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On the diagnostics of the quiet Sun's magnetic fields: application of the SIR inversion to the full-disk Stokes-meter observations in 15 spectral lines

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Abstract. Although quiet solar magnetic fields are weak and they are difficult to measure, they cover most of the solar disk, even the whole one during epochs of minimal activity. They are basically responsible for the formation of the open flux from the Sun, and, consequently, reliable diagnostics of them are very important. In this study, we use a raster scan covering the whole solar disk of high precision Stokes-meter measurements of the quiet solar magnetic fields in 15 simultaneously recorded lines in the vicinity of Fe I 525.02 nm. A two-component model atmosphere and the SIR (Stokes Inversion based on Response functions) approach were used for theoretical modeling. Two types of inversion results were obtained for magnetic component: one with kG magnetic field strength, high temperature and small filling factor, and the other one with relatively weak magnetic field (no more then 200 G), low temperature and big filling factor. A possible explanation of such result is briefly discussed. An application of the obtained results for the urgent issue to calibrate SOHO/MDI magnetograms is presented.

Keywords : Sun: photosphere – Sun: magnetic topology

1. Introduction

Active phenomena exist on the Sun very often but not always, in contrast to magnetic fields of the quiet Sun, which permanently are present. It is one of the reasons to investigate the quiet solar magnetic fields. The interest to explore such fields increased

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significantly in recent years because of the prolongated and extremely deep solar minimum (Sánchez Almeida & MartÍınez González 2011). These magnetic fields play a significant role in the evolution of solar magnetism, but a reliable measurement of such fields is very complicated because of the rather low degree of polarization in spectral lines. A powerful tool for diagnostics of solar magnetic fields, including the quiet ones, is a comparison of measurements made in different spectral lines and observatories. Due to possible impact of instrumental effects on the results (Demidov et al. 2008), it is quite obvious that observations in different lines on the same instrument are preferable.

In this study the high-precision spectro-polarimetric (Stokes V and Stokes I parameters) simultaneous observations in 15 spectral lines in the vicinity of Fe I 525.02 nm are analyzed. Observations with spatial resolution roughly 10″, covering the full disk, were made at STOP telescope (Demidov et al. 2002) of Sayan observatory on 1, 2 and 3 February 2009, when the solar disk was void of any activity. The same observa-

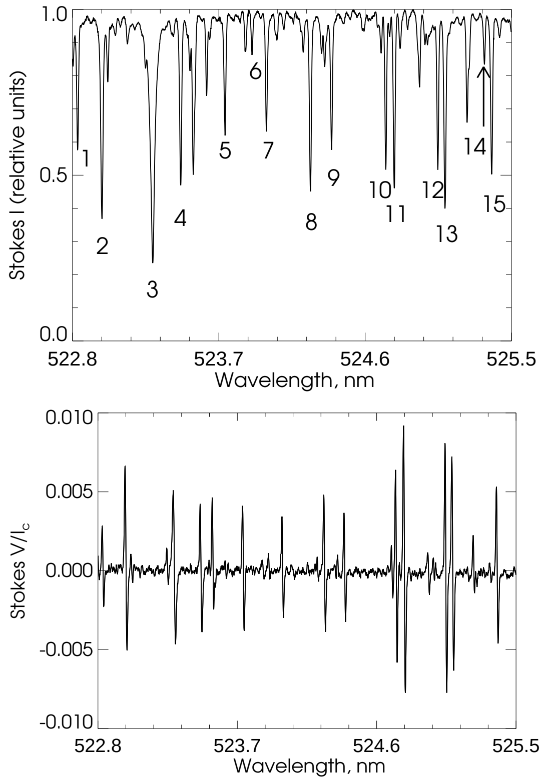

Figure 1. Example of observations of Stokes parameters I (top panel) and V/I_c (bottom panel) obtained at the point close to eastern limb of solar disk ($\mu = \cos\theta = 0.66$) with a magnetic field strength 21 G in Fe I 525.02 nm (line 12) and 31 G in Fe I 523.29 nm (line 3).

