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The status of intranetwork magnetic-field observations with THEMIS(*)

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Summary. — Weak magnetic fields inside network cells are an important component of the solar magnetic field and they have been observed by a number a groups in the past few years, which yielded important clues to their behavior. However it is important to confirm these different results and to state with greater precision the properties of intranetwork magnetic features (vector magnetic field, lifetime...). In this paper we describe some of the multi-line spectro-polarimetric observations made with the THEMIS telescope in June 2000 in order to study the intranetwork magnetic fields. We highlight the data processing and some limitations we met when performing this study.

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1. – Introduction

Weak magnetic fields observed inside network cells are an important component of the solar magnetic field besides the magnetic fields concentrated in active regions and the network. Important clues have been obtained by different teams during the recent years (see, among others, [1-7]). However, the observed properties cover a wide range and it is important to confirm them, for example by studying the vector magnetic field and the lifetime of the intranetwork features.

We present here the first observations made with THEMIS to address this problem. We highlight the data processing and the limitations. We first describe the observations

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and the data processing. Then we identify some important sources of uncertainty. Lastly, we present the results obtained using different approaches on these data.

2. – Observations

2˙1. *Instrumental set-up.* – The observations were performed using the MTR mode with the THEMIS telescope. This multi-line spectro-polarimetric mode, described by [8], allows simultaneous $I+$ Stokes and $I-$ Stokes observations. The field of view was ~ 50 arcseconds (in the direction along the 0.5 arcsecond wide slit). Spatial scans with a step of 0.8 arcseconds were performed to make 2D maps, and we observed $[Q, -Q, U, V]$ sequences to allow for a beam exchange analysis (the beam exchange was possible for one Stoke parameter only). It took ~ 6 seconds to record a 4 Stokes sequence on 6 cameras. We focus here on 2 of the spectral domains that were observed: the 6302.5 Å / 6301.5 Å Fe I lines (Lande factor, respectively, 2.49 and 1.67) and the 5576.1 Å Fe I line (this line is non-sensitive to the Zeeman effect and is therefore very useful to check the amplitude of various cross-talks).

2˙2. *Targets and observing conditions.* – We concentrate on 2 scans made, respectively, on June 2000, 23 and June 2000, 28. *Scan* 1 was made on a very quiet region close to disk center and consisted of a spatial scan of 25 steps of the $[Q-QUV]$ sequence. The time exposure was 300 ms and the seeing was one of the best in our observing run. *Scan* 2 consisted of a spatial scan of 75 steps of 5 $[Q-QUV]$ sequences and the time exposure was 800 ms. Both exposure times are larger than the typical time scale of image motions and this scan was still the best we obtained with several observations for each spatial position.

3. – Data processing

After extraction of the useful zones on the camera and dark correction, the different steps of the data analysis are the following:

3˙1. *Flat-field and line curvature correction.* – For each Stokes parameter of the averaged flat field, we compute the line curvature. After a correction of the curvature, a mean spectral profile is computed. The flat-field images are divided by this profile to remove the spectral signatures and shifted back to the initial line curvature. The scan spectra are corrected from the flat field before the curvature correction, which is then performed using the coefficient computed on the flat field.

3˙2. *Shift in x (wavelength) and y (spatial).* – The shift in x is computed using a profile averaged over each spectrum. A cut in the slit direction averaged over the continuum is used to compute the shift in y (cross-correlation of the granulation signal used).

4. – Main sources of uncertainties

Table I presents some important sources of uncertainties in the analysis of this type of data. The first problems in the table relate to the observations themselves, while the latter originate in the data processing. The different methods used to compute the Stokes parameters (spectra subtraction or beam exchange technique with a multiplicative method) are not sensitive to the same problems.

