Mem. S.A.It. Vol. 78, 54

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Magnetic strength analysis in the quiet Sun regions using the Mn I line at 553 nm

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Abstract. In this work we present a quantitative analysis of the magnetic field stength in quiet Sun regions using Mn I lines. The hyperfine structure (HFS) of this atom results for its 553 *nm* line in a change of profile if the magnetic strength is inferior to one kiloGauss. Spectropolarimetric data obtained at the THEMIS telescope is presented and analysed. With this purpose, we have developped and tested an inversion code based on a Milne-Eddington atmospheric model. Close to half the total amount of data shows enough signal in circular polarization (V) to be inverted. We have found that quiet sun regions are dominated by weak magnetic strengths (*hG*) but that strong intensities (*kG*) are not absent, being these last ones close to one quarter of the total of inverted profiles.

Key words. Quiet Sun: Hyperfine structure – Magnetic strength inversions – spectroplarimetric data – Granular Intergranular regions – THEMIS

1. Introduction

The quiet Sun regions are characterized by the absence of any strong magnetic activity like sunspots, plages, etc. However these quiet regions, that cover most of the part of the solar surface, are not free of magnetic flux and presents small scale magnetic structures. During decades it was accepted that these magnetic structures were flux tubes whith magnetic strengths in the order of kiloGauss (Stenflo 1973) or (Livingstone & Harvey 1969). With the progresive improvements in spectral and spatial resolution and in the quality of the observations, new results have motivated, once more, a discussion about the nature of the magnetic strengths in the quiet sun regions. Some of the recents results using the Zeeman efect to invert the Fe doublet at *630.1* and *630.2 nm* preserve the previous result that the quiet regions are mostly permeated of strong magnetic fields, (Sánchez Almeida & Lites 2002; Domínguez Cerdeña et al. 2003b). However, these results are contrary to the Zeeman inversions obtained using Fe lines in the infrared spectral region at *1564 nm*, (Lin 1995; Khomenko et al. 2003), where the autors find that the weak magnetic fields dominate in the solar quiet regions. The discrepancy in the results has been studied recently, (Lin & Rimmele 1999; Socas Navarro & Sánchez Almeida 2003; Domínguez Cerdeña et al. 2006), but there still no general conclusion admited about it.

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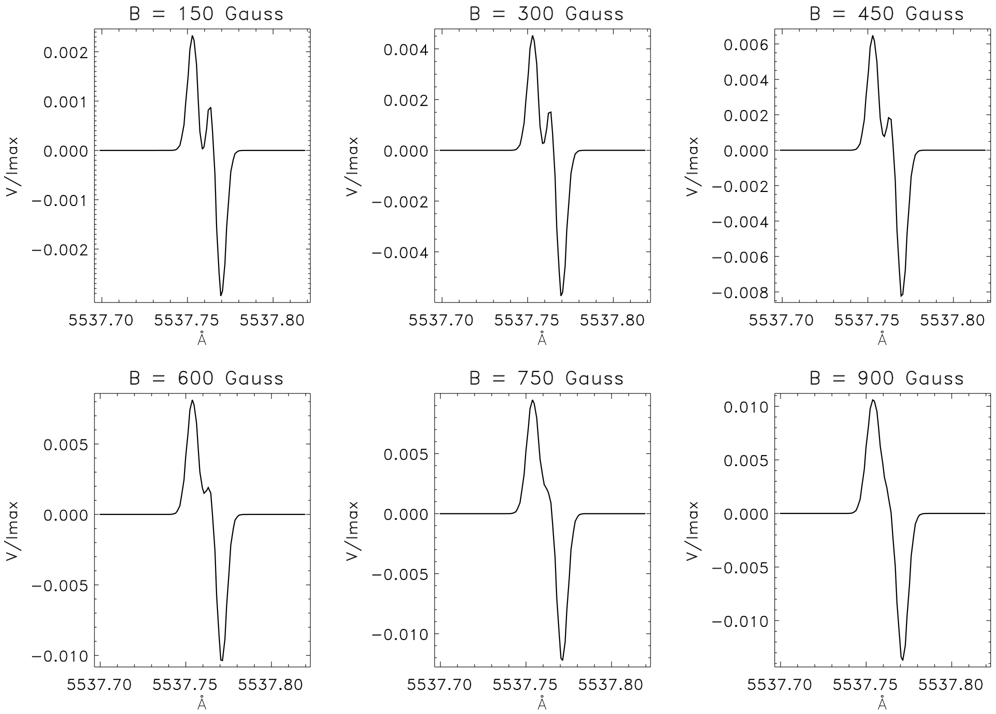

Fig. 1. Example of the cirular polarization profiles of the Mn I line as a function of the magnetic field strength. The classical antisymmetric V shape disappears for weak fields (see the central part of profiles).

