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On the Diagnostics of the Quiet Sun Magnetic Fields: Multi-Line Spectro-Polarimetric Observations and Inversion Results

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Abstract. Sophisticated diagnostics of the quiet Sun magnetic fields are a very important issue of modern solar physics because of the existence of their deep genetic connections with active regions. For this aim, we use high-precision spectro-polarimetric observations in about twenty spectral lines in an almost 3 nm wide spectral domain around the line Fe I 525.02 nm. These observations cover the whole solar disk. A detailed statistical analysis of magnetic strength ratios in different combinations of spectral lines is performed. For seven sufficiently strong Fe I lines observed at disk center, we applied the SIR code (Stokes Inversion based on Response functions). It was impossible to reproduce the Stokes *I* and *V* profiles of these selected lines simultaneously in the framework of models with only one atmospheric component. But a very good agreement between observations and inversion results was obtained for a model with two atmospheric components, one with magnetic field and the other without. Reliable values were found for the magnetic field strength and the filling factor.

1. Introduction and Observations

One of the most remarkable trends in recent years of experimental solar physics is a significant increase of interest in the exploration of the quiet Sun in general and of the quiet Sun magnetic fields in particular (Socas-Navarro & Sánchez Almeida 2002; Martínez González et al. 2006; Domínguez Cerdeña et al. 2006; Orozco Suárez et al. 2007; Socas-Navarro et al. 2008; del Toro Iniesta et al. 2010). An obvious reason is the untypically prolongated minimum of solar activity during the last couple of years, when the Sun very often was just without sunspots and active regions at all. In this case solar observers, including those who deal with the excellent Hinode space craft, were just forced to study only the quiet regions of the Sun (Orozco Suárez et al. 2007). Another reason is to understand the fact that the quiet Sun magnetic fields are an important component of solar magnetism, and in some aspects even the most important one. Already simple estimations show that the huge amount of solar magnetic flux, just because of the covered surface area in comparison to that of active regions, belong to the quiet Sun magnetic fields. During the minima of activity, almost the whole solar surface is covered by very weak magnetic fields.

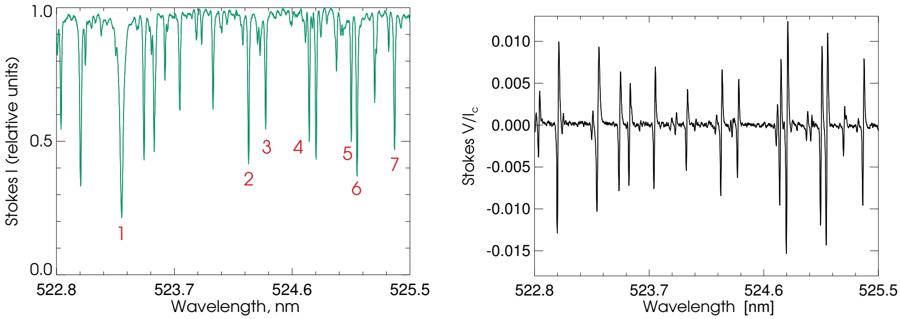

Figure 1. Spectra of Stokes parameters *I* (left panel) and *V* (right panel) recorded along the whole wavelength band including Fe I 523.29 nm and Fe I 525.02 nm. These observations were obtained close to the solar disk center with a magnetic flux density of –26 G measured in Fe I 525.02 nm. Enumerated are the lines processed with the SIR code.

Observations in various lines and observatories often provide magnetic field measurements that differ significantly. Among other reasons, it is urgent to clarify this point for the calibration issues of SOHO/MDI and the recently launched SDO/HMI project. This is connected with the complicated spatial structure of the solar atmosphere and, probably, with instrumental effects. Therefore, high precision measurements made simultaneously at the same instrument in as many spectral lines as possible are extremely valuable.

Martínez González et al. (2006) and Socas-Navarro et al. (2008) investigated the reliability of magnetic flux density determinations using data from the well-known strength ratio pairs in the green (Fe I 524.70 nm and Fe I 525.02 nm) and red (Fe I 630.15 nm and Fe I 630.25 nm) spectral bands. Socas-Navarro et al. (2008) made the conclusion that only comparisons of simultaneous observations made in the green and red pairs could provide reliable information about the magnetic field strengths in magnetic elements. Recently, del Toro Iniesta et al. (2010) obtained even more optimistic results using the same doublet of red lines. A practically important conclusion made from the comparison of Mount Wilson observatory observations in the pair of lines Fe I 523.29 nm and Fe I 525.02 nm (Tran et al. 2005; Ulrich et al. 2009) is the suggestion to re-calibrate the widely used SOHO/MDI full-disk magnetograms. However, this result was not confirmed by the Stokes-meter observations made at the Sayan observatory (Demidov & Balthasar 2009).

