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Using reduction and inversion tools for THEMIS-MTR data: chromospheric reversals of a moving magnetic feature and an ephemeral region

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Abstract. New tools have been developed for THEMIS spectropolarimetric data. In this paper we present how these tools work and can be used in order to understand two interesting observed phenomena: a moving magnetic feature and an ephemeral region.

Key words. Sun: photosphers - chromosphere - magnetic structures

1. Introduction

The moving magnetic features (hereafter MMFs) were discoverd by Sheeley (1969)[1]. They are magnetic structures that live at an annular region around the sunspot, so-called the moat (Harvey & Harvey, 1973; Brickhouse & Labonte, 1988). Several models have been proposed to explain the different types of MMFs (see Shine & Title, 2001),(see Thomas & Weiss, 2004). From the very first studies, the MMF activity has been related with the Evershed flow and the penumbral filaments. These relationships have been recently observed by Cabrera Solana et al. (2006) and Sainz Dalda & Martínez Pillet (2005) respectively. Their physical properties are well known at the photosphere from dopplegrams and magnetograms, but until now their real topology has kept hidden. To this aim, we have used the capabilities of THEMIS telescope (Rayrole & Mein, 1993) to observe an active region at photosphere and chromosphere simultaneously, getting spectropolarimetric data and recovering the magnetic field vector and other physical parameters.

The ephemeral regions (hereafter ERs) are small bipolar regions which opposite polarities show the following behaviour (Martin, 1990): i) they appear almost simultaneously and very close to each other, ii) they increase their magnetic flux as time goes on, and iii) they move in opposite directions as they increase in magnetic flux. ERs were first observed by Dodson (1953) and studied in detail by Harvey & Martin (1973). A summary of their physical properties can be found in

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[1] A good summary of MMFs can be found at Shine & Title (2001)

Hagenaar (2001). Until now, the mechanisms at the origin of ephemeral regions are unknown. Their contribution to the global solar magnetic field could be important due to their large number in the solar cicle (Schrijver et al., 1997; Hagenaar, 2001). Roughly, they appear over the solar photosphere at a rate of 4×10^4 per day, contributing in several 10^{22} Mx day^{-1} to the total flux rate (Hagenaar, 2001). The emergence comes from the photosphere layer to the corona, but the magnetic evolution of these bipoles in their emergence process through the photospheric and chromospheric layers is missing.

In this work, we show how we have used the THEMIS MTR[2] instrument for studying the activity around the sunspot, and how we have got the physical information from spectropolarimetric, simultaneous observation. THEMIS MTR instrument allows full spectropolarimetry of several lines of interest simultaneously and in the absence of any parasitic instrumental polarization. However, the reduction and inversion of the obtained data have been a hard problem for a long time. We have developed several tools trying to improve this aspect. A general purpose demodulation code, i.e. for all wavelengths and for all kind of MTR observing modes, so-called *Stokes QUick Viewer* (hereafter SQUV) and a PCA-based code for photospheric Fe I 6301 and 6301 Å lines are available for the observers and the solar community. Furthermore, we have used the code developed by Socas-Navarro (1999) for the inversion of the Ca II IR triplet lines.

We have found reversed polarities of the Stokes V profiles in the chromosphere with respect to those of the photosphere (we refer to this fact as *chromospheric reversals*) in a MMF and a ER. Taking a quick look at the Stokes profiles we suggest a possible topology that could explain the observation. We also show the very preliminar results of the inversions made on the Ca II IR triplet lines.

[2] MTR stands for multi-wavelength observing mode, from french expression *MulTiRaei*. Usually it works joined to the polarimeter.