We contribute to the subject presenting here the inversion of the Mn I line in the visible spectral region at *553 nm* because it has the relevant caracteristic that hyperfine structure (HFS) results in strong changes of the profiles. This kind of changes is produced only if an external magnetic field (the solar magnetic field) does not exceed the strength value of 800 Gauss. As a consequence of the HFS coupling, an unambiguous spectral feature appears in the central part of the V profiles, see figure 1. When the line loses those features, the atom passes to the Paschen-Bach regime (B ~ 750 Gauss) and the magnetic field strength is in the strong regime. We take advantage of this fact to determine the magnetic strength uncoupled from flux measurements.

2. Data adquisition, reduction and inversion

Two campaings, June 2005 and June 2006, were carried out at the THEMIS telescope at the Observatorio del Teide, Tenerife, in the Canary Islands. The observations consisted of temporal sequences made at disk center, where no magnetic activity where present. In each sequence there were exposed 100 images of 300 *msec* each with fixed slit, and a total time span comaparable to the granular life time.

The data reduction was done with the *DeepStokes* software tool, provided by the telescope system facilities. After reduction, the noise levels reached in circular polarization signal are between $5x10^{-5}$ and $2x10^{-4}$ of the continuum level, and the spatial resolution obtained is better than 1 arcsec in average. The signal amplitudes of linear polarization were below noise in most of the cases and consecuently the inversions were done only considering the I and V Stokes parameters.

In order to invert the observations, we have developped a Milne-Eddington atmospheric model with 8 free parameters. The magnetic strength, one of the parameters, varies from 0 to 2 kiloGauss. The profiles are decomposed using PCA and the solution is searched among a database of 80000 profiles. Several synthetic tests were run over the code to validate the results: Three sets of 500 synthetic profiles each were inverted. In two of the sets we added an artificial noise at $5x10^{-5}$ and $1x10^{-4}$ levels, respectively. In table 1 we present the results for the efficency of the code to determine the magnetic field strength: ΔB represents the difference between the known value of the magnetic strength of the syntetic profile and the magnetic strength corresponding to the profile found as solution by the code. A complete description of the code will be published in the near future (paper in preparation).

Table 1. Inversions efficency of the magnetic field strength, expressed in percentage of correct inversions as function of ΔB .

ΔB	Noise	0	$5x10^{-5}$	10^{-4}
$\pm 50G$		69 %	46 %	40 %
$\pm 100G$		89 %	74 %	65 %
$\pm 150G$		96 %	88 %	80 %
$\pm 200G$		99 %	93 %	89%

3. Conclusions

4. Results

In figure 2 we show a representative set of inverted profiles; this set exemplifies the variety of magnetic strengths present in the quiet Sun, from the very weak ($< 10\ G$) to the strong regime ($\sim 2\ kG$). The total number of inverted profiles is close to 1650. From these, only 20 % belongs to the network, while the resting 80 % are in the intranetwork. Considering only the inverted cases, the mean values are respectively 920G and 390G. This result was found before in the case of the network by many authors and seems to be well accepted that the network magnetic strength is in strong regime (kG). Contrary, in the intranetwork, where an open disscusion exist, we are finding that the magnetic strength is mostly in the weak regime (hG) renforcing with this some of the previous results like those in (Lin 1995; Khomenko et al. 2003).

In figure 3 we show separately the network and intranetwork PDF distribution functions.

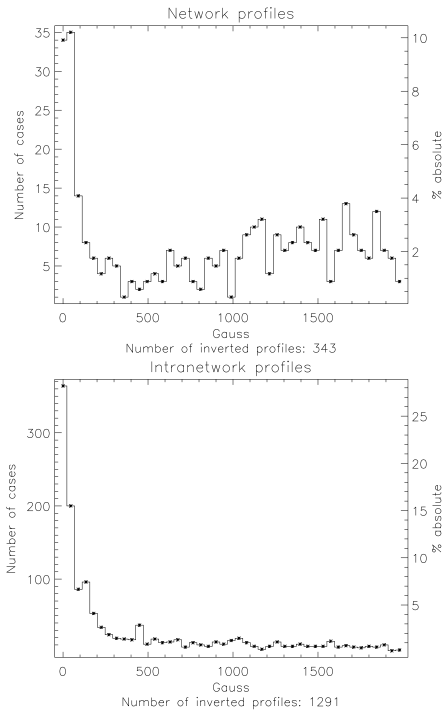

Fig. 3. Histrograms of the magnetic strength in the network and intranetwork regions. The binsize is 45 G.

