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Internetwork magnetic fields observed in the visible

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Abstract. We present internetwork quiet Sun spectropolarimetric observations taken simultaneously at the Fe I lines at 630 and 525 nm. The magnetometry at 630 nm in these low flux regions of the Sun's photosphere has been put in doubt by a recent work. The 525 nm lines are supposed to give reliable results concerning the magnetic field strength in regions where the magnetic structures are not resolved. We study the compatibility of the results obtained in both spectral ranges to confirm or deny the affirmation that the 630 nm lines are not valid for recovering the magnetic field strength at the internetwork quiet Sun. We conclude that both the 630 nm and the 525 nm pair of lines give no trustable results concerning the magnetic field strength. However, the magnetic flux density is correctly recovered from both spectral ranges.

Key words. Magnetic fields — polarization — Sun: photosphere

1. Introduction

The determination of the intrinsic field strength of the magnetic features that give rise to the low polarization signals in internetwork regions is nowadays restrained mainly by the observational limitations. The 1.5 μm Fe I infrared magnetometry and the one in the visible range at the widely used 630 nm lines seem to be incompatible (Socas-Navarro & Sánchez Almeida 2003; Sánchez Almeida 2003; Domínguez Cerdeña et al. 2006). While some works that analyze observations at 1.5 μm find sub-kG magnetic field strengths (Keller et al. 1994; Lin 1995; Lin & Rimmele 1999; Khomenko et al. 2003; Martínez González et al. 2007), other works, dealing with the 630 nm lines, conclude that the majority of the magnetic flux is contained in structures with kG field strengths (Grossman-Doerth et al. 1996; Sigwarth et al. 1999; Sánchez Almeida & Lites 2000; Socas-Navarro & Sánchez Almeida 2002; Domínguez Cerdeña 2003; Socas-Navarro & Lites 2004). Recently, Bellot Rubio & Collados (2003) and Martínez González et al. (2006) suggested that there is no inconsistency in the results coming from the two different magnetometries since the studies performed at internetwork regions using the 630 nm lines are not reliable. In order to confirm or to discard this result, we take simultaneous and cospatial observations at 630 nm and at 525 nm. The latest spectral region contains the well known Fe I lines at 524.7

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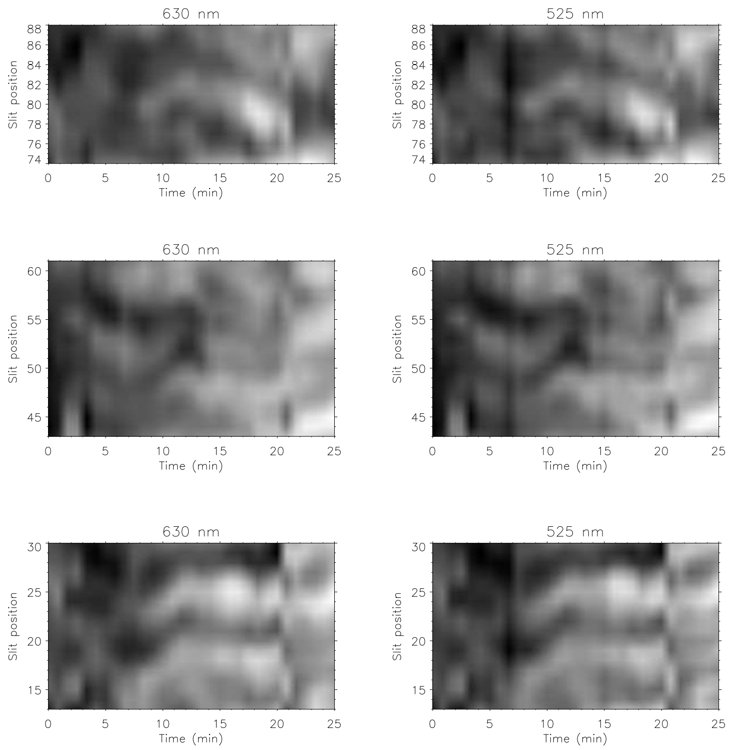

Fig. 1. Time series of the continuum intensity at 630 nm (left panel) and time series of the continuum intensity at 525 nm (right panel). The three different images are different regions along the slit and correspond to different regions on the Sun separated each other 16″. They are plotted separately because we have substracted the bars used in the MTR mode that appear in the real image.

and 525.0 nm that give the line ratio technique used by Stenflo (1973) to investigate network regions. This diagnostic technique applied to this particular pair of lines that fulfill all the strict requirements to be used (same $\log gf$ and excitation potential but different Landé factors) is supposed to give a trustable value for the field strength in unresolved structures. Then, by studying the compatibility of the results found in both spectral domains we can discuss about the validity of the magnetic field strength in internetwork regions retrieved by using only the 630 nm. Since both pair of lines are situated in the visible, they will not suffer (if it is the case) from a bias due to the wavelength (Socas-Navarro & Sánchez Almeida 2003).