TABLE I. – *Main sources of uncertainties. The most important ones are indicated in italic.* (*) *The 2 slits do not observe the same region.* (**) *It is not very sensitive to the flat field but is still sensitive to the line curvature correction.*

Origin	Spectra subtraction	Beam exchange
Different magnification for the 2 paths	*yes*	no
Different focus for the 2 paths	*yes*	no
Bad co-spatiality*	*yes*	*yes*
Seeing	No (for 1 Stokes)	*yes*
Photon noise	yes	yes
Fringes	yes	yes
Flat field and line curvature	yes	Yes/no**
Shift in wavelength between spectra	*yes*	no
Shift in y (spatial) between spectra	*yes*	*yes*
Continuum normalization between the 2 paths	*yes*	no

4˙1. *Photon noise.* – The photon noise for one pixel (in one spectrum) is $1/\sqrt{235 I_{\mathrm{ADU}}}$. An estimation of the expected photon noise for our scans in the 6302.5 Å line (for *scan* 2, 5 successive spectra can be averaged together) is shown in table II. Note that we expect a different noise level while using the beam exchange computation (see subsect. **5˙3**).

4˙2. *Image motions.* – We note that there is no image stabilization on THEMIS and that the spatial scanning is made moving the whole telescope. A cross-correlation analysis of a field image series shows that the pointing difference between consecutive Stokes measurements is very variable: the width at half-maximum of the distribution is 1.5 arcseconds. Therefore it is impossible to measure a sequence of Stokes parameters such as $Q-QUV$ (or even QUV) corresponding to the same region on the Sun (this is particularly true for small-scale features). The beam exchange analysis combines the images of a sequence of observations. Therefore, we expect the resulting Stokes parameters to get a contribution from a much larger surface (and with inequal weighting) than for a single measurement. The actual spatial resolution after averaging many spectra would be between 1 and 2 arcseconds at best (note that the dispersion indicated above is for the case of our best seeing).

5. – Results

5˙1. *Longitudinal magnetic-field calculations using the* $[pos(I+V)-pos(I-V)]$ *technique.* – Using the center-of-gravity method ([9], for example), we calculate a map of $B_{\|}$ for 2 lines: 6302.5 Å and 5576.1 Å, the latter being non-sensitive to the magnetic field. Comparison of this "magnetic field" in pixel units (before calibration with the spectral

TABLE II. – *Photon noise estimations.*

Position	*scan* 1	*scan* 2 (before aver.)	*scan* 2 (after aver.)
Line core	$3.2 \cdot 10^{-3}$	$1.9 \cdot 10^{-3}$	$8.5 \cdot 10^{-4}$
Continuum	$2.0 \cdot 10^{-3}$	$1.2 \cdot 10^{-3}$	$5.2 \cdot 10^{-4}$

