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On the validity of the 630 nm Fe I lines for magnetometry of the internetwork quiet Sun

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ABSTRACT

Aims. The purpose of this work is to analyze the reliability of the magnetic field strengths inferred from the 630 nm pair of Fe I lines in internetwork quiet Sun regions.
Methods. Some numerical experiments have been performed that demonstrate the inability of these lines to recover the magnetic field strength in such low flux solar regions.
Results. It is shown how different model atmospheres, with magnetic field strengths ranging from a few hundred Gauss to kiloGauss, give rise to Stokes profiles that cannot be distinguished. The reasons for this degeneracy are discussed.

Key words. Sun: magnetic fields – Sun: atmosphere

1. Introduction

The magnetometry of quiet Sun regions is strongly restrained by important difficulties. The very small circular polarization signals and the fact that structures in those regions are unresolved make the interpretation with standard techniques complicated. Different works based on data taken with different instruments (spectroscopic or imaging polarimetry), various wavelengths (near infrared or visible spectral lines) and analysis procedures (line ratio, inversions following ME, LTE or MISMA schemes) lead to a diversity in the results larger than that expected from observational uncertainties.

Most works studying quiet Sun regions in the visible part of the spectrum have used the Fe I pair of lines located at 630 nm (Socas-Navarro & Sánchez Almeida 2002; Domínguez Cerdeña et al. 2003b; Socas-Navarro et al. 2004; Lites & Socas-Navarro 2004). Simple methods, such as the line ratio technique and also more sophisticated inversion procedures have been used to infer magnetic field strengths in network and internetwork regions. But, until now, no deep study of the physical properties of this pair of lines has been performed to support their validity for the analysis of the quiet Sun magnetism in low flux regions (such as the internetwork). Bellot Rubio & Collados (2003) have pointed out some restrictions of the 630 nm lines due to uncertainties introduced by noise.

Results from the near infrared Fe I lines at 1.56 microns usually lead to the conclusion that most of the magnetic fields in the internetwork are in the form of weak fields (see Lin 1995; Lin & Rimmele 1999; Khomenko et al. 2003). This result is confirmed by Martínez González et al. (2006b) but contradicted by Sánchez Almeida et al. (2003) and Domínguez Cerdeña et al. (2006). These last three works analyze simultaneous 1.5 μm and 630 nm observations.

As explained below, the often-used Fe I pair of lines located at 630 nm suffer from a major drawback: their different formation heights makes them sensitive to different parts of the atmosphere. As a consequence, all results obtained using analysis techniques that ignore this fact shoud be regarded with care.

The structure of this paper is as follows: first, we demonstrate that the Fe I 630 nm line pair has their maximum sensitivity at different layers in the quiet Sun atmosphere. Second, we show how low amplitude circular polarization signals (like those present in the internetwork quiet Sun) can be retrieved using model atmospheres with weak or strong magnetic fields, provided one allows other atmospheric parameters to compensate for the magnetic field effect. Also, we show that the amplitude ratio of the circular polarization signals is not a good indicator of the magnetic field strength. Finally, different PDFs resulting from the inversion of real data are presented.

2. Different line formation heights

Response Functions (RFs) (Ruiz Cobo & del Toro Iniesta 1994; Sánchez Almeida et al. 1996) are suitable indicators of line formation height. The maximum of a RF to the perturbation of a parameter provides an estimate of the height in the atmosphere where a given spectral line is most sensitive to the parameter.

The RFs to several physical magnitudes have been calculated for the Fe I lines at 630.1 nm and at 630.2 nm. For the calculations, an HSRA model atmosphere (Gingerich et al. 1971) was used as representative of the quiet Sun. Several different configurations with constant, vertical magnetic field with values ranging from 0 to 1000 G and macroturbulent values between 0 and 2 km s^{-1} were. No bulk velocity was included. A constant with height microturbulent velocity of 0.6 km s^{-1} was added to the model atmosphere.

Figure 1 shows some RFs to the magnetic field strength of the line core intensity. In all of the cases, for a given magnetic field strength, the 630.1 line has the maximum of the RF at higher layers than the 630.2 line, the difference being larger for lower magnetic field strengths.