2. Observations and data reduction

The observations were taken on April 26th 2006 using the MTR mode at the THÉMIS telescope on El Teide observatory. The slit was fixed in a position at disc centre at a very quiet region. We avoided the magnetic activity regions using the real time MDI magnetograms. We recorded the four Stokes parameters at 630 nm and at 525 nm by integrating during 300 ms.

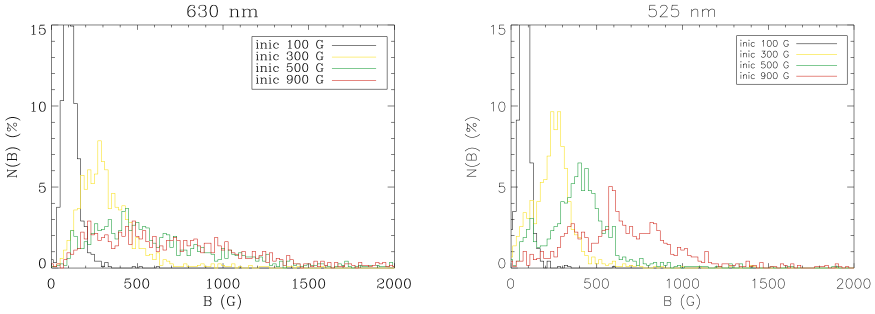

Fig. 2. Magnetic field strength distribution inferred from the separated inversion of the pair of lines at 630 nm (left panel) and the one at 525 nm (right panel). The different colors represent the result obtained if we fed up the code with different values of the magnetic field strength.

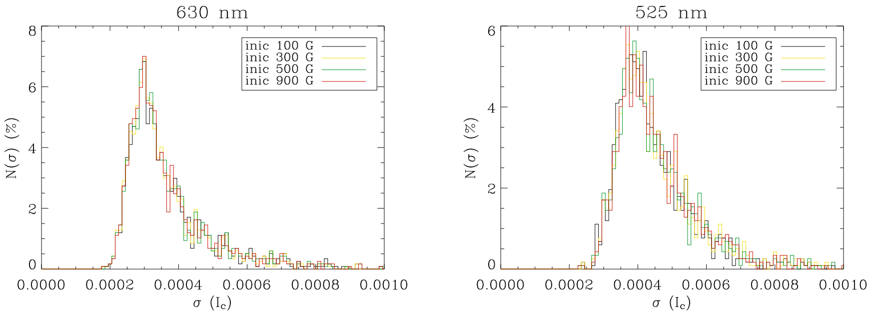

Fig. 3. Standard deviation of the difference between the observed Stokes V profiles and the best fits found by the inversion procedure at the pair of lines at 630 nm (left panel) and the one at 525 nm (right panel). The different colors represent the result obtained if we feed up the code with different values of the magnetic field strength.

The seeing conditions during the observation were exceptional. However, in order to get an appropriate signal to noise ratio in circular polarization (3×10^{-4} I_c, being I_c the continuum intensity), we had to add 10 steps having an integration time of 50 sec which resulted in a spatial resolution of the order of $1''$. In any case, this limitation is not severe since the pixel size of the cameras is $0.5''$.

The data reduction was performed as usual, including dark current and flatfield correction and demodulation using the SQUV[1] (Sainz Dalda & López Ariste 2007) code available at the telescope. In Figure 1 we show the continuum intensity maps of the two time series at 630 and 525 nm. In both time series, we can clearly see the evolution in time of granular and intergranular structures.