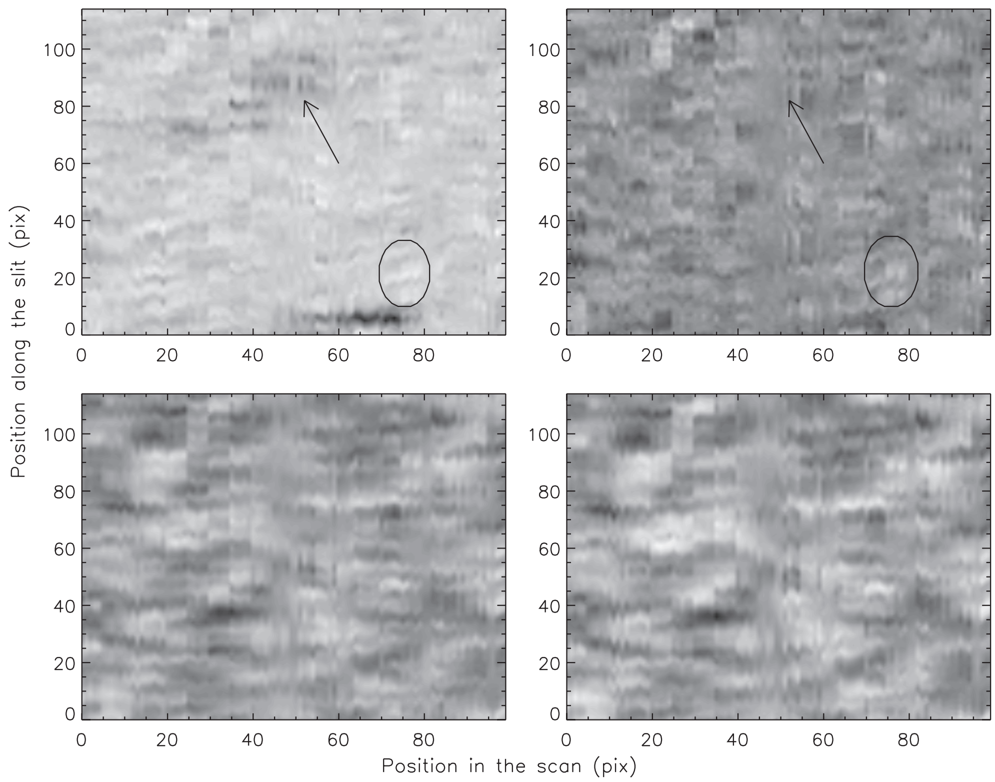

Fig. 1. – A portion of the maps for *scan* 2 before averaging. Each 5 consecutive column is supposed to correspond to the same region on the sun (top: "magnetic field", bottom: longitudinal velocity; left: 6302.5 Å; right: 5576.1 Å).

resolution and with the Lande factor for the 6302.5 Å line) shows how far above the noise due to various sources (all except magnetic noise sources in fact) the 6302.5 Å signal is. A portion of the maps is shown in fig. 1 for *scan* 2 before averaging. We confirm on *scan* 2 that even on a network feature, the signal is not always present on all 5 observations (*i.e.* the image motions are sometimes too large to keep a network feature on the slit), as shown by the arrow for example. 2D maps in the 2 lines are very similar (see, for example, the patterns in the 2 circles) except for dark network features (one at the top and one at the bottom in this example). Therefore this method does not seem adapted to the study of intranetwork magnetic fields given the current data quality. The same patterns in the 5576.1 Å and 6302.5 Å $B_{\|}$ maps are observed, and it is very likely that this is due to the fact that the pointing is different for the 2 paths. The other uncertainties should lead to a different pattern (because the analysis is made independently) or should have no influence (for example no seeing influence because the measurements are made simultaneously).

5˙2. *Subtraction of spectra made simultaneously.* – Because there is no image stabilization on THEMIS, it was important to try to compute each Stokes parameter without using the beam exchange technique, *i.e.* taking full advantage of simultaneous measurement of $I+$ Stokes and $I-$ Stokes. A normalization of the continuum is necessary. On

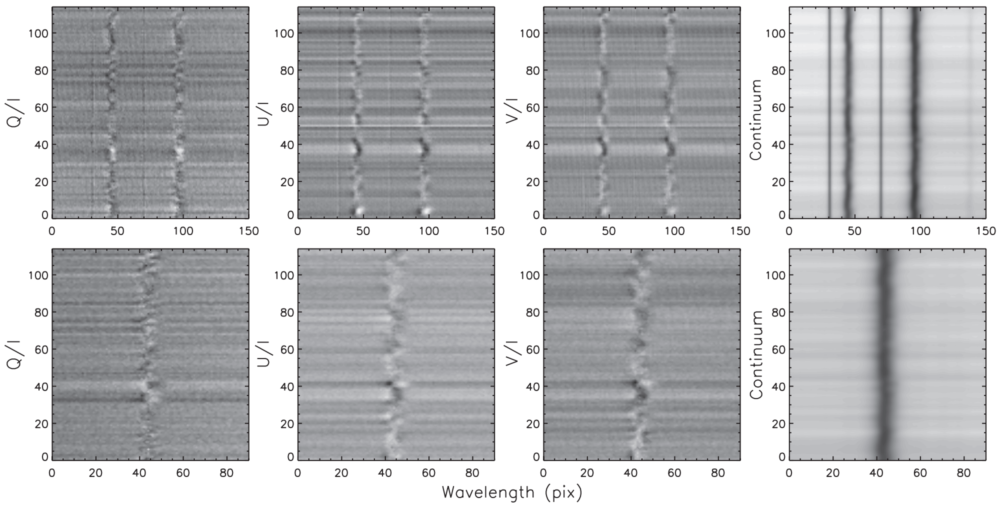

Fig. 2. – Stokes spectra for one position in *scan* 2 and for the 2 lines (top: 6302.5 Å and 6301.5 Å, bottom: 5576.1 Å).

