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# Spectro-Polarimetry of a Sunspot in Atomic and Molecular Lines with THEMIS

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**Abstract.** We present spectro-polarimetric observations of a sunspot, which were recorded simultaneously with THEMIS in various atomic and molecular lines. These observations include the first full Stokes measurements of the band-head of TiO around 7055 Å.

## 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 non-LTE 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, which form at different heights in the sunspot atmosphere, and are strongly sensitive to the magnetic field, temperature, and pressure. We present hereafter observations of a sunspot during good seeing conditions.

## 2. Observations

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

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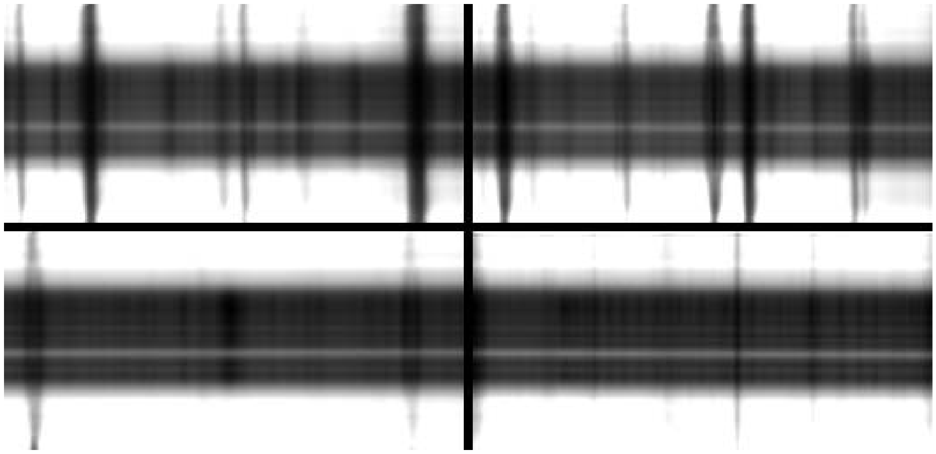

Figure 1. Four of the six spectral regions simultaneously observed in NOAA 10667 sunspot: 5197.9–5202.8 Å (top left); 5247.2–5253.0 Å (top right); 6704.5–6711.2 Å (bottom left); and 7052.5–7058.1 Å (bottom right). The Zeeman splitting is evident in highly magnetically sensitive lines like the 5250.2 Å Fe I line (Landé factor of 3). Many molecular lines, as well as the 6708 Å Li I doublet, show up only in the umbra (the horizontal dark stripe). The bright, narrow stripe in the umbra is a light bridge.

- *5139–5145 Å*: includes several magnetically sensitive atomic, $C_2$, and MgH lines. The $C_2$ lines are strong in the penumbra and weak in the umbra.
- *5197–5203 Å*: includes 5 strongly magnetically sensitive MgH lines from the A-X(0,0) band, and other atomic lines. The MgH lines are temperature and pressure sensitive and visible in both umbra and penumbra.
- *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, allowing to determine both the magnetic field strength and the filling factor.
- *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 observed in the umbra.
- *7053–7059 Å*: includes the TiO (0,0) $R_3$ band-head of the $\gamma$-system. The lines are strongly magnetically and temperature sensitive, and they form only in cool regions of the umbra.

The spatial scale on the detectors is 0.465 arcsec/px, and the spectral scale between 18 and 24 mÅ/px depending on the spectral region. The slit is $1''$ wide and $58''$ long.

The THEMIS polarization analysis package consists of two achromatic quarter wave-plates followed by a beam splitter, so to have $I+S$ in one beam and $I-S$ in the other beam. A polarization sequence consists in a set of six measurements, $S$ taking successively the values $Q$,$-Q$, $U$,$-U$, $V$,$-V$. To get enough sensitivity

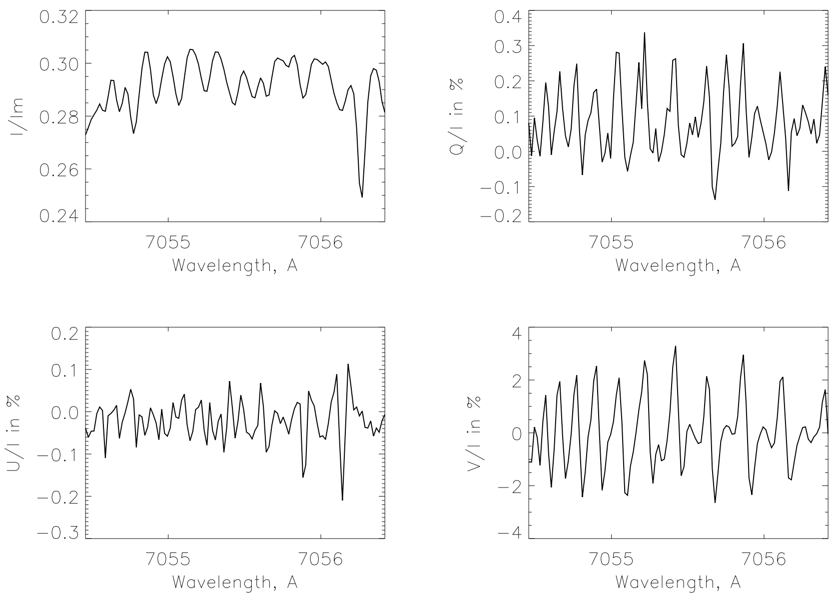


Figure 2. Stokes parameters in the TiO band-head for a $1'' \times 1''$ square in the sunspot umbra. $I_{\mathrm{m}}$ is the continuum intensity outside the sunspot.