2. Codes

SQUV has been designed to recover the Stokes parameters from a given sequence of modulation of polarization. It is a code based on the demodulation matrix technique from Collados (1999). This technique returns the Stokes parameters using the optimun demodulation matrix $\mathbf{D}$ of all possible ones that satisfy $\mathbf{S} = \mathbf{D}\widetilde{\mathbf{S}}$, where $\mathbf{S}$ is the Stokes vector and $\widetilde{\mathbf{S}}$ are the raw measurements (i.e. the signals measured on the CCD). This the demodulation matrix is retrieved using the single value decomposition method. The setup parameters of the code correspond to THEMIS telescope polarization analyzer or polarimeter: the thickness and physical properties of the lames of the polarimeter (one set for the visible, the other one for the infrared). The sequence of modulation of polarization must be composed by more than three polarization states. Otherwise, SQUV returns the data ready for a *manual* add and/or substraction. That is, the data are clean with the standard corrections of dark current (DC), flat-field (FF) and curvature of each orthogonal Stokes images. The last one is computed as the position of the minimum of a given spectral line interpolated with cubic splines. More details on SQUV can be found at Sainz Dalda & López Ariste (2006). As SQUV output we have the Stokes vector for each observed wavelength. The output is given as a standard *FITS* file. The header of this file has the information of the original observation and some additional information on the redution and demodulation proccess. More details on SQUV can be found at Sainz Dalda & López Ariste (2006).

Several useful tools have been developed for reading and mapping the SQUV output files. With them the observer can easily visualize the Stokes profiles, make Stokes maps (generated for a determined wavelength from the Stokes profiles) and displays them at solar coordinates on the solar disk. Besides, the user can easily and quickly take a first idea of the physics involved in the observation using the fast PCA-based inversion code for the photospheric Fe I 6301 and 6301 Å lines. This code was created by López Ariste et al. (2000). The code provides a good approxima-

