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Spectro-polarimetry of a sunspot simultaneously in atomic and molecular lines

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Abstract. We performed with THEMIS spectro-polarimetric observations simultaneously in various atomic and molecular lines. We present the observations and discuss an important aspect of spectro-polarimetric data reduction: the recentering of the frames in the spectral direction needed before substracting spectra to extract polarized Stokes parameters. We conclude that THEMIS has the unique capability, among present time large solar telescope, of providing polarization data almost free from instrumental effects.

Key words. Sun: Magnetic fields – Sunspots

1. Introduction

The magnetic field at the solar surface manifests itself most prominently in the form of sunspots, but a completely coherent picture of the thermal and magnetic structure of sunspots still has not emerged (Solanki, 2003). The current models of sunspots could be significantly improved by means of simultaneous inversions of Stokes profiles of molecular and atomic lines. The inclusion of molecular lines brings real gains for sunspot models. One is their extension to layers where atomic lines suffer from NLTE effects but molecules can still be treated in LTE. Another one is to probe the thermal and magnetic structure of the coolest parts of sunspots. We took advantage of the unique multi-line spectro-polarimetric capabilities of THEMIS to simultaneously observe spectral regions with lines of various molecular and atomic species, forming at different heights in the sunspot atmosphere, which are strongly sensitive to the magnetic field, temperature, and pressure.

2. Observations

We performed spectro-polarimetry of the NOAA 10667 sunspot during several consecutive days. Six spectral regions were observed simultaneously:

– *5139–5145 Å*: includes several magnetically sensitive atomic, C_2, and MgH lines.
– *5197–5203 Å*: includes 5 strongly magnetically sensitive MgH lines from the A-X(0,0) band, and other atomic lines. The

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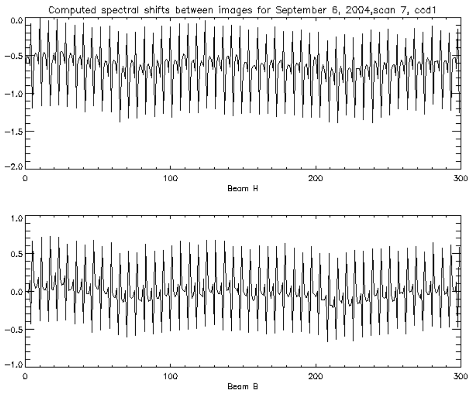

Fig. 1. Computed spectral shifts between frames for the observation described in the text, shifts are given between the first and the current frame. The horizontal axis is in frames number units (the time between two consecutive frames is 3.4 second). The vertical axis is in pixels units.

MgH lines are temperature and pressure sensitive.

- *5247–5253 Å*: includes 2 strongly magnetically sensitive Fe I lines which have almost identical properties but form at different heights and have different Landé factors.
- *5872–5879 Å*: includes the He I D_3 line, which forms in the chromosphere, and is a good indicator of flares.
- *6705–6709 Å*: includes the Li I 6708 Å doublet which can be observed in the umbra.
- *7053–7059 Å*: includes the TiO (0,0) R_3 band-head of the γ-system. The lines are strongly magnetically sensitive, they form only in cool regions of the umbra.

Preliminary results from those observations include the first full Stokes polarimetry of the TiO (0,0) R_3 band-head of the γ-system (Arnaud et al. 2007) and the first incorporation of MgH and TiO lines into inversions (Afram et al. 2007).