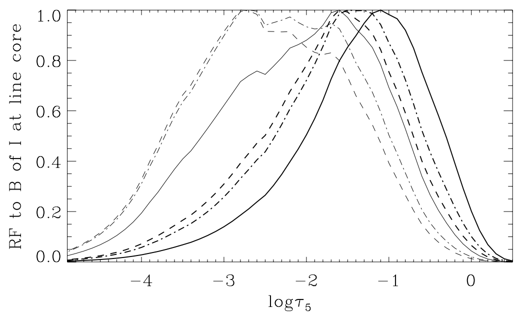

Fig. 1. Response Function to the magnetic field of the intensity line core of the 630.1 nm and 630.2 nm lines using an HSRA quiet Sun model atmosphere (Gingerich et al. 1971) with different constant vertical magnetic fields. τ_5 is the continuum optical depth at 500 nm. Thick (thin) lines are the RF for the 630.2 nm (630.1 nm) line. Solid lines are the RF when the magnetic field is set to 1000 G, dashed-dotted lines correspond to 500 G and dashed lines to 200 G. The macroturbulent velocity has been fixed to 1 km s^{-1}.

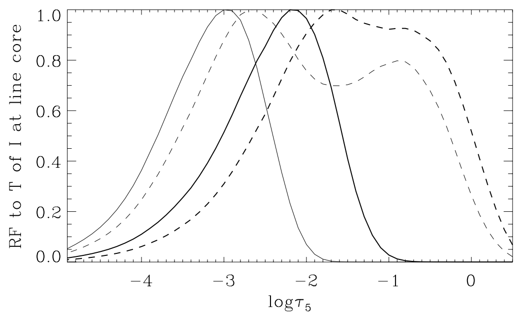

Fig. 2. Response Function to the temperature of the intensity line core of the 630.1 nm and 630.2 nm lines using an HSRA quiet Sun model atmosphere (Gingerich et al. 1971) with two different values for the macroturbulent velocity. Thick lines correspond to the 630.2 nm line and the thin lines to the 630.1 nm ones. The solid lines are the RF when the macroturbulent velocity has a value of 0 km s^{-1} while dashed lines correspond to a value of 2 km s^{-1}. No magnetic field has been introduced.

Figure 2 presents the RFs to temperature of the line core intensity, for the $B = 0$ model atmosphere and with the extreme values of the macroturbulent velocity. This parameter works as a convolution with the Stokes profiles. As a consequence, a mixing of the information at each wavelength occurs. The higher the macroturbulence velocity, the larger the information blurring, and the lower the height corresponding to the maximum of the RF. As in the previous case of the RF to magnetic field strength, for all macroturbulent velocity values both lines are sensitive to different temperature layers in the atmosphere, the 630.1 nm line tracing higher layers than the 630.2 nm one. This result is in agreement with that of Shchukina & Trujillo Bueno (2001), where these authors studied the formation height of many Fe I spectral lines, including NLTE effects.

3. LTE inversions

Inversion methods are powerful techniques to retrieve the most information contained in the Stokes profiles. To study the effect of the different heights of formation of the 630 nm line pair on the results retrieved using these techniques, we have carried out a numerical experiment. A synthetic data set of Stokes I and V, covering both spectral lines that will be analyzed as if they were *observed* profiles has been constructed using a two component model: a magnetic component occupying a fraction of the

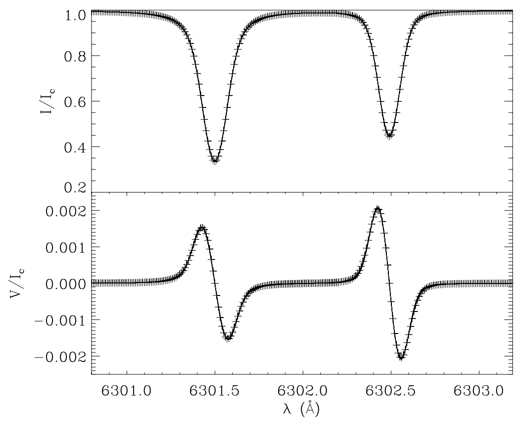

Fig. 3. Fits to 1000 G synthetic I and V profiles at 630 nm with different model atmospheres having the following fixed field strengths: 100, 300, 500, 700, 900 and 1000 G. Plus signs represent the synthetic profiles and lines are the fits.