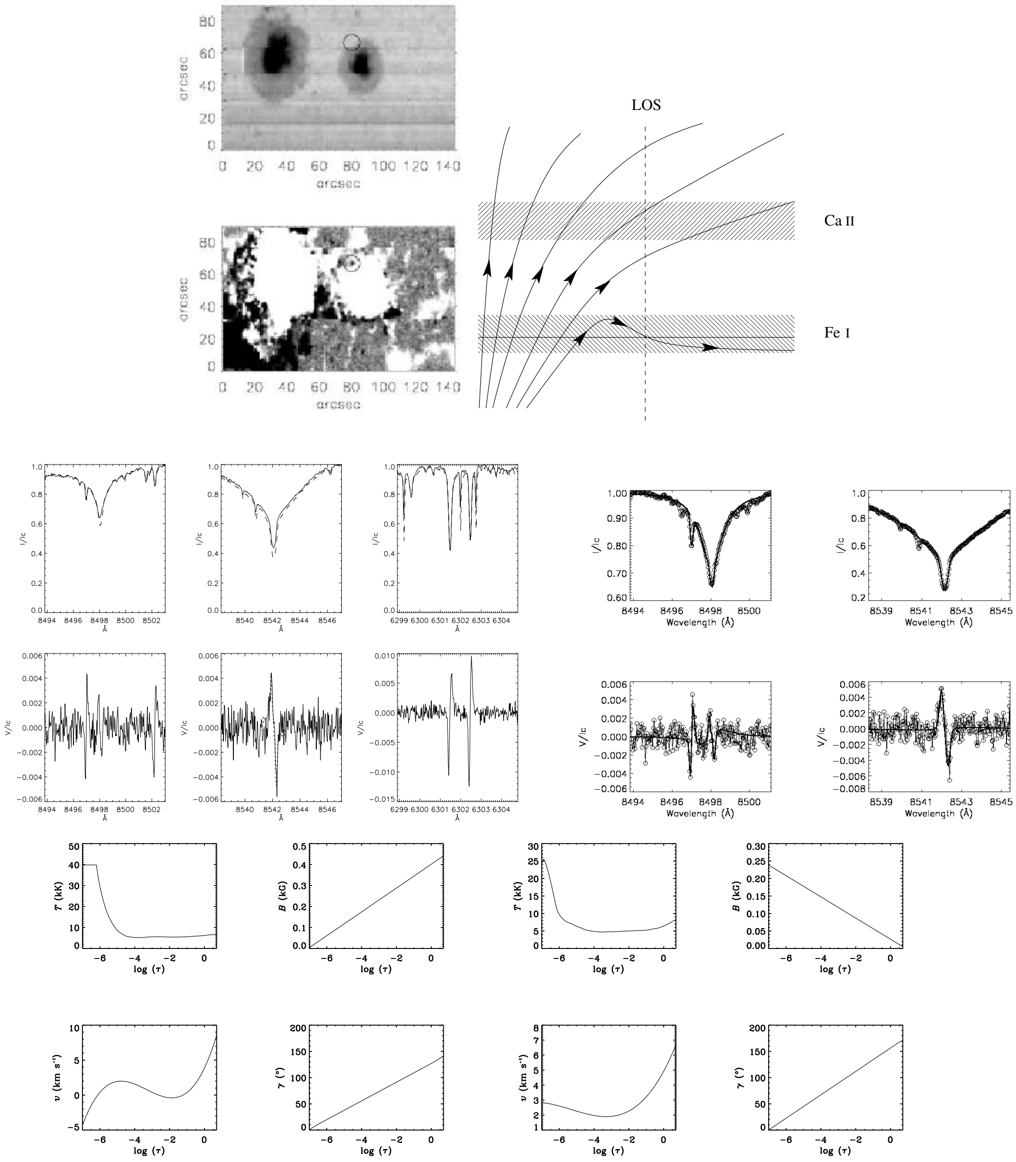

Fig. 1. Top: (left) reconstructed intensity image and magnetogram of NOAA AR 1662 on 17th August 2004, 14h51min. The circle marks the location of a candidate of MMF (opposite polarity with regard to parent sunspots). (right) A possible scenario for the observed profiles. The MMF (type III) is observed at the phothosphere with the LOS component of the magnetic field coming upwards. At the chromosphere the LOS component of the magnetic field associated to the canopy is coming downwards. Middle: (left) the I/Ic and V/Ic Stokes profiles. The photospheric Stokes V profiles of this MMF show a reversed polarity with respect to the chromospheric ones, but not emission signature at I/Ic profiles. (right): the profiles calculated by the inversion code (thick line) for 8498 and 8542 Å observed profiles (thin line and circles). Bottom: the atmosphere models retrieved by the inversion code for 8498 Å (left) and 8542 Å (right).

tion to the magnetic field in a standard Milne-Eddington atmosphere. A graphic user interface allows to check the inverted profiles and to visualize the physical parameters returned by the inversion code, e.g. **B**, v_{LOS}, filling factor, etc. In addition, we have started to invert the chromospheric Ca II IR triplet lines using the Non-LTE inversion code developed by Socas-Navarro et al. (1998). This code is based on the Levenberg-Marquart method and the singular value decompositon techniques. It uses the response functions: they tell us how the emergent profiles change due to a variation in the atmospheric conditions (Ruiz Cobo & del Toro Iniesta, 1994, and references inside). This code calculates them with the fixed departure coefficients approximation (Socas-Navarro et al., 1998). The guess model provided by the inversion code strongly depends of the number of nodes (grid points of discretizated atmosphere where the depth-dependent perturbation is calculated). We have to be very careful with the number of nodes chosen in each physical paramater and keep a critical mind with the output model.

3. Data

The NOAA AR 10661 was observed at THEMIS telescope on August 17th, 2004. This AR is formed by two sunspots, both of them with positive polarity. Their negative following parts are their faculae. In fact, the sunspots result from the splitting of a single sunpot (NOAA 10652). We have used the so-called *Semel's mask* or *Grid* observing mode (Semel, 1980). We observed simultaneously four spectral ranges: the photospheric Fe I 6301 and 6302 Å lines and the chromospheric Ca II IR 8498, 8542 and 8662 Å lines[3]. The polaritazion observing sequence was I+Q, I-Q, I+U, I-U, I-V, I+V. We took several scans of roughly 140 x 90 arsec^2 of both sunspots, their moat and the network. We spent 15 min for one observing sequence, that is: a scan plus FF plus DC. Later, the reduction was done by SQUV, spending 7 min for each spectral line. Finally, we inverted the Fe I 6301 and 6302 Å lines with the PCA-based inversion code, spending 5 min. In this way, we can correct almost on real-time our position on the studied area and then concentrate on our interested targets: the MMFs and the ERs.