3. Data reduction

The Themis polarization analysis package consists in two achromatic quater-wave plates followed by a polarizing beam-splitter. In the set up we used the two resulting spectra are, for each spectral region, detected on the same CCD. The use of two, complementary polarized, beams is needed to avoid getting seeing cross-talk in the measured Stokes parameters when polarization modulation is slow compared to seeing. For each polarimetric observation, frames from the two beams have to be recentered, in both the spectral and the spatial directions, before one can extract the polarized Stokes parameters. Recentering in the spectral direction is the most critical part of data reduction. Due to the spectrograph off axis design, the entrance slit image in the detector plane is a second order curve, not the same for the two beams which have different optical pathes. Slight flexures and some seeing may occur in the THEMIS spectrograph where the optical path is long of about 30 meters. Resulting spectral displacements get very easily to the order of several *m* at the detector level.A 1 *m* displacement of the spectrum already corresponds to 5% of a pixel and, if not corrected, may create, for a strong line, a false V/I signal of more than 1.10−3 which is already large, but for strong magnetic fields measurements. For those reasons, it is mandatory to recenter very accurately along the spectral direction, to avoid artificial V type signals which would, in particular, modify the symmetry of linear polarization profiles. To correct the shift between spectra one needs to determine the relative position of the spectrum for each CCD row of each frame. We did that using either correlations between spectra, either the bisector method (Rayrole, 1967), to determine a given line center position. Both method give comparable results. Spectra are then shifted in a way to obtain iso-lambda columns reduced frames. We performed to determine the best precision one can expect for spectral recentering and found it to be of 10^{-2} pixel (Carfantan and Arnaud, 2007). We also recenter frames in the spatial direction. An accurancy of 2 or 3 tenths of a pixel (0.1 to 0.15 arc second) is there adequate, the image quality beeing of the order of 1 arc second. A good spectral recentering precision can be obtained only on the quiet Sun for polarimetric observations. On active regions, magnetic lines shape get asymmetrical due to the

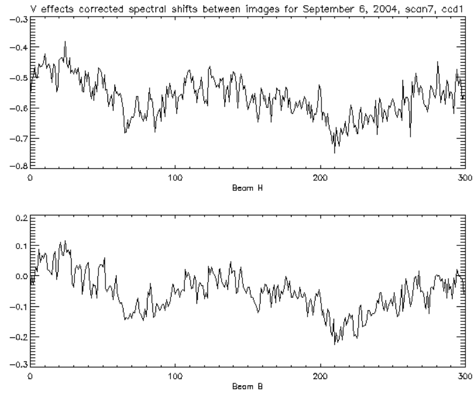

Fig. 2. Same as figure 1 but corrected from the "V" effect on the shifts measurements, as decribed in the text.

Zeeman effect, for I±V spectra. Shifts computed using such spectra are falsified due to this asymmetry and can not be directly used for recentering. Fig. 1 presents computed spectral shifts between frames for a sunspot observation (NOAA active region 10667), in a spectral region including the Fe I doublet at 525 nm. This observation was performed with a fixed slit position and the following polarization measurement sequence: I+Q, I-Q, I+U, I-U, I+V, I-V for one beam, the signs beeing inverted for the second beam. This sequence was repeated 50 times, 300 frames beeing recorded for each beam. For I±V spectra, systematic differences in the computed shifts, of about ±0.5 pixel compared to I±Q or I±U spectra, are observed. This is huge. One order of magnitude fainter systematic errors are also present for linear polarization spectra. This comes from V signal present in those spectra, due to a cross-talk of 0.10*V in Q and 0.15*V in U as the polarization analyser plates retardance is of about 95^o at 525 nm. The "V" induced error is, for a given slit position, assumed to be constant for each of the 6 analyser configurations used and to be, for a given configuration, the mean value of of the computed shifts for all the frames obtained with this configuration (shift in respect with the configuration giving I+Q for the first beam). The correction is done by removing those mean values from the corresponding frames. Fig. 2 displays the same spectral shifts than Fig. 1 but corrected from those "V" effects. The shape of the shifts variations with time is very similar for the two beams, demonstrating the good precision of their measurements. During the 17 minutes this sequence lasted, the shift amplitude was of about 0.3 pixel. It is a large value in terms of false V signals on can get if it is not corrected, it is really mandatory to take it into account.

4. Conclusion

Themis possesses the unique capability of Multi-line spectro-polarimetric. This capability is a very powerfull tool for sunspots structure diagnosis as proved by our observations (Afram et al., 2007). An image stabilization device has recently been implemented at Themis. It will very significantly enhance the Themis sensitivity in measuring the Zeeman effect in structured regions of the Sun. New detectors, faster and more sensitive, are now available at Themis, improving its efficiency. To perfectly avoid cross-talk between Stokes parameters, it should be usefull to implement a possibility for a precise determination, in observations conditions, of the quarter-wave plates retardation. This, with an improved thermal control of the spectrographs environment, will provide almost instrumental effects free measurements of the solar emission Stokes parameters. Themis is the only present time large solar telescope where this is possible.

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