The spectral separation between the Zeeman components of a spectral line grows linearly with wavelength. Because of this reason we expect more sensivity in the infrared, i.e., more easiness to mesure field strengths that in the visible. However, in our case the magnetic strength determination takes advantage of the fact the observed Mn I line presents a strong coupling with hyperfine structure,

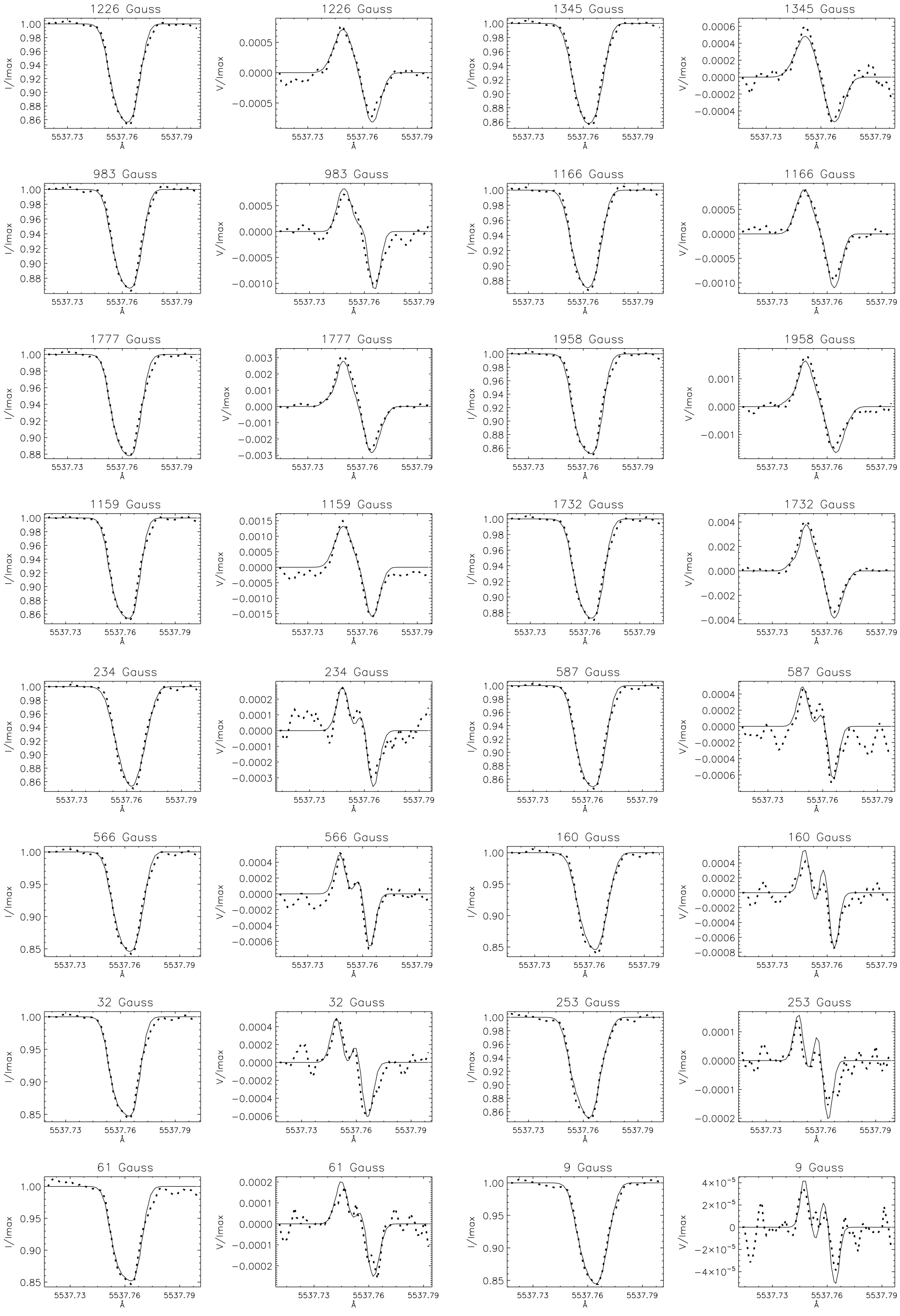

Fig. 2. Examples of the inverted I and V profiles. The dotted lines correspond to the observed data and the solid lines are the fit profiles.

allowing for an unambiguous distangling of field strength and flux. In this way, the field strength inversions done with the Mn I line avoid the fact that the inversions in the visible with the widely used Fe doublet at 630 *nm*, could be lacking of information to determine the magnetic strength as proposed in (Martínez González et al. 2006) and (López Ariste et al. 2007), or put it in another way, the Mn I inversions could be a key element to complete those of Fe in the visible and infrared regions.

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