4. Results

Fig. 1 (top left) shows a magnetogram where a candidate of MMF sited on the edge of the leader sunspot of NOAA AR 10661 has been marked by a circle. The reduced I/Ic and V/Ic profiles are shown at Fig. 1 (middle left). The reversal polarity is clear at V/Ic profiles of 8498 Å with respect to 6301 and 6302 Å. The Stokes V profiles of the chromospheric lines 8498 and 8542 Å are reversed with respect to the photospheric 6301 and 6302 Å lines, but also with respect to photospheric 8497 Å line. The intensity profiles do not show the emission signatures associated to the chromospheric reversal polarity profiles up to now (Sanchez Almeida, 1997; Briand & Vecchio, 2003). We have sucessfuly inverted the V/Vc profiles at photosphere and chromosphere. The PCA-based inversion on 6301 Å and 6302 Å returns the following values at this point: strength of magnetic field B=325 ± 100 G, the inclination with respect to the vertical Θ_B=81 ± 30 degrees. The fits of the inverted Ca II IR 8498 and 8542 profiles are shown at Fig. 1 (middle right). Although the fits look rather good, the atmosphere models that we get (see Fig. 1 bottom left for 8498Å and right for 8542Å) do not completely match a real case. The atmosphere model retrieved from the inversion of 8498 Å (Fig. 1 bottom left) has the following roughly values: a temperature of 35 kK, too high at the chromosphere; the strength of magnetic field B decreases from the photosphere (300 G) to the chromosphere (50 G) in agree with the observations; v_{LOS} at photosphere is negative (-0.1 kms^{-1}) and in the chromosphere is positive (1 kms^{-1}); Θ_B changes roughly from 130 degrees at photosphere to 40 degrees at chromosphere. For 8542 Å the values of temperature (12 kK), v_{LOS} (2.7 kms^{-1}) and the Φ_B are acceptable, but not the increasing of $B$from

[3] In this work the profiles of Ca II IR 8662 Å are not shown because we have not included them the inversion process.