To explore the diagnostic potential of spectro-polarimetric observations in many spectral lines in the rather wide spectral band in the vicinity of Fe I 525.02 nm, high-precision Stokes-metric full-disk measurements (Stokes *V* and Stokes *I* parameters), made at the Solar Telescope for Operational Predictions (STOP) telescope of the Sayan solar observatory, were used. This band includes almost 20 diagnostically important lines, among them Fe I 523.29 nm and Fe I 525.02 nm. Observations in all spectral lines are perfectly correlated with each other (the correlation coefficients are larger than 0.9),

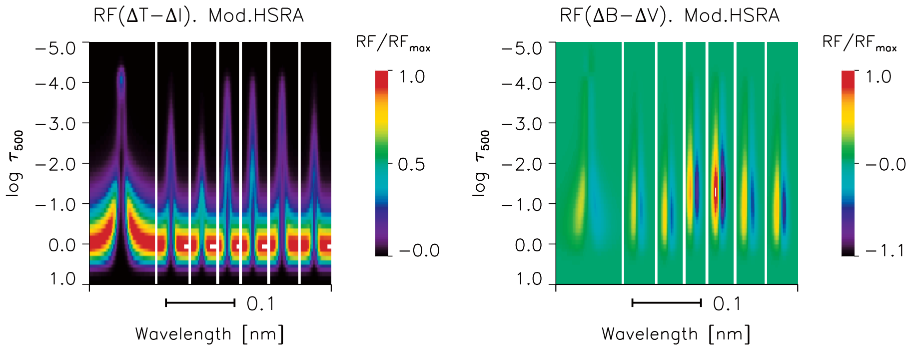

Figure 2. Left panel: temperature response functions to the Stokes *I* for the seven iron lines, indicated at the Fig. 1. Data for different lines are separated by white vertical strips. Right panel: magnetic field response functions to the Stokes *V*.

but they have, depending on the combination of lines, systematic differences. The regression coefficients *R* are in the range from 1 to 2.7. The disk averaged value of *R* for the ratio B(Fe I 523.29 nm)/ B(Fe I 525.02 nm) is equal to 1.97. Center-to-limb variations (CLV) of *R* occur in all combinations of spectral lines with decreasing *R* closer to the limb. The smallest CLV is found for the combination of the lines Fe I 524.70 nm and Fe I 525.02 nm. Figure 1 shows the example of the distribution of Stokes *I* and *V* profiles at the point near disk center (size ≈ 10″) with a magnetic flux density of – 26 G in Fe I 525.02 nm and of – 64 G in Fe I 523.29 nm. Enumerated are the seven Fe I lines used for the SIR inversions.

2. Application of the SIR Inversion Code to Seven Fe I lines

To explore the diagnostic potential of spectro-polarimetric observations in many spectral lines, we applied the SIR code (Stokes Inversion based on Response functions, Ruiz Cobo & del Toro Iniesta 1992) for the seven strongest iron spectral lines: 523.29 nm, 524.25 nm, 524.38 nm, 524.70 nm, 525.02 nm, 525.06 nm, and 525.35 nm. The intensity response functions on temperature, calculated with SIR using the Harvard Smithsonian Reference Atmosphere (HSRA, Gingerich et al. 1971) are shown in the left panel of Fig. 2, while the right panel displays the response functions of the Stokes *V* parameter on the magnetic field strength. These data allow to estimate the contribution of different solar atmospheric layers to the formation of the spectral lines.

We could not reproduce the Stokes *I* and Stokes *V* profiles of the selected spectral lines simultaneously in the framework of any model with only one atmospheric component. The best agreement between observation and inversion results was found for a model with two atmospheric components within the resolved spatial element. One component is without magnetic field, and the other one is a magnetic component which fills a certain fraction of the resolved element (filling factor). As non-magnetic compo-

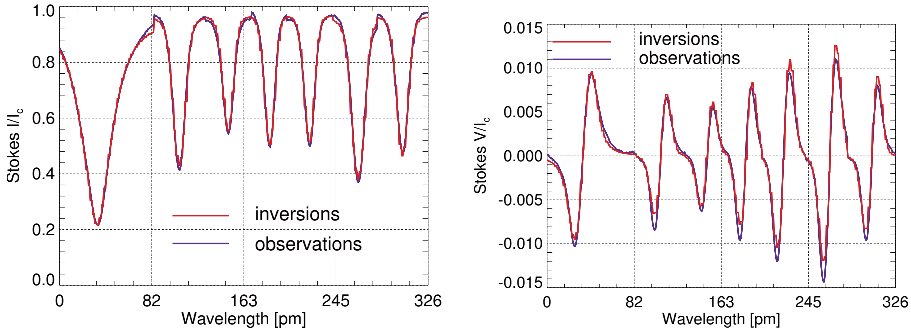

Figure 3. Comparison of the observed and inverted Stokes I and V profiles for seven iron lines. To obtain the best fitting results, the two-components model was used.

nent, we started with the HSRA model, and as starting magnetic component, the plage model of Solanki (1986) is used. The obtained profiles are shown on Fig. 3 in the left (Stokes I profiles) and in the right panel (Stokes V profiles). The best fit is obtained with a filling factor of 0.05 (spatial resolution of 10°) and a magnetic field strength 1.5 kG at $lg\tau = -1.5$. The strength is monotonically decreasing with height what is physically justified. If we artificially multiply the Stokes V parameter by a factor of two to simulate the five times large difference between Fe I 523.29 nm and Fe I 525.02 nm to reproduce the results of Ulrich et al. (2009), we obtain an unrealistic non-monotonic gradient.

Our near future plans are to add in the SIR inversion analysis all other spectral lines from the observed wavelength band and apply the code not only to near disk center points but for those ones closer to the limb.

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