resolution element and a non-magnetic component filling up the rest of the space. Both components are based on the HSRA quiet Sun model. They only differ in the magnetic field, which has been assumed to be vertical and constant with height, with strengths from 100 to 1000 G, and a corresponding filling factor such that, in all cases, the magnetic flux density is 10 G (similar to that measured in internetwork regions). No noise has been added to the synthetic profiles to avoid any uncertainty related to this parameter. The reason for choosing a vertical magnetic field relies on the low linear polarization values that are measured. Strong fields are supposed to be predominantly vertical due to buoyancy effects (Grossmann-Doerth et al. 1998) while weak fields are expected to have all possible inclinations (or more horizontal, Sigwarth 2000). Taking the weak field approximation for circular and linear polarization (Landi degl'Innocenti & Landolfi 2004), we obtain a relationship between their amplitudes as follows:

$$\frac{\sqrt{Q^2+U^2}}{V} = 0.082\frac{\sin^2\theta}{\cos\theta}, \tag{1}$$

where θ is the inclination angle with respect to the line of sight. Note that, for an intermediate value ($\theta = 45°$) and typical circular polarization amplitudes at internetwork regions ($10^{-3}I_c$), the Stokes $\sqrt{Q^2+U^2}$ amplitude equals $5.8\times10^{-5}I_c$, i.e., almost a factor of 20 smaller than the amplitude of V. This makes them negligible and undetectable even with extremely low noise observations.

The synthetic set of Stokes I and V profiles has been inverted using the SIR[1] code (Ruiz Cobo & del Toro Iniesta 1992). In each inversion, the magnetic field strength has been forced to a wrong value, treating the rest of the magnitudes (temperature stratification of both components, magnetic filling factor, and micro and macroturbulent velocities) as free parameters. The purpose of this experiment is to find out to what extent the effect of the magnetic field on the Stokes profiles can be compensated by the rest of the magnitudes of the model atmospheres.

Figure 3 shows the Stokes I and V synthetic profiles (plus signs) for the case $B = 1000$ G and, overplotted, the results of the inversion obtained for the different fixed mistaken magnetic field strengths. The differences between the retrieved and the input Stokes parameters are tiny in all cases. Figure 4 displays the difference between the retrieved Stokes V profiles and the input

[1] Stokes Inversion based on Response functions.

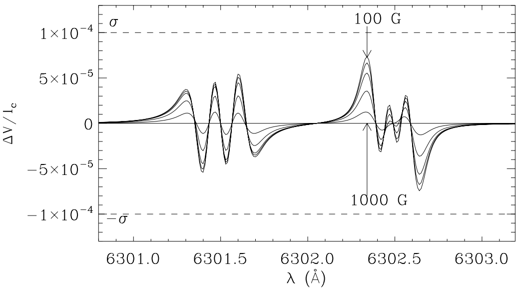

Fig. 4. Fitting mismatches to a 1000 G V profile with smaller field strength model atmospheres. Dashed lines denote the typical noise level value of present high spatial resolution spectropolarimetric data.

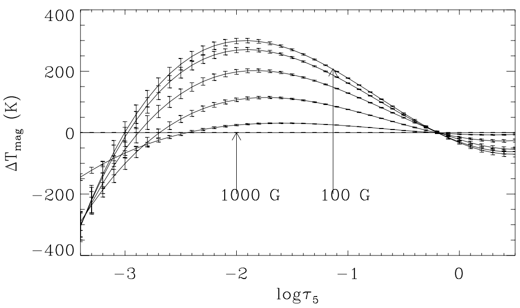

Fig. 5. Difference between the temperature of the initial magnetic model atmosphere and that of the magnetic atmospheres recovered from the inversion of a 1000 G profile forcing the field strength to smaller values.

one. As expected, the fit with a field strength of 1000 G is perfect. The smaller the field strength the higher the mismatch. If a typical value for the noise of spectropolarimetric observations is taken to be of the order of $10^{-4}I_c$, the discrepancies lie, in all cases, well below the noise level and very far from the value of 3σ. Therefore, we conclude that it is possible to reproduce the shape of the 1000 G I and V profiles with very different magnetic field strengths.

To confirm that these good matches represent degenerated solutions of the problem, we have checked that the calculated temperature stratifications are realistic. In Fig. 5 we have plotted the difference between the temperature of the "actual" and the retrieved magnetic component, for each inversion with a fixed wrong value of the magnetic field. The variations are only of a few hundred degrees in the optical depth range where the lines are sensitive. Due to the different heights of formation of the Fe I lines, a small change in the temperature stratification can modify the ratio of the amplitudes of the Stokes V profiles between both lines. As a consequence, we are compensating the effect of the wrong magnetic field with a slightly different temperature gradient. Figure 6 shows the microturbulent velocity for the magnetic component recovered from the inversions. There is a clear tendency: in order to reproduce the 1000 G profile with a smaller field strength, an increase of the microturbulent velocity is needed. The excess broadening of the line is produced by a microturbulent velocity rather than by the magnetic field.

In this simple case, the modification of the temperature gradient and the microturbulent velocity compensates for the effect of the magnetic field strength. In more realistic situations, magnetic field strengths and bulk velocities may vary with height. These gradients may also affect in a different manner both spectral lines; when taken into account in the inversion process as additional free parameters they may introduce another source of uncertainty or degeneracy (see Khomenko & Collados 2006).

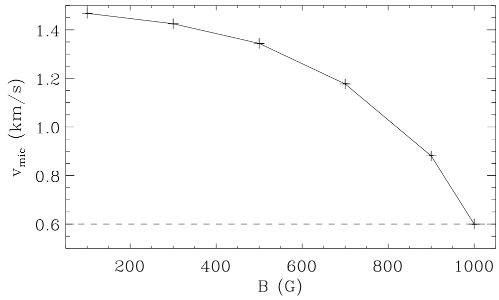

Fig. 6. Microturbulent velocity resulting from the inversion of a 1000 G profile forcing the field strength to smaller values (solid line). The dashed line is the initial value of the microturbulent velocity fed to the inversion process.

4. The line ratio technique

The line ratio technique, first presented by Howard & Stenflo (1972) is a powerful method to retrieve magnetic field strengths from structures that are not resolved. Many works on internetwork regions are based on this simple method (Keller et al. 1994; Domínguez Cerdeña et al. 2003a; Lites & Socas-Navarro 2004; Socas-Navarro et al. 2004), since it allows us to have an idea of the magnetic properties of these regions only taking into account the information given by Stokes V. This method demands a pair of lines fulfilling strict requirements: the same wavelength, line strength ($\log gf$), excitation potential (same response to the temperature), and different effective Landé factors. Under these hypotheses, one can infer the magnetic field strength outside the weak field regime. The weak field approximation can be applied to a range of field strengths that depends on the transitions. In the case of the 630 nm lines, field strengths smaller than approximately 500 G belong to the weak field regime. For larger field strengths, the ratio of the amplitudes of the Stokes V signals is a function of the magnetic field, and this makes it possible to assign a magnetic field strength given the amplitude ratio. To check the validity of the line ratio technique applied to this pair of lines, we have computed the ratio between the amplitudes of V of both lines, taken from the previously inverted profiles. As expected, since all the fits match very well, the line ratio value ranges between 0.74 ± 0.01, indicating that, for this pair of lines, the ratio between the amplitudes of Stokes V is not a good indicator of magnetic field strength with values ranging from 100 to 1000 G.

5. Lack of observables

Figure 4 could lead to the conclusion that by decreasing the noise level to values smaller than the mismatch, the correct magnetic field strength could be recovered. To test this assumption we have performed a numerical study synthesizing a particular Stokes vector and inverting it following two different schemes.