for weakly polarized molecular lines, we repeated this sequence at least 10 times for each slit position during a scan. This observational strategy is comparable to a very low polarization modulation of 0.08 Hz frequency. The exposure time depends on the spectral region, the longest being 1.2 second. Our strategy also reduced image motion effects on the polarization. No image stabilization was available at this time at THEMIS.

## 3. The TiO Band Lines and the Li I Doublet

First Stokes-V sunspot measurements in the TiO (0,0) $R_3$ band-head lines were presented by Berdyugina et al. (2000), while first observations in starspots are reported by Berdyugina et al. (2006). Synthetic Stokes profiles were computed by Berdyugina et al. (2000), and by Berdyugina, Solanki, & Frutiger (2003). We report here what is, to our knowledge, the first full-Stokes polarimetry of the TiO band lines in a sunspot. Figure 2 displays a September 6, 2004 measurement, while the sunspot was at $\mu = 0.907$. TiO lines are visible in the umbra in all the Stokes profiles. They are also marginally visible in the narrow lightbridge (Fig. 1). This may be due to image motion spreading the umbra spectrum slightly outside the umbra.

Figure 3 displays simultaneous full-Stokes polarimetry of the Li I doublet. This doublet is almost invisible in intensity in the quiet Sun. In the umbra, it becomes the strongest absorption feature of the spectral region and the two lines, broaden in intensity, are blended. They appear narrow and well separated in linear polarization. The polarimetric precision is $3 \times 10^{-4}$ of continuum intensity. It decreases in the main lines cores by a factor of 2 to 4. This signal-to-noise ratio reduction is likely caused mainly by image motion effects.

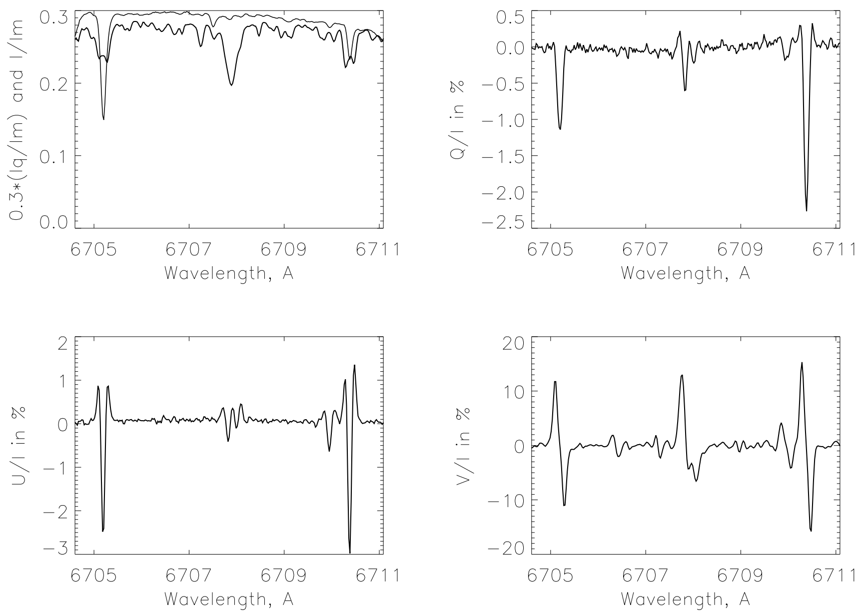


Figure 3. Stokes parameters observed in the Li I 6708 Å doublet in the same field inside the sunspot umbra, and at the same time, as the observation displayed in Fig. 2. $I_{\rm m}$ has the definition given in Fig. 2. $I_{\rm q}$ is the intensity spectrum of the quiet Sun. The continuum intensity is not flat due instrumental effects. The two highly polarized lines on both sides of the spectrum are Fe I lines. Many weak lines of this spectral region exhibit polarization inside the sunspot.

## 4. Conclusion

We presented in this paper an example of observations taking full advantage of the THEMIS multi-line capabilities in the visible part of the spectrum. This allows more comprehensive investigations of sunspots (Afram et al. 2006). Solar atmosphere science will furthermore benefit of the improvements underway at THEMIS. An image stabilization device (tip-tilt) is to be implemented for the 2006 observing campaign. New detectors, faster and more sensitive, are planned to be installed in 2007.

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