Table 1. List of spectral lines used in this study and results of correlation and regression analysis

N	λ [nm]	Elem.	χ [eV]	g_{emp}	$R = B(LineN)/B(Line12)$	ρ
1	522.8383	Fe I	4.22	0.875	1.370 (± 0.022)	0.860
2	522.9849	Fe I	3.28	1.500	1.590 (± 0.017)	0.942
3	523.2940	Fe I	2.94	1.300	1.970 (± 0.024)	0.927
4	523.4620	Fe II	3.21	0.869	2.124 (± 0.026)	0.923
5	523.7325	Cr II	4.07	1.335	1.772 (± 0.022)	0.919
6	523.8969	Cr I	2.71	1.500		
7	523.9823	Sc II	1.45	1.006	1.685 (± 0.022)	0.912
8	524.2491	Fe I	3.63	1.004	1.634 (± 0.019)	0.931
9	524.3777	Fe I	4.26	1.337	1.098 (± 0.014)	0.924
10	524.7050	Fe I	0.09	1.992	1.074 (± 0.005)	0.988
11	524.7574	Cr I	0.96	2.512	1.194 (± 0.007)	0.983
12	525.0209	Fe I	0.12	2.999	1.000 (± 0.000)	1.000
13	525.0646	Fe I	2.30	1.500	1.716 (± 0.014)	0.966
14	525.3033	Fe I	2.28	1.000		
15	525.3462	Fe I	3.28	1.502	1.329 (± 0.013)	0.953

tions were already used by Demidov & Balthasar (2009) and by Demidov & Balthasar (2011) for other purposes. Here a detailed statistical analysis of full-disk Stokes-meter simultaneous measurements in 15 spectral lines, including such diagnostically instructive ones as Fe I 523.29 nm and Fe I 525.02 nm, is made. For theoretical interpretation of such multi–spectral–lines observation the SIR (Stokes Inversion based on Response functions) code (Ruiz Cobo & del Toro Iniesta 1992) is used.

2. Observations

In the analyzed observations the image of the Sun (with a diameter ≈ 50 mm, what corresponds to spatial resolution about 10″) was focused on the entrance slit of the spectrograph and the scanning step was 91″ in both directions (X and Y). We were able to complete such a raster of measurements covering he whole solar disk within about two hours. Fig. 1 shows an example of Stokes I and Stokes V/I_c spectra, measured at one of the scanning points not far away from the eastern limb of the disk. The magnetic field strength at this point, calculated using the center-of-gravity method in the weak field approximation, was 21 G for Fe I 525.02 nm and 31 G for Fe I 523.29 nm. Fifteen spectral lines used for the SIR inversions are indicated by corresponding numbers. Details about these lines are given in Table 1. The lines belong to different chemical elements, neutral and ionized ones, and have different excitation potentials χ and Landé factors g.

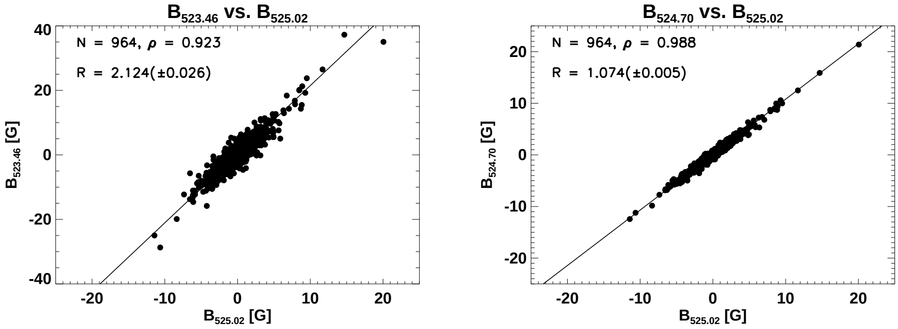

Figure 2. Example of correlation and regression analysis of solar magnetic field measurements for combinations of spectral lines Fe II 523.46 nm – Fe I 525.02 nm (left panel) and Fe I 524.70 nm – Fe I 525.02 nm (right panel). N is the number of points, ρ is the correlation coefficient, and R is the linear regression coefficient.

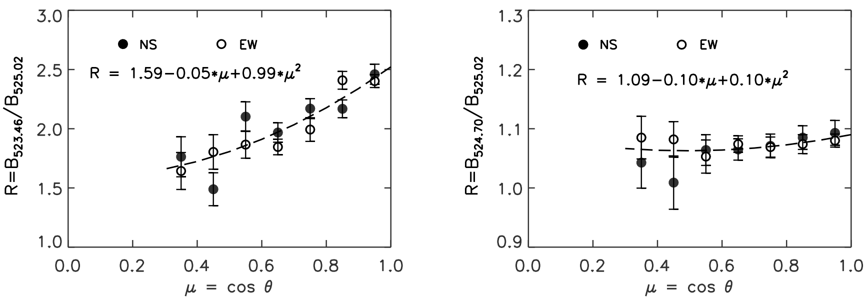

Figure 3. Center-to-limb variations (CLV) of the magnetic strength ratios for combinations of spectral lines Fe II 523.46 nm – Fe I 525.02 nm (left panel) and Fe I 524.70 nm – Fe I 525.02 nm (right panel). Values were averaged in equally spaced slots for the polar (NS) and equatorial (EW) sectors of the solar disk.

The two right columns in Table 1 show coefficients of regression R and correlation ρ, calculated for all three days of observations for the entire solar disk. Lines 6 and 14 were excluded from statistical analysis because they show too weak polarization signals. Examples of scatter plots for two combinations of spectral lines are shown in Fig. 2. The R value for all combinations of spectral lines is not constant over the disk, but shows center-to-limb variations (CLV). The most significant CLV of R ($R(\mu = 1.0)/R(\mu = 0.3) \approx 2.75/1.25 \approx 2.2$) is found for Fe I 523.29 nm – Fe I 525.02 nm (see Figure 5 in Demidov & Balthasar (2009)), the smallest one - for Fe I 524.70 nm – Fe I 525.02 nm. Fig. 3 shows as examples the CLVs of R for the same combinations of spectral lines as in Fig.2.

3. Inversion results

A two component model (one component with magnetic field and the other one is non-magnetic) was used for the SIR inversion. As starting model, HSRA (Gingerich et al. 1971) was used for the quiet component, and a modification of the model of Solanki & Brigljevič (1992) for the magnetic component. To avoid a violation of the condition div$B$ = 0, the magnetic field (assumed oriented vertically) and filling factors were considered as constant with depth. Temperature, electron pressure and Doppler velocity were height-dependent. Results only from February 3 are considered here. Pixels with a mean absolute value of $|V|$ less than 0.025 were removed from the analysis of the magnetic component, because the V-signal then does not significantly exceed the noise level.

For the quiet Sun atmosphere, expected results were achieved – the highest temperature T occurs at the disk center and it decreases to the limb. Two types of solutions are found for the magnetic elements. One group of pixels shows high magnetic field strengths (1500–2000 G), high temperature (5500–6500 K), and small filling factors (less then 0.05). For the other pixels, we obtained weak field (50–150 G), low temperature (5000–5300 K), and large filling factors (up to 0.50). We selected the temperatures at an optical depth of $log\tau_{500} = -1.5$ for both components. The reason of these differences is not clear, yet. However, there are some indications that it could be connected not only with CLV effects, but also with some peculiarities in the magnetic strengths ratios in some combinations of spectral lines. Note that recently a co–existence of two populations of magnetic fields on the Sun, weak and strong, was discovered by Stenflo (2010).

The SIR-inversions of multi–lines Stokes-meter observations might have an interesting impact on the urgent SOHO/MDI magnetograms calibration problem. The recent re-calibration of SOHO/MDI magnetic field data is based on the ≈ 5-times larger strengths measured in Fe I 523.29 nm than in Fe I 525.02 nm, according to the observations of the Mount Wilson observatory (Ulrich et al. 2009). This contradicts to our results (Demidov & Balthasar 2009), where we found that the regression coefficient for this ratio is less than two. We made a numerical experiment and performed inversions without these two lines. The agreement between observed and inverted profiles for the 13 other lines was excellent. Using the so obtained atmospheric models, we calculated Stokes profiles for all 15 lines. These synthetic profiles were in perfect agreements with all observed profiles confirming our previously published conclusion about the value of magnetic strength ratio for spectral lines Fe I 523.29 nm and Fe I 525.02 nm.

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References

Demidov M.L., Balthasar H., 2009, Solar Phys., 260, 261

Demidov M.L., Balthasar H., 2011, in Kuhn J.R., Berdyugina S.V., Harrington D.M., Keil S., Lin H., Rimmele T., Trujillo Bueno J. eds, Solar Polarization 6, ASP Conf Ser., 437, p. 189

Demidov M.L., Golubeva E.M., Balthasar H., Staude, J., Grigoryev V.M., 2008, Solar Phys., 250, 279

Demidov M.L., Zhigalov V.V., Peