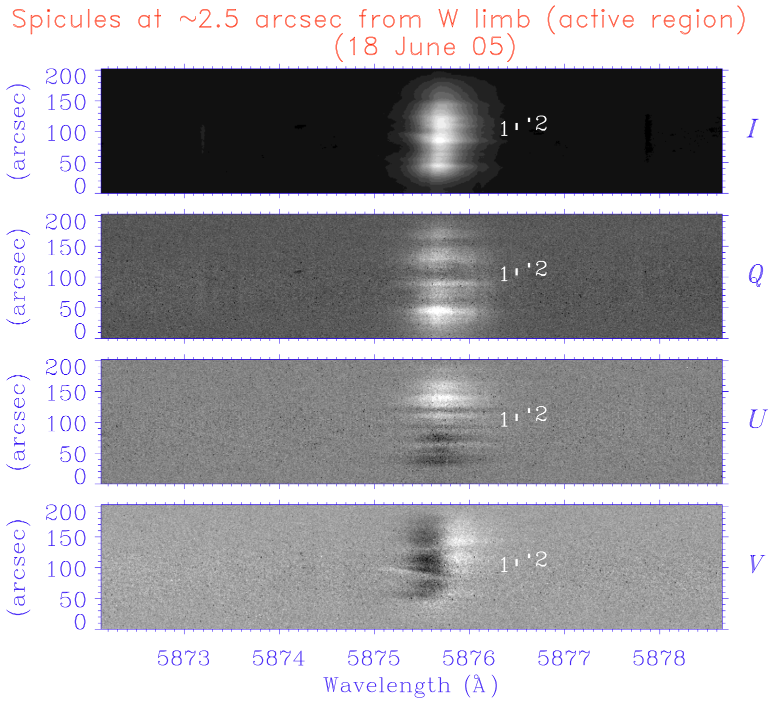

Figure 5. Spectropolarimetric observation of spicules near an active region showing antisymmetric Zeeman-like Stokes V profiles, which indicates stronger magnetic fields. Two regions marked with “1” and “2” are selected for inversions, which are shown in the next figure.

5. Conclusion

Using ZIMPOL at the GCT telescope in Locarno it was possible to obtain a large set of high quality full Stokes spectropolarimetric measurements of spicules in He-D_3. The observations of spicules in quiet regions indicate that the magnetic fields involved are around 10 gauss. In one measurement taken in the proximity of an active region, magnetic fields up to 50-60 gauss were found.

Acknowledgments. We are grateful for the financial support that has been provided by the canton of Ticino, the city of Locarno, ETH Zurich and the Fondazione Carlo e Albina Cavargna. This work has been also partially supported by the Spanish Ministerio de Educación y Ciencia through project AYA2004-05792 and by the European Solar Magnetism Network.

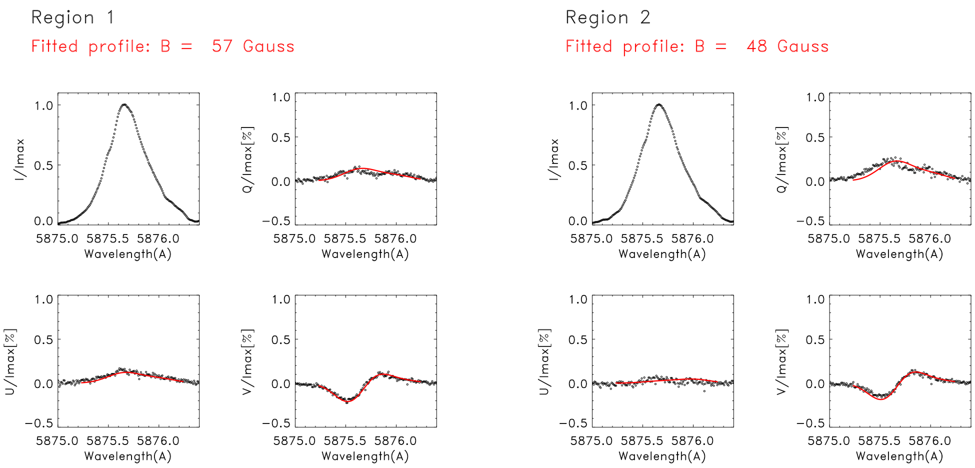

Figure 6. Stokes profiles obtained after integrating the two regions selected in Fig. 5 together with fitted theoretical profiles (solid lines)

References

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

Gandorfer A. et al. 2004, A&A, 422, 703

Kemp J. C., Macek J. H., & Nehring, F. W. 1984, ApJ, 278, 863

Landi Degl'Innocenti E., & Landolfi M. 2004, Polarization in Spectral Lines, (Dordrecht: Kluwer Academic Publishers)

López Ariste, A., & Casini, R. 2005, A&A, 436, 325

Ramelli, R., Bianda, M., Trujillo Bueno, J., Merenda, L., & Stenflo, J. O. 2005, in ESA SP-596, Chromospheric and Coronal Magnetic Fields, ed. B. Fleck & D. Danesy (Noordwijk: ESA Publications Division)

Ramelli, R., Bianda, M., Merenda, L., Trujillo Bueno, J., & Stenflo, J. O. 2006, these proceedings

Sterling, A. C. 2000, Solar Phys., 196, 79

Sánchez Almeida J., Martínez Pillet V., & Wittmann A. D. 1991, Solar Phys. 134, 1

Trujillo Bueno, J., Merenda, L., Centeno, R., Collados, M., & Landi Degl'Innocenti, E. 2005, ApJ, 619, L191