Direct and indirect evidence indicate that the quiet Sun is full of magnetic elements (Stenflo 1987; Manso Sainz et al. 2004; Trujillo Bueno et al. 2004). This magnetic background is not detectable with Zeeman diagnostic tools. Thus, the most plausible approximation must deal at least with two different atmospheres (magnetic and non-magnetic) that can show a large disparity between their atmospheric variables. The two magnetic components of the synthesis differ in the temperature gradient, the microturbulent velocity and the magnetic field. The intensity and circular polarization profiles of the pair at 630 nm coming from this two-model atmosphere are synthesized. The temperature of the magnetic component differs from the non-magnetic one as

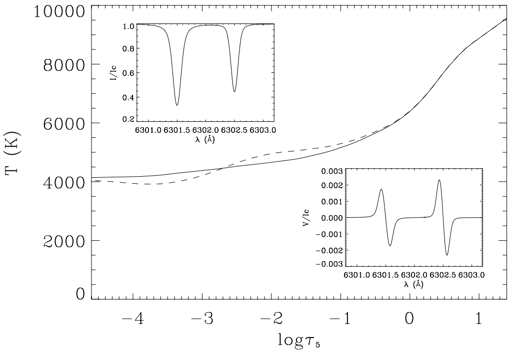

Fig. 7. Temperature stratifications for the synthesis of the Stokes vector used for the numerical test. The solid line is the temperature stratification for the non-magnetic component and the dashed line for the magnetic one. The small plots inserted are the Stokes I and V profiles synthesized from them (see text for details).

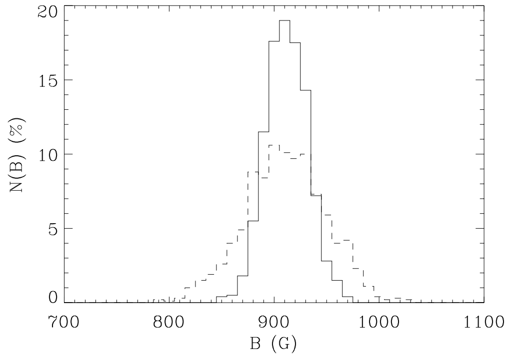

Fig. 8. Histogram of the inferred magnetic field strengths for the two different noise levels. The solid line represents the case with a noise level of $5 \times 10^{-5} I_c$ and the dashed line the one with $10^{-4} I_c$. The inversion procedure assumes the same temperature stratification with optical depths and microturbulence for both magnetic and non-magnetic components. The input synthetic profiles have been generated with a magnetic field strength of 300 G.

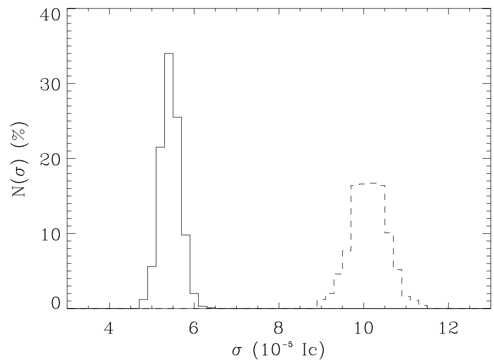

Fig. 9. Standard deviations of the difference between the noisy synthetic profiles and their fits. The solid and dashed lines represent the cases with a noise level of $5 \times 10^{-5} I_c$ and $10^{-4} I_c$, respectively. The inversion procedure assumes the same temperature stratification with optical depths and microturbulence for both the magnetic and the non-magnetic components.

shown in Fig. 7. The magnetic microturbulent velocity is set to 1.4 km s^{-1} while the non-magnetic one is fixed to 0.6 km s^{-1}. The magnetic field with a strength of 300 G has been supposed to be vertical and constant with optical depth. Consistently with the previous test, the magnetic flux density is forced to 10 G in order to have circular polarization signals of the same order of magnitude as the ones observed.

The synthetic I and V profiles with a magnetic field strength of 300 G are inverted adding a random noise distribution with a standard deviation of $5 \times 10^{-5} I_c$ and $10^{-4} I_c$. For each case, one hundred realizations of the noise are done to make sure that the test is statistically significant. We follow two different schemes for the inversion procedure. In the first one, we force the temperature stratification and the microturbulence to be the same both in the non-magnetic and in the magnetic components. And, in the second one, we allow the microturbulence and the temperature to vary independently in both atmospheric components. In both cases, the magnetic field strength and the filling factor are free parameters of the inversion and are initialized randomly. The rest of the variables are treated as in Sect. 3.