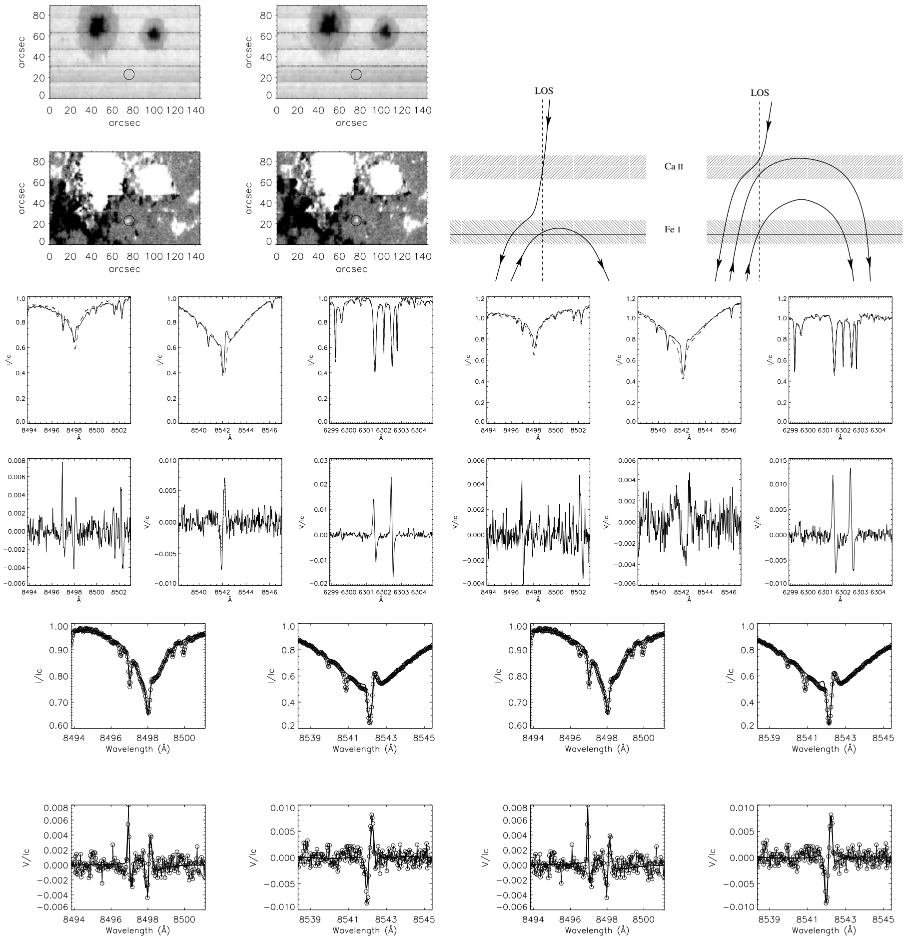

Fig. 2. Top: (left) reconstructed intensity image and magnetogram of NOAA AR 1662 on 17th August 2004, 17h23min and 17h55min. The circle marks the position of the positive polarity of the ER. (right) the evolution of ER from the photosphere coming to the chromosphere and cancelling with the background field there. Middle: Stokes profiles of Ca II 8498 and 8542 Å and Fe I 6301 and 6302 Å for the selected position of the first scan showing the reverse polarity (left) and for the second one showing the cancellation (right). Bottom: two possibilities of inverted Ca II IR profiles for the first state.

the photosphere to chromosphere. Of course, as the inversion of 8498 and 8542 Å was done separetaly the models talk about the information given by this line independently. An inversion taking into account simultaneously both lines will give us more realistic information.

Although some parameters of the atmospehere models are clearly wrong, we can suggest an scenario from the information given by the profiles and the inversions. They tell us that we are observing an MMF (type III) at photosphere, and the canopy at the chromosphere. The sketch in Fig. 1 (top right) shows the scenario. The LOS component of the magnetic field vector would be in opposite sense at the photospere with respect to the chromosphere, in agree with the Stokes V profiles, but also with the values got through the inversions.

An ER was detected on the scans on 17th August 2004 at 17h23min and 17h55min. We did the same study as in the MMF case. From the Stokes profiles we have sketched a possible evolution of the ER. In this case, the first V Stokes profiles (see Fig. 2 middle left) tell us that we are observing one of the foot of the ER, at photosphere, with the LOS component of the magnetic field upward, and the LOS component of magnetic component of the background field, likely the faculae, going downward at chromosphere. In the second scan, on 17h55min, the ER has reached the chromosphere and there is a cancellation, as the Stokes V profiles show (see Fig. 2 middle right). The inversion on 6301 and 6302 Å provides that the strength of the magnetic field increases to kilogauss and the inclination comes more vertical, from 53 ± 18 to 23 ± 32 degrees with respect to the vertical. The inverted profiles of Ca II IR look good, but the atmosphere models retrieved by the inversor are really unacceptable: the initial conditions and number of nodes given to it were wrong. We are trying with a better and more realistic inversion.

5. Conclusions

New tools, SQUV and PCA-based inversion code, for THEMIS MTR data have been succesfully used for studying an MMF and ER. Besides, we have used a Non-LTE code developed by inversion on Ca II IR lines. We hope that this study, beyond its scientific interest, serves as a motivation to use these tools and exploit the powerful capabilities of THEMIS telescope, one of the best simultaneous multiwavelength spectropolarimetric instrument in the world.

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