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LETTER

Letter to the Editor

Probing downflows in solar magnetic elements: the Fe II test

L.R. Bellot Rubio, B. Ruiz Cobo, and M. Collados

Instituto de Astrofísica de Canarias, E-38200, La Laguna (Tenerife), Spain

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Abstract. In an attempt to assess the physical realism of the plage flux tube model derived by Bellot Rubio, Ruiz Cobo & Collados (1997, 1998) we extend its predictions to the Stokes V zero-crossing shifts of a number of Fe II lines. For this analysis, accurate Fe II central wavelengths are required. We have devised a procedure for bringing the available Fe II laboratory wavelengths to the system of accurate Fe I wavelengths of Nave et al. (1994). It is shown that, relative to this system, the Fe II system of Kurucz (1981) is shifted by 6.4 mÅ towards longer wavelengths. Some lines, however, are displaced by more than 10 mÅ. Corrected central wavelengths have been used to extract the observed Stokes V zero-crossing shifts of 16 Fe II lines. Comparison with the values resulting from the model of Bellot Rubio et al. (1997, 1998) suggests that the velocity gradients derived by these authors are esentially correct.

Key words: atomic data – line: formation – Sun: faculae, plages – Sun: granulation – polarization – radiative transfer

1. Introduction

Recently, the problem of the origin of the asymmetrical shapes of the Stokes V profiles emerging from facular regions has attracted renewed interest. As a result, different scenarios that reproduce to a similar extent the observed shapes of the Stokes I and V profiles of several Fe I lines have been proposed (Bellot Rubio, Ruiz Cobo & Collados 1997, hereafter BRC; Sánchez Almeida 1997; Frutiger & Solanki 1998).

The inversion approach followed by Bellot Rubio et al. (1997) assumes the simplest two-component model, namely one single thin flux tube surrounded by a nonmagnetized external atmosphere. Remarkably, the Stokes profiles of the Fe I lines observed with the Advanced Stokes Polarimeter (ASP; Martínez Pillet, Lites & Skumanich 1997) were matched with the help of models harboring downflows in the magnetized interior. The possible origin of such motions is discussed in detail by Bellot Rubio, Ruiz Cobo & Collados (1998).

Determining the actual structure of solar magnetic elements is important for deepening our understanding of such basic processes as the distribution of magnetic fields in the photosphere and the heating of the solar chromosphere and corona. In this context, assessing the physical realism of the different models is crucial. Since the various approaches give similar results in what concerns the quality of the fits to the line profiles, the adequacy of the retrieved models can be determined only by their ability in reproducing observations other than those used strictly to obtain the free parameters of the models. In this regard, BRC demonstrated that their scenario (resulting from the inversion of only two spectral lines) is capable of matching the Stokes V zero-crossing wavelengths of nearly one hundred Fe I lines. However, Frutiger & Solanki (1998) claim that BRC's scenario is far inferior in reproducing the Stokes V zero-crossing wavelengths of Fe II lines.

In the present Letter we investigate the conjecture of Frutiger & Solanki. More specifically, we aim at ascertaining whether the Stokes V zero-crossing wavelengths of Fe II lines are also reproduced by BRC's model. The success of this test would lend additional support to the simple scenario proposed by these authors. However, a careful analysis is in order. Unlike Fe I, for which accurate laboratory wavelengths exist (e.g., Nave et al. 1994, hereafter NAV), the available Fe II central wavelengths measured in the laboratory are rather imprecise. Dravins, Larsson & Nordlund (1986) list wavelengths for Fe II originating from pulsed hollow-cathode measurements by Johansson (1978) which were improved by means of a numerical fit to the atomic energy levels of Fe II (Kurucz 1981) to reduce the large uncertainties in the original laboratory wavelengths (up to 20 mÅ according to Johansson 1978).

The observed zero-crossing shifts are strongly dependent upon the adopted central wavelengths (errors of just 1 mÅ, for instance, produce spurious shifts of roughly 50 m s^{-1}). For this reason, a knowledge of accurate wavelengths is essential. In addition, if the observed zero-crossings of both Fe I and Fe II lines are to be compared with the predictions of a model, it is mandatory that the same wavelength system for neutral and ionized iron be used. Prior to the comparison of the observed Stokes V zero-crossing shifts of Fe II lines with those resulting from the model of BRC, we address the problem of determining their central wavelengths in the Fe I wavelength system considered by NAV.

Send offprint requests to: L.R. Bellot Rubio (lbellot@iac.es)

2. Fe II central wavelengths

A common practice in solar physics is to measure the polarization of several spectral lines for deriving information, via inversion techniques, about the atmosphere in which they originate. Conversely, it is possible to use sufficiently well characterized atmospheres for deriving accurate atomic parameters (central wavelengths, oscillator strengths, etc). With this in mind we have obtained a two-component model of the quiet Sun by inverting the disk-center intensity profiles of four Fe I lines extracted from the FTS spectral atlas (FTSA) of Brault & Neckel (1987). A short description of the data can be found in Neckel (1994). Recently, the wavelength calibration of the FTSA has been tested by Allende Prieto & García López (1998), the conclusion being that the atlas is free from systematic deviations.

The inversion of the Fe I lines was carried out with SIR (Stokes Inversion based on Response functions, Ruiz Cobo & del Toro Iniesta 1992). The model derived from the inversion was refined by sequentially adding another three FTSA Fe I lines to the set of lines used for inversion. The addition of the new lines produced only minor variations in the retrieved model. The atomic parameters of these lines are summarized in Table 1. Their central wavelengths (λ_0) have been taken from the compilation of accurate laboratory wavelengths by NAV and have maximum uncertainties of ± 3 mÅ (± 0.15 km s^{-1}).

Our two-component model may be considered as representative of the granular and intergranular components of the quiet Sun. The free parameters of the model are temperature, line-of-sight (LOS) velocity and microturbulent velocity stratifications with optical depth in the two components. The macroturbulence is assumed to be the same in both atmospheres and depth-independent. The last free parameter of the model is the fractional area ($\alpha_{\rm g}$) of the resolution element occupied by the granular component. Fig. 1 shows the various stratifications recovered from the inversion of the Fe I lines. The macroturbulence turns out to be 0.80 km s^{-1}, and $\alpha_{\rm g} = 0.70$. With these parameters, the observed and synthesized intensity profiles of the seven Fe I lines differ by less than 3.3×10^{-3} (rms) in units of the continuum intensity. The basic properties of our two-component model are similar to those of real granules and intergranules. Quiet Sun granules, for example, are known to be hotter than intergranules in deep layers, but become cooler higher up (around $z \sim 140$ km, according to Ruiz Cobo et al. 1996). For the purpose of the present Letter, however, the important point is that the inferred LOS velocity fields reproduce the observed convective blueshifts, which is a direct consequence of the matching of the intensity profiles of the Fe I lines. In addition, we note that these velocity fields are compatible with the wavelength system of NAV.

We have used this model to determine accurate central wavelengths for 16 unblended Fe II lines in the wavelength range 4600–5450 Å. The lines were selected from the list by Dravins et al. (1986) with the requirement that they are not saturated. The λ_0 values given by Kurucz (1981) were employed as approximate central wavelengths. Values for $\log gf$ were taken from Meylan et al. (1993) when available, otherwise from Thévenin (1989). The procedure for determining Fe II central wavelengths compatible with the wavelength system of NAV works as follows: the intensity profiles of the selected lines are synthesized with the two-component model retrieved from the inversion of the Fe I lines and then compared with those extracted from the FTSA. Erroneous central wavelengths are revealed by different displacements of the observed and synthetic intensity profiles with respect to the assumed line center. Displacements of the synthetic spectra from line center depend only on the adopted LOS velocity fields which, as pointed out before, reproduce the wavelength system of NAV. In contrast, the displacements of the observed profiles depend not only upon the LOS velocity fields, but also on the assumed λ_0. Indeed, the correct value of λ_0 is the one for which the observed and synthetic profiles coincide.

Table 1. Atomic parameters of the Fe I lines used to determine the two-component model of the quiet Sun. Central (air) wavelengths (λ_0) have been taken from NAV. $\chi_{\rm e}$ is the excitation potential of the lower level, and gf the degeneracy of the lower level times the oscillator strength. Oscillator strengths are from Thévenin (1989, 1990)

λ_0 (Å)	$\chi_{\rm e}$ (eV)	$\log gf$	Transition
5247.0504	0.09	-4.97	$^5D_2$–$^7D_3$
5250.2089	0.12	-4.96	$^5D_0$–$^7D_1$
6301.5012	3.64	-0.59	$^5P_2$–$^5D_2$
6302.4936	3.69	-1.16	$^5P_1$–$^5D_0$
5213.8071	3.94	-2.76	$^3F_3$–$^5G_4$
5217.3893	3.21	-1.00	$^5D_4$–$^5D_3$
5225.5261	0.11	-4.74	$^5D_1$–$^7D_1$