5.1. Inversion with fixed temperatures at both atmospheres

Some works dealing with LTE inversions at internetwork regions (see, for example, Socas-Navarro & Lites 2004) assume that the temperatures of both the non-magnetic and the magnetic components have the same stratification with log (τ_5). The same approximation is implicit in Milne-Eddington inversions. The line absorption coefficient is the same for both components and it is usually fixed by the intensity profiles. In the same way, in this first test, the temperature stratification and the microturbulent velocity are forced to be the same for both components in our inversions. To achieve this, the same model initialization is used for the non-magnetic and the magnetic atmosphere and the perturbations to these parameters are forced to be equal.

Regardless of the noise level, the computed strengths concentrate around 900 G. As expected, the inversions with higher noise level result in a slightly wider range of magnetic fields. The "real" temperature differences are compensated by an increase of 600 G of the "true" magnetic field strength. The important fact is that this behaviour is independent of the initialization.

The standard deviation histograms of the difference between the inverted and the synthetic V profiles are plotted in Fig. 9: all the inversions fit the synthethic profile equally well. The standard deviations are similar to the corresponding noise level in each case, meaning that all solutions to the inverse problem are acceptable. The assumption of two atmospheres with the same temperature stratification tends to overstimating the weak input magnetic field to almost 1 kG in this particular case. The resulting mean magnetic flux is 11 G, slightly higher than the input for the synthesis.

5.2. Inversion with free temperature stratifications

In the second test, we have left the temperature and microturbulence as independent free parameters for both atmospheric components. If the information of the thermodynamical and magnetic properties were present in the Stokes V profile, the inversion code should be capable of finding the correct solution. We have proceeded, as in the previous test, by initializing both components with the same model atmosphere except for the magnetic field strength (random initialization).

The results of the inversions are presented in Fig. 10. The magnetic field strength inferred from the inversions is plotted as a function of the magnetic field initialization. For both noise realizations, while the "true" magnetic field is 300 G, the computed value is nearly the same as the one fed to the inversion code until 700 G. Stronger field initializations return field strengths around 700–900 G. The dependence on the input

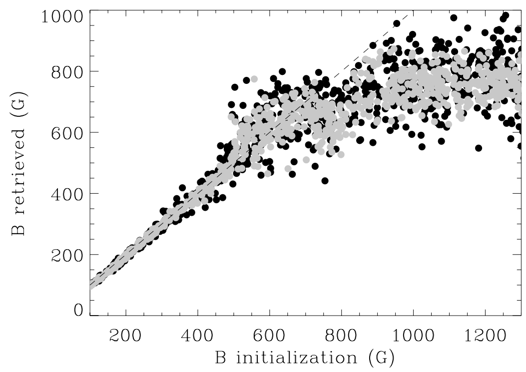

Fig. 10. Magnetic field strengths inferred from the inversions with the temperature stratification and the magnetic microturbulent velocity as free parameters. Grey dots represent the results with the noise level of $5 \times 10^{-5} I_c$ and the black dots the ones for $10^{-4} I_c$. The inversion procedure has the temperature stratification with optical depths and microturbulence as free parameters for both magnetic and non-magnetic components.

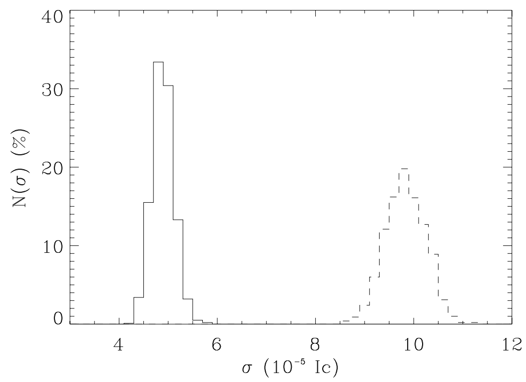

Fig. 11. Standard deviations of the difference between the noisy synthetic profiles and their fits. The solid and dashed lines represent the cases with a noise level of $5\times10^{-5} I_c$ and $10^{-4} I_c$, respectively. The inversion procedure has the temperature stratification with optical depths and microturbulence as free parameters for both magnetic and non-magnetic components.

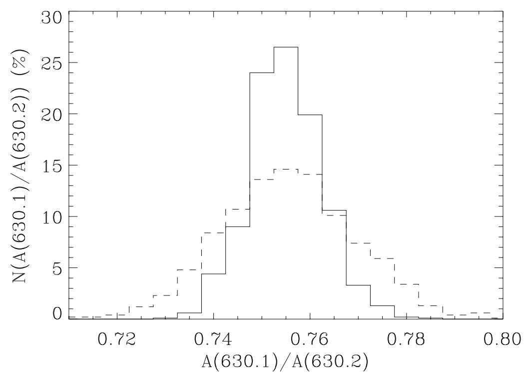

Fig. 12. Histogram of the ratio between the amplitudes of Stokes *V* for the 630.1 and the 630.2 lines. The solid line represents the case with a noise level of $5 \times 10^{-5} I_c$ and dashed one that of $10^{-4} I_c$. The inversion procedure sets free the temperature stratification with optical depths and microturbulence for both the magnetic and the non-magnetic components.

magnetic field is not a problem of the code since all the fits have the same quality. Figure 11 shows the histograms of the standard deviation of the difference between the synthetic and the fitted Stokes *V* profiles for each noise level case. Both distributions are narrow and peak at the added noise value. The mean magnetic flux is 10 G. Figure 12 shows the histogram of the amplitudes of the Stokes *V* profiles with a narrow distribution around 0.755. For this particular profile, even if the noise level is as low as $5 \times 10^{-5} I_c$ and the temperature and microturbulent velocity of the magnetic component are free parameters, one cannot distinguish between 100 and 800 G. Low flux internetwork Stokes spectra of the 630 nm lines do not seem to carry enough observables to separate the thermodynamic and the magnetic effects. The magnetic field is compensated by temperature gradients and microturbulent velocities in the same way as in Sect. 3.

6. Observational data

To confirm the numerical results found in the previous paragraphs, we have analyzed a data set corresponding to a $33'' \times 42''$ internetwork region observed on August 17, 2003 at the disc centre. Network regions were deliberately avoided using the real-time Ca K image available during the observations. The spectropolarimeter POLIS[2] (Beck et al. 2005) was used, attached to the German VTT at El Teide observatory, to obtain full Stokes spectropolarimetric data in the 630 nm wavelength region. The image was stabilized using a device correlation tracker (Ballesteros et al. 1996), which also made possible an accurate stepping perpendicular to the slit at steps of $0.35''$. The integration time at each slit position was around 27 s. After the data reduction, a noise level of $7 \times 10^{-5} I_c$ and a spatial resolution of $1.3''$ were achieved.

As before, the SIR code was used to invert the 630 nm *I* and *V* data following two different strategies: in the first one, we initialized the code with 1200 G; in the second, a starting value of 200 G was used. The free parameters and the model initialization were the same as in the numerical experiment of Sect. 5.2. For both inversion sets, we retrieved the same magnetic flux but very different magnetic field strength distributions (Martínez González et al. 2006a). With a strong (weak) field initialization, a peak around 1300 (200) G in the PDF is obtained. Both magnetic field distributions can be seen in Fig. 13. The most important fact is that both distributions fit the observations equally well. The small window in Fig. 13 compares the standard deviation of the difference between the observed and fitted Stokes *V* profiles computed for both initializations. Both distributions have the same σ. The conclusion is reached that with our experimental data we cannot distinguish between the two magnetic field distributions presented in the figure. Temperature and microturbulent velocities of both components behave as predicted by the numerical tests. Figure 14 shows the histogram of the microturbulent velocity recovered from the inversions. Larger values are found in the weak initialization procedure rather than in the strong one. In the inserted graphic the difference between the mean temperature stratifications recovered from the weak and the strong initializations is plotted. Strong fields can be compensated by cooling the layers where the 630.1 nm line has its maximum of sensitivity, and by heating the 630.2 nm formation region. This thermal change translates to a variation of the number of absorbers, more for the 630.1 nm transition and less for the 630.2 nm line. Adding a higher microturbulence to broaden the line, the effect of a strong magnetic field can be well reproduced in terms of other atmospheric properties, resulting in an intrinsic degeneracy of magnetic and thermodynamic properties.