3. Data analysis and results

The data were analyzed using the SIR[2] inversion code (Ruiz Cobo & del Toro Iniesta 1992). The inversions were performed using a two component model: a magnetic atmosphere covering some portion of the resolution element and a non magnetic one filling the rest of the space. The Stokes I and V profiles were used in the inversion

(the linear polarization signal cannot be distinguished over the noise level) leaving the

[1] Stokes QUick Viewer

[2] Stokes Inversion based on Response functions

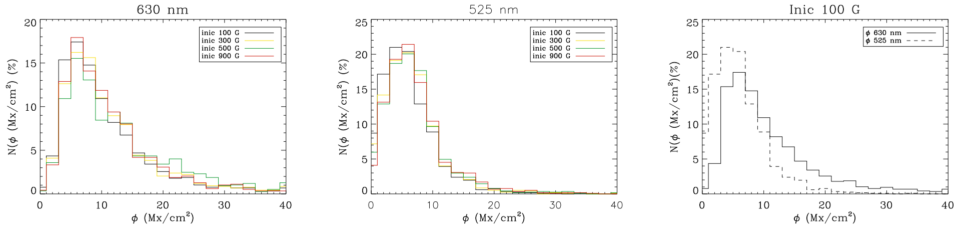

Fig. 4. Magnetic flux density recovered separately from the inversion of the pair of lines at 630 nm (left panel) and the one in 525 nm with different initializations of the magnetic field strength (central panel). Comparison of the magnetic flux density for both pair of lines initializing the code with 100 G (right panel). Note that we have assumed vertical magnetic fields.

magnetic and the non magnetic temperature stratifications vary independently with 5 nodes. This allows the inversion code to cool or heat different layers of the model atmosphere. The microturbulent velocity in both components, the macroscopic velocity of the magnetic component, the magnetic field strength and the filling factor are supposed to be constant with height. The macroturbulent velocity is also constant with height and is forced to be the same in both atmospheres. The macroscopic velocity of the non magnetic component is allowed to vary with height using 3 nodes.

In order to study the reliability of the magnetic field strengths inferred from the 630 nm lines, we analyze the data following two different strategies. The first one consists on inverting both data sets independently. If both spectral ranges are measuring the same structures, we also invert them simultaneously. For the analysis, we only select those profiles whose amplitude in circular polarization is higher that 3 times the noise level. These amounts to 1173 points, representing 40.25 % of the total number of observed profiles.

3.1. Separated inversion

We invert separately the pair of lines at 630.1 an 630.2 nm and the ones at 524.7 and 525.0 nm. In both cases, we initialize the code with different values of the magnetic field strength: two values in the weak field regime (100 and 300 G), a value of 500 G that is between the weak and strong field regimes and a value of 900 G, that is well inside the strong field regime. Figure 2 shows the magnetic field strength distributions recovered from the separated inversion of both data sets with different initializations of the magnetic field strength. In both cases it is clear that the results depend on the initialization. In spite of this, all these different magnetic field strength distributions fit equally well the observations. This is better shown in Fig. 3 where we plot the standard deviation of the difference between the observed Stokes V profile and its best match. It is evident from the figure that all the inversions with different initializations fit the observed profiles with a similar quality. Moreover, the fit is extremely good since the standard deviations are distributed around the noise level of the data. To compute the goodness of the fits we have only taken into account the Stokes V profiles. The reason for neglecting the intensity profiles is that they are very nicely reproduced by the non magnetic component and they would mask the quality of the Stokes V profiles fits.

As a consequence, it is not possible to recover the magnetic field strength from the inversions of the 630 nm lines as was already stated by Martínez González et al. (2006). The same happens with the 525 nm lines. In the latter case, this is a surprising result but these lines also lack from the information needed to reliably retrieve the magnetic field strength.

Even if the magnetic field strength distributions that we derive separately from the analysis of both data sets depend on the initialization, the magnetic flux density is correctly

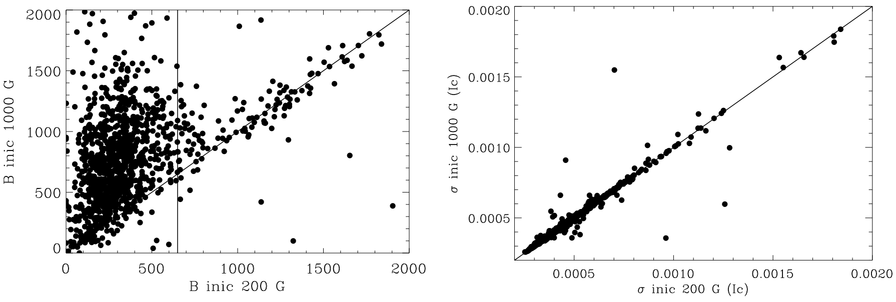

Fig. 5. Magnetic field strengths inferred from the simultaneous inversion of the four spectral lines situated at 630.1, 630.2, 524.7 and 525.0 nm initialized with 1000 G versus the ones determined by the inversion with a 200 G initialization (left panel). Standard deviation of the difference between the Stokes V observed and fitted profiles for the initialization with 1000 G versus the 200 G one (right panel).