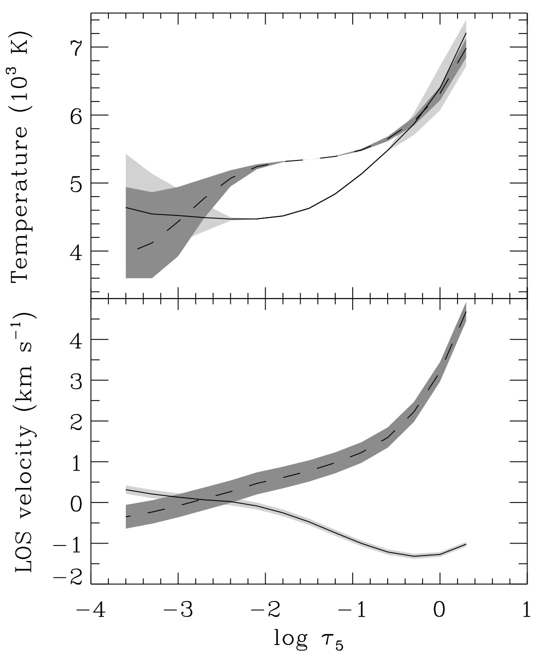

Fig. 1. Two-component model of the quiet Sun derived from the inversion of seven Fe I lines. The solid and dashed lines indicate the granular- and intergranular-like components, respectively. Positive velocities indicate downflows. The shaded areas represent formal errors in the retrieved parameters

Table 2. Atomic parameters of the Fe II lines as deduced from the two-component model of the quiet Sun. $\lambda_{0,\mathrm{corr}}$ represents the corrected central wavelengths and $\lambda_{0,\mathrm{K}}$ the laboratory wavelengths by Kurucz (1981). Oscillator strengths marked with an asterisk are from Meylan et al. (1993) after being corrected by less than 0.04 dex. The remaining oscillator strengths originate from Thévenin (1989), but have been corrected to account for the observed line depths

$\lambda_{0,\mathrm{corr}}$ (Å)	$\lambda_{0,\mathrm{K}}$ (Å)	χ_e (eV)	$\log gf$	Transition
4620.5125	4620.521	2.82	−3.32	$^4F_{7/2}$–$^4D_{7/2}$
4656.9760	4656.981	2.88	−3.62(*)	$^6S_{5/2}$–$^4D_{5/2}$
4666.7505	4666.758	2.82	−3.33	$^4F_{7/2}$–$^4F_{9/2}$
4670.1700	4670.182	2.57	−4.06	$^4P_{5/2}$–$^6F_{7/2}$
4720.1330	4720.149	3.18	−4.44	$^2P_{3/2}$–$^4P_{5/2}$
4993.3505	4993.358	2.79	−3.67	$^4F_{9/2}$–$^6P_{7/2}$
5100.6545	5100.664	2.79	−4.14	$^4F_{9/2}$–$^6F_{7/2}$
5132.6660	5132.669	2.79	−4.01	$^4F_{9/2}$–$^6F_{9/2}$
5136.7960	5136.802	2.83	−4.31	$^4F_{5/2}$–$^6F_{3/2}$
5197.5700	5197.577	3.22	−2.11	$^4G_{5/2}$–$^4F_{3/2}$
5234.6250	5234.625	3.21	−2.13(*)	$^4G_{7/2}$–$^4F_{5/2}$
5264.8050	5264.812	3.22	−3.06	$^4G_{5/2}$–$^4D_{3/2}$
5284.1060	5284.109	2.88	−3.11	$^6S_{5/2}$–$^6F_{7/2}$
5325.5530	5325.553	3.21	−3.19(*)	$^4G_{7/2}$–$^4F_{7/2}$
5414.0705	5414.073	3.21	−3.51(*)	$^4G_{7/2}$–$^4D_{7/2}$
5425.2495	5425.257	3.19	−3.22(*)	$^4G_{9/2}$–$^4F_{9/2}$

For the selected Fe II lines, we have determined the correction to the λ_0 values of Kurucz (1981) by minimizing the sum of the squared differences between the synthetic and observed intensity profiles. In general, it was necessary to modify the Thévenin oscillator strengths by $+0.2$ dex to account for the observed line depths. Only minor corrections (< 0.04 dex) were required for the oscillator strength values of Meylan et al. (1993). Note that these corrections are equivalent because the iron abundance adopted by Meylan et al. is $+0.15$ dex larger than that used by Thévenin. The results of the analysis are summarized in Table 2. Given the uncertainties in the LOS velocities of our two-component model (of the order of 100 and 300 m s^{-1} for the granular and intergranular components, respectively), an upper limit for the uncertainty in the corrected Fe II wavelengths is ± 2 mÅ. As can be seen, most of the laboratory wavelengths of Kurucz are offset by several mÅ with respect to the wavelength system of NAV. Differences as large as 16 mÅ are occasionally present, the average difference being 6.4 mÅ. In our sample, there is the general tendency for the Kurucz wavelengths to be *longer* than the corrected ones (which are compatible with neutral iron wavelengths). This appears to indicate that the Fe II wavelength system of Kurucz suffers from a relative zero point shift of 6.4 mÅ.

Our results strongly suggest that the available Fe II laboratory wavelengths contain significant errors. For analyses in which precise values of λ_0 are required (as, for example, the interpretation of the observed Stokes V zero-crossings), the use of these wavelengths should be avoided unless they are properly brought to a more accurate system. In Fig. 2 we show the corrections required to make the 16 Fe II lines compatible with the system of NAV. For comparison, we also show the corrections to the laboratory wavelengths of another 140 Fe I lines to which the same procedure has been applied. Now, however, their central wavelengths have been taken from NAV. Since this system is accurate to ± 3 mÅ, no significant corrections are to be expected. Indeed, this is what Fig. 2 reveals. The average correction to the laboratory wavelengths of NAV amounts to 0.4 mÅ, the standard deviation being 1.8 mÅ. These values confirm the internal consistency of the measurements by NAV. In addition, the lack of any significant trend for the Fe I lines displayed in Fig. 2 indicates that the LOS velocity fields of our quiet Sun model are capable of reproducing the observed line shifts, since otherwise convective blueshift would systematically produce larger corrections the weaker the lines.

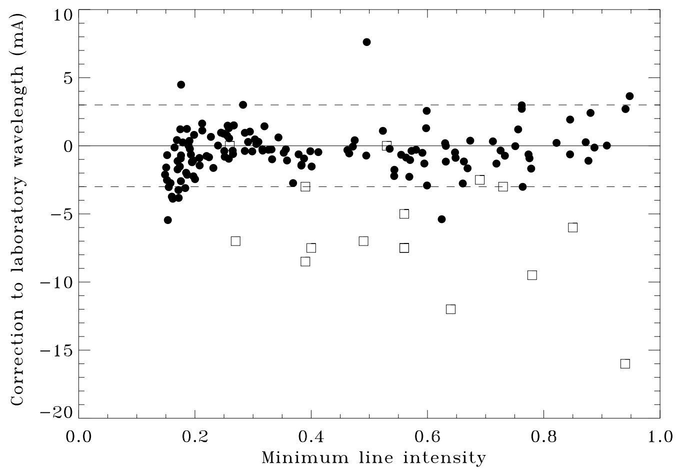

Fig. 2. Corrections to the Kurucz laboratory wavelengths needed to bring 16 Fe II lines (open squares) to the system of NAV as a function of minimum line intensity. Circles indicate the corrections resulting from the application of the same procedure to 140 Fe I lines whose laboratory wavelengths (accurate to within ± 3 mÅ) have been taken from NAV. The horizontal dotted lines represent corrections of ± 3 mÅ. Notice that the Fe I lines cluster within these limits, thus confirming the accuracy of the Fe I wavelength system of NAV

3. Comparison of observed and computed Fe II zero-crossing wavelengths

We have used the plage flux tube model derived by BRC and a macroturbulent velocity of 1.0 km s^{-1} to synthesize the Stokes V profiles of the 16 Fe II lines dealt with in the previous section. In contrast to what was done in BRC, we now adopt the absolute wavelength calibration of the ASP, which corrects the observed spectra for gravitational redshift, solar rotation and relative Earth–Sun motion (see Bellot Rubio et al. 1998 for details). It is important to bear in mind that the absolute velocity scale is strongly dependent on possible displacements of the absolute wavelength calibration. For the ASP data, such a calibration is estimated to be correct to within ± 0.15 km s^{-1} (Martínez Pillet et al. 1997).