[2] POlarimetric LIttrow Spectrograph.

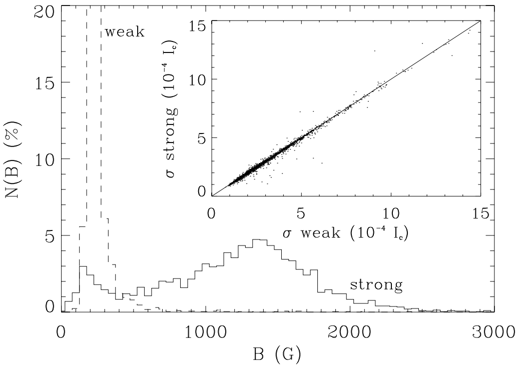

Fig. 13. Magnetic field distribution recovered from the observed data using two different inversions, with a strong (solid line) and a weak (dashed line) magnetic field strength initializations. The small plot represents the standard deviation, σ, of the difference between the observed and the fitted Stokes V profiles. The overplotted continuum line is the diagonal.

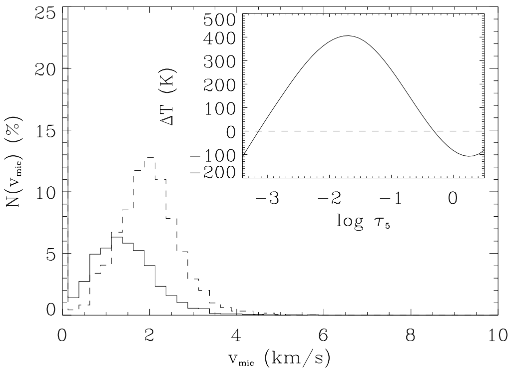

Fig. 14. Histograms of the microturbulent velocity recovered from two different inversions of the observed data, with a strong (solid line) and a weak (dashed line) magnetic field strength initializations. The plot in the small window represents the difference between the mean temperature stratification inferred from the weak and the strong initialization inversions.

7. Discusion and conclusions

The work by Westendorp Plaza et al. (1998) suggested that the 630 nm line pair can give reasonable estimates of the magnetic field vector for moderately unresolved weak fields. But the physical scenario they deal with differs substantially from that of the internetwork quiet Sun. First, the smallest filling factor used by those authors is 10% and the smallest circular polarization signal is $4 \times 10^{-3} I_{\rm c}$. These numbers are respectively 10 and 4 times larger than those characteristic of internetwork regions. Second, both the magnetic and the non-magnetic components have the same temperature stratification for their synthetic data and in the model atmospheres resulting from their inversions. Thus, they do not study the effect of different thermodynamical (magnetic and non-magnetic) properties. Their results are compatible with the assumptions made during their tests. As presented in this work, the relaxation of the constraint of equal temperature stratifications leads to different conclusions.

In this paper, a set of arguments have been presented that prove that the Fe I line pair at 630 nm is not reliable for the magnetic field strength determination in weak flux quiet Sun regions. The reason lies in the separate heights of formation of both lines, that makes them sensitive to different layers in the solar atmosphere. Model atmospheres with different magnitudes and gradients can result in indistinguishable Stokes profiles, with differences well below typical noise values of present high spatial resolution spectropolarimetric observations. Slightly different temperature stratifications, combined with adequate microturbulent velocities and magnetic field strengths ranging from a few hundred of Gauss to kiloGauss, give rise to the same Stokes profiles.

Previous estimations of magnetic field strengths at internetwork quiet Sun regions based on the 630 nm lines assume, explicitly, that the temperature stratification of the magnetic element is like that of the non-magnetic quiet Sun. The present paper reveals that the inferred magnetic properties of the internetwork are strongly coupled to the hypotheses made to constrain the analysis. Thus, those cited works must be regarded with care until the knowledge of the internetwork atmosphere is precise enough to confirm their hypotheses.

In addition, velocity and magnetic field gradients (not considered in this work) may lead to a larger degeneracy of the problem when using these lines. This suggests that the possibility of using alternative lines for the study of the quiet Sun magnetism, such as the Fe I pair at 525 nm, or the mentioned 630 nm line pair together with other spectral lines to constrain the problem, needs to be explored.

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