recovered (it is independent of the initialization). This can be seen in left and central panels of Fig. 4. All the histograms in both spectral ranges do not depend on the exact value of the magnetic field strength used for the initialization. Moreover, the inferred magnetic flux density is the same point by point. Comparing the magnetic flux density distribution (for a given initialization) recovered from the 630 doublet and from the 525 nm lines (right panel of Fig. 4) we see how the values of the former pair of lines are always slightly higher. This can be explained by means of different formation heights: the 525 nm lines are formed in higher layers in the atmosphere, approximately 100 km above the 630 nm lines (Shchukina & Trujillo Bueno 2001).

3.2. Simultaneous inversion

All the studied profiles present the same polarity both at 630 and at 525 nm and they also present compatible values of the magnetic flux density. This might be an indication that both spectral ranges are tracing the same structure in the Sun. The following step is to perform a simultaneous inversion of the four spectral lines to study to what extent the magnetic field strength is better retrieved when all the available information is put together. We initialize the inversions with two different magnetic field strengths: 200 and 1000 G.

Figure 5 shows the magnetic field strength recovered from the simultaneous inversion initialized with 1000 G versus the results from the inversion initialized with 200 G. Only those magnetic field strengths higher than approximately 650 G remain in the diagonal of the plot. Below this value, the 1000 G initialization clearly gives larger values of the field strength with respect to the 200 G initialization. We have included more information because we are dealing with four spectral lines and it seems that we can, at least, distinguish between fields in the weak or in the strong field regime. For very high values of the field strength (1000-2000 G) the magnetic field strength that we derive from the two different inversions is the same. For weaker field strengths, the uncertainty (apart from the one intrinsic to the measurement) starts growing and, finally, for field strengths below 650 G (this can be considered as the limit for the weak field regime in these conditions) the magnetic field strength can not be recovered in a reliable way since the quality of all the fits is the same for both initializations (see Fig. 5). Since the magnetic flux density is independent of the initialization, it can be considered as an observable, as it results from Fig. 6. Consistently, the values retrieved from the simultaneous inversion are in good agreement

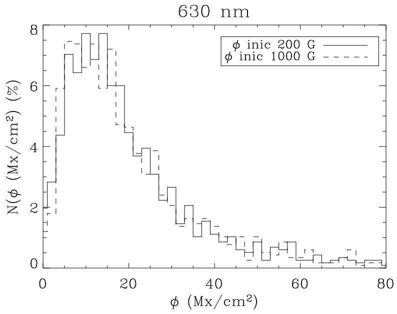

Fig. 6. Magnetic flux density recovered from the simultaneous inversion of the spectral lines situated at 630.1, 630.2, 524.7 and 525.0 nm initialized with 200 and 1000 G. Note that we have supposed that the magnetic fields are vertical.

with the ones obtained from the separated analysis.

4. Conclusions

We have studied the compatibility of the results retrieved from the inversion of the spectral lines at 630 and at 525 nm. The separated analysis reveals that the magnetic field strength can not be recovered from our data (at 1″ and with a noise level of 3×10^{-4} I_c) by using only the 630 nm pair of lines or the 525 nm one. However the magnetic flux density is an observable. Both spectral ranges give values that are compatible having in mind that the 525 nm lines are formed upper in the atmosphere so that they recover slightly smaller values that the ones inferred from the 630 pair of lines.

If we add all the information contained in both wavelengths by inverting all four lines simultaneously, it seems that the determination of the magnetic field strengths slightly improves. We can perfectly distinguish whether the magnetic field is in the weak or in the strong regime and we can determine the field strength for values higher that 1000 G. For lower values the dispersion increases and in the weak field regime (below 650 G) we are not able to reliably retrieve the magnetic field strength. However, we can also measure correctly the magnetic flux density that turns out to be around 10 Mx/cm^2 (assuming a vertical magnetic field).

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