The zero-crossing wavelengths of the synthetic Stokes V profiles were extracted and their displacements with respect to

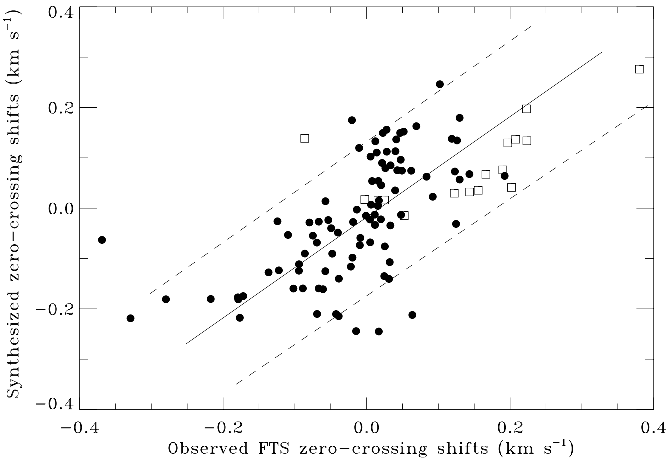

Fig. 3. Comparison of observed and computed zero-crossing wavelengths for 92 Fe I lines (circles) and 16 Fe II lines (squares). The solid line has slope equal to unity. The dotted lines indicate the range of uncertainty of the Fe I laboratory wavelengths (taken from NAV) and lie ± 0.15 km s^{-1} apart.

line center converted to velocities. The same process was carried out for the Stokes V profiles of the Fe II lines observed with the Kitt Peak Fourier Transform Spectrometer (FTS, Stenflo et al. 1984) in plage regions near disk center. We have used the absolute wavelength calibration of Solanki (1986), accurate to within ± 0.25 km s^{-1}, to remove the effects of solar rotation, relative Earth–Sun motion and gravitational redshift from the FTS measurements. The comparison of observed and computed zero-crossing shifts derived by the procedure just outlined is presented in Fig. 3, where circles indicate the zero-crossings of the Fe I lines considered by BRC. The Fe II lines analyzed in this Letter are represented by open squares. For Fe I, central laboratory wavelengths from NAV were used, implying that all the data points refer to the same wavelength system. Certainly, this is a contributing factor to the remarkable correlation displayed in Fig. 3. We emphasize, however, that the important diagnostic is the *slope* of the data in Fig. 3, because it does not depend on possible (systematic) errors in either of the two absolute wavelength calibrations. In so far as the slope is determined by the *velocity gradients* of the model, Fig. 3 demonstrates that those derived by BRC are capable of reproducing the observed Stokes V zero-crossing shifts.

4. Summary and conclusions

We have brought the available Fe II laboratory wavelengths to the system of accurate Fe I wavelengths of Nave et al. (1994). This has been done by minimizing the relative displacements of the observed and computed intensity profiles of 16 Fe II lines. The two-component model used for the spectral synthesis is intended to represent the quiet Sun atmosphere and was derived from the inversion of seven Fe I lines. Comparison of the observed and computed Fe II intensity profiles has revealed that the Fe II laboratory wavelengths of Kurucz (1981) are systematically redshifted by several mÅ. In our sample, the average offset is 6.4 mÅ (corresponding to $\simeq 320$ m s^{-1}), with a standard deviation of 4.2 mÅ.

This analysis has allowed us to extend the predictions of our plage flux tube model (Bellot Rubio et al. 1997, 1998) to the Stokes V zero-crossing wavelengths of Fe II lines. We have shown that, in addition to reproducing the observed behavior of the Stokes V zero-crossings of neutral iron lines, our simple scenario is also capable of explaining the observed zero-crossings of 16 unblended Fe II lines in the wavelength range 4600–5450 Å. While it is now accepted that different models fit equally well the shape of the spectral lines used in the inversion, we are convinced that the degree of success of predictions concerning observables other than those employed to obtain the free parameters of the models will ultimately determine the physical realism of the various scenarios put forward to describe the structure of solar magnetic elements.

The success of the model by Bellot Rubio et al. (1997, 1998) in reproducing the observed Stokes V zero-crossing wavelengths of more than 100 Fe I and Fe II lines makes a strong case in favor of the scenario proposed by these authors. It is important now to assess whether other scenarios pass this stringent test equally well, in which case additional observables would be needed to verify the predictions of the different models.

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