scan 1, for example, the typical "percentage of polarization" in the telluric line is of $\sim 4\%$ and in the 6302.5 Å and 5576.1 Å lines the signal is around $\sim 2\%$ everywhere, with large similarities between the different Stokes parameters, Q or U signal looking like V, etc. This subtractive technique is very sensitive to uncertainties, which can be quite large compared to what we want to measure (see table I). An important point is the fact that the 2 slits do not observe the same position on the Sun. This was not directly measured, however a comparison of the typical current amplitude of the signal with our November 2000 observations (for which there was a shift of 0.22 arcsecond between the 2 paths) shows that in June the 2 paths probably had a separation of the order of 0.1 arcsecond. The uncertainties are therefore too large to detect intranetwork magnetic fields. This means that it is not possible to take full advantage of the fact that the Stokes parameters are measured simultaneously.

5˙3. *Using the beam exchange*. – Given the previous results and the THEMIS configuration (the 2 paths are very different), the use of the beam exchange seemed the most promising. Figure 2 shows Stokes spectra for one position in *scan* 2 and for the 2 lines. We see that some patterns are similar for different Stokes measurements. We note that because of the beam exchange technique they are not independent.

In table III, we compare the standard deviation in different domains (continuum and

Table III. – *Standard deviation in different domains for scan* 1.

Spectral domain	$\sigma_{\rm obs}$ (Q/I)	$\sigma_{\rm ph}$ (Q/I) expected
5576 line	$3.55 \cdot 10^{-3}$	$2.7 \cdot 10^{-3}$
5576 continuum	$1.86 \cdot 10^{-3}$	$1.5 \cdot 10^{-3}$
6302 line	$2.52 \cdot 10^{-3}$	$1.6 \cdot 10^{-3}$
6302 continuum	$1.34 \cdot 10^{-3}$	$1.0 \cdot 10^{-3}$

line core) with the expected photon noise. Part of the signal in the lines corresponds to a solar pattern. Note that the standard deviation for U/I and V/I are observed to be twice the values for Q/I (the beam exchange has indeed been performed with Q only), while we expect a factor $\sqrt{2}$. The beam exchange technique is less sensitive to the flat-field correction, which could explain the difference. A large part of the noise is therefore due to the photon noise, in both the continuum and in the lines. In the continuum, a small part of the noise could be due to fringes (which are visible on certain spectra, for example on the V/I spectrum for the 6302.5 Å line). However the patterns seen on the Stokes spectra have another origin and it proved to be difficult to average the bursts together without any image stabilization. Although the ratio between the signal in the line and in the continuum seems to be slightly larger for the 6302.5 Å line than for the 5576.1 Å line, the difference is marginal. Many patterns in the Stokes spectra are also very similar between the 2 lines. We believe that those patterns are not due to the data processing but to a difference in pointing between the 2 paths (bad co-spatiality). A simulation using realistic velocity gradients shows that it is the combination between the seeing and the difference between the 2 paths that leads to such patterns. The amplitude of the distorted signal is slightly larger than the true signal.

6. – Conclusion

In this paper we attempted to observe intranetwork magnetic fields with THEMIS. The analysis of the biases and the comparison between the signals provided by a line sensitive to the magnetic field and a line which is not sensitive to it show that it is impossible to detect these weak fields in the quiet sun at the present time. We estimate that the main problem is due to the combination of a bad co-spatiality between the 2 slits and the seeing. This problem should be crucial for all observations requiring both high spatial resolution and high polarization sensibility. Also important are the fringes, which remains when averaging the data, and the photon noise. The signal-to-noise ratio could be increased if it was possible to average the data. However, this proved to be difficult because the actual spatial resolution is degraded to 1.5–2 arcseconds in the best conditions we had, due to the absence of image stabilization. An attempt to average a large number of short scans together (30 scans over 45 minutes) shows that here again there is no signal outside the network except due to velocity residuals. Because we are performing spectroscopic observations, a different region is observed for each frame and the information is lost: it is not possible to recover the information using data processing after the observations. It is therefore necessary to improve the image quality at THEMIS (and to install an image stabilization as a first step as soon as possible) and to estimate the limits of the adjustments that can be made between the 2 slits if one wants to observe these intranetwork magnetic fields with THEMIS. Because the detection threshold we get for the polarization is quite high, these observations did not provide any strong constraints on the intranetwork magnetic fields.

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