On the Determination of Magnetic Field Strength and Flux in Inter-Network

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Abstract. The results of the determination of magnetic field strength and flux from weak polarimetric signals in solar inter-network regions are contradictory. We investigate the origin of this contradiction with the help of MHD simulations. It is shown that the Stokes-V line ratio of the Fe \textsuperscript{i} 5247/5250 Å and 15652/15648 Å line pairs is a good indicator of kG magnetic field concentrations, even for magnetic fields with a complex internal structure like those in MHD simulations. On the contrary, the Stokes-V line ratio of the Fe \textsuperscript{i} 6301/6302 Å lines shows no correlation with magnetic field strength. The reason lies in the large difference in the heights of formation of these two lines. The value of the magnetic field strength obtained from the inversion of the Fe \textsuperscript{i} 6301 Å and 6302 Å lines depends crucially on the treatment of gradients of magnetic field, LOS velocity, and temperature even at numerical spatial resolution of 20 km.

1. Introduction

There is no agreement among the magnetic field strength distributions measured in inter-network with the help of different spectral lines. The infrared Fe \textsuperscript{i} lines at 1.56 \( \mu \)m reveal mostly weak fields with an exponential distribution (Lin 1995; Lin & Rimmele 1999; Khomenko et al. 2003; Martínez Gonzalez, Collados, & Ruiz Cobo 2006; Domínguez Cerdeña, Sánchez Almeida, & Kneer 2006). On the contrary, the visible Fe \textsuperscript{i} 6301 Å and 6302 Å lines suggest that the characteristic field strength is of the order of kG (Lites 2002; Socas-Navarro & Sánchez Almeida 2002; Sánchez Almeida, Domínguez Cerdeña, & Kneer 2003; Domínguez Cerdeña et al. 2003, 2006).

Several sources of uncertainties can affect the determination of the internetwork magnetic fields. Firstly, the polarimetric signals are very weak, of the order of \( 10^{-3} \) in units of the continuum intensity. Thus, noise and insufficient polarimetric sensitivity do not allow these weak signals to be reliably detected and analyzed. Bellot Rubio & Collados (2003) have demonstrated that noise can produce a shift of the maximum of the PDF obtained with the visible lines towards kG values. Secondly, the spatial structure of the magnetic fields remains unresolved even in the best-resolution observations. As a consequence, measurements based on the Zeeman effect can be affected by polarity cancellations, leading to the undetection of a (possibly) significant part of the flux. Socas-Navarro & Sánchez Almeida (2003) suggested that, if the fields are spatially unresolved, the IR lines tend to detect the weak component while the visible
lines are selective to the strong component in the resolution element. This effect is due to the different Zeeman sensitivity in the two spectral regions.

Finally, the weak profiles in inter-network are strongly asymmetric and have irregular shapes. The interpretation of such kind of spectra in terms of simplified models may lead to confusion and contradictions between the different measurements. The results based on Stokes $V$ or magnetogram calibration (weak field approximation), line ratios, and Milne-Eddington inversions, depend on the assumption that the gradients of parameters such as temperature, velocity, and magnetic fields, are absent. However, this approach is only valid if the pair of spectral lines used for the analysis have exactly the same sensitivity to all atmospheric parameters, except for the magnetic field, and form at the same height. In the present paper, we investigate the validity of the Stokes-$V$ line ratio method for the Fe I 5247/5250 Å, 6301/6302 Å, and 15652/15648 Å pairs of lines, as applied to the complex fields in MHD simulations.
Figure 2. Ratio of the Stokes-V amplitudes of the Fe i 6301 Å and 6302 Å lines. Top left: all the pixels have the same thermodynamics. Top right: B is constant with height in all the pixels. Bottom left: B and V_{LOS} are constant with height. Bottom right: B and V_{LOS} are constant with height and all the pixels have the same thermodynamics.

2. MHD Simulations

We used a snapshot of realistic 3D simulations of solar magneto-convection (Vögler et al. 2005). The simulation has a bi-polar structure of the magnetic field and an average unsigned magnetic field strength of 30 G at log τ_5 = −1 (for details, see Vögler et al. 2005; Khomenko et al. 2005). The horizontal spatial resolution is 20 km. The Stokes spectra of the Fe i lines at 5247, 5250, 6301, 6302, 15648, and 15652 Å, formed at solar disk center (μ = 1), were calculated for every vertical column of the selected snapshot. In addition, in order to make a realistic comparison of the synthetic spectra with observations, we performed a convolution of the two-dimensional snapshot with an adequate point-spread function (Khomenko et al. 2005). The resolution of the smoothed images is about 1″ and the contrast matches typical observed values.

3. Magnetograms at Full Numerical Resolution

Figure 1 gives maps of the Stokes-V amplitude ratio in the simulation snapshot calculated for the different pairs of lines. The profiles are taken at their original numerical resolution of 20 km and no noise is added.
The values of the Stokes-V amplitude ratio depend (among other parameters) on the field strength and atomic parameters of the spectral lines used. In a simplest case of constant magnetic field, this ratio changes within 0.5–0.95 for the Fe i 6301/6302 \( \text{Å} \) lines, 0.67–1.0 for the Fe i 5247/5250 \( \text{Å} \) lines, and 0.37–0.8 for the IR lines, where the first value corresponds to the case of a weak field and the second value to the case of a strong field. Note that these values are calculated assuming both \( V_{\text{mic}} \) and \( V_{\text{mac}} \) equal to zero for a constant vertical magnetic field and thermodynamic parameters taken from the model HSRA. The line ratios presented in Fig. 1 are scaled in such a way that the orange and yellow colors would correspond to a kG field strength. The original “true” snapshot is presented at the bottom right panel. It follows that the locations with strong fields in the original snapshot correspond rather well to locations with maximum line ratio for the Fe i 5247/5250 \( \text{Å} \) and 15648/15652 \( \text{Å} \) line pairs. This is not the case for the Fe i 6301/6302 \( \text{Å} \) lines. There, the line ratio is largest not where the field is largest, but rather in the canopy regions surrounding the magnetic field concentrations and in the transition regions between granules and intergranules.

4. The Reason for the Incorrect Line Ratio of Fe i 6301 \( \text{Å} \) and 6302 \( \text{Å} \)

In order to find the reason for the wrong behavior of the Fe i 6301 \( \text{Å} \) and 6302 \( \text{Å} \) lines, we performed several test calculations. The results of these calculations are displayed in Fig. 2. In the first test (top left panel of Fig. 2), we removed all the horizontal variations of the thermodynamic parameters from the original snapshot, but preserved the original values of the magnetic field and velocity. Then, the radiative transfer calculations were repeated. Comparing to the case displayed in Fig. 1 (top left), the spatial distribution of the line ratio has become slightly more homogeneous in granular regions. However, it still shows no correlation with the original magnetic field distribution.

In the second test (top right panel of Fig. 2), we retained the original variations of the thermodynamic parameters. The field strength and orientation were kept constant, though, in the vertical direction, varying from pixel to pixel according to their values at log \( \tau_5 = -1 \) in the original snapshot. Now the map of the line ratio changes significantly. The strongest values are located in intergranular lanes, similar to the original field distribution. However, the line ratio map suggests the presence of kG fields in all intergranular lanes, while originally only some intergranules contained strong fields. Also, the amplitude of the spatial variations of the line ratio remains too large.

In the next test (bottom left panel of Fig. 2), both LOS velocity and magnetic field strength were kept constant with height. The removal of velocity gradients has led to an increase of the correlation between the line ratio and the original field strength. However, the spatial variations of the line ratio are still larger than those for the Fe i 5247/5250 \( \text{Å} \) and Fe i 15648/15652 \( \text{Å} \) lines (Fig. 1).

In the last calculation (bottom right panel of Fig. 2), we removed the horizontal variations of thermodynamic parameters as well as vertical variations of the velocity and field strength. Only in this case the Stokes-V amplitude ratio of the Fe i 6301/6302 \( \text{Å} \) lines reflects well the true magnetic field distribution. Thus, the vertical gradients of the magnetic field and velocity and variations of
the thermodynamic parameters along the snapshot produce a distortion of the line ratio of these lines in the way that appears in Fig. 1. The reason of such a behavior is the large difference in the height of formation of the Fe i 6301/6302 Å lines, which amounts on average to about 100 km (Shchukina & Trujillo Bueno 2001). This does not happen for the Fe i 5247/5250 Å and 15648/15652 Å line pairs, whose heights of formation are close enough, and the assumption about the absence of gradients is not crucial. Thus, the results of the magnetic field measurements based on the line ratios using the Fe i 6301/6302 Å lines should be taken with care even at a numerical spatial resolution of 20 km. Our additional calculations of the magnetogram signal ratios (not presented here) show that they behave in a similar way to the line ratios. The same restriction probably applies to Milne-Eddington inversions as well. If the asymmetry of the lines is not fitted and the inversion relies on the amplitude ratio of these lines as a reliable parameter, the results of such an inversion may be far from reality.

5. Magnetograms at 1″ Resolution

Figure 3 gives the results of the Stokes-V amplitude ratio calculations for the profiles at about 1″ resolution. Now the correlation between the magnetic field strength and line ratio is worse than in the case of no-smearing for all line pairs. The patches with an enhanced line ratio are much larger than the actual field concentrations, for the Fe i 5247/5250 Å and Fe i 15648/15652 Å line pairs. This is expected in observations with a limited spatial resolution. However, the
line ratio corresponding to kG fields is only present in the surroundings of kG magnetic field concentrations and it is small where the field is weak. The latter is not the case for the Fe $i$ 6301/6302 Å line pair. There, almost the full snapshot shows the line ratio characteristic of kG fields. Had this line-ratio result been obtained after observational data, one would have been tempted to erroneously conclude that the whole observed area contained strong fields.

6. Conclusions

The calculations of the Stokes-$V$ amplitude ratio of the Fe $i$ 6301 Å and 6302 Å lines for the complex magnetic fields of MHD simulations show that this is not a good parameter for the indication of kG magnetic field concentrations. The line ratio is affected by the vertical gradients of the magnetic field, velocity, and thermodynamic parameters, due to the large difference in the heights of formation of the Fe $i$ 6301 Å and 6302 Å lines. The treatment of the gradients is thus crucial in the inversion of these lines. If the Stokes-$V$ asymmetry is not fitted, and the inversion takes the Stokes-$V$ amplitude ratio as a reliable parameter, the resulting magnetic field distribution can show an excess of kG values. This problem is much less important in the case of the Fe $i$ 5247/5250 Å and Fe $i$ 15648/15652 Å line pairs, whose heights of formation are closer.

Acknowledgments. The authors are grateful to A. Vögler for his kind permission to use 3D model atmosphere for the purposes of our study. This research was funded by the Spanish Ministerio de Educación y Ciencia through project AYA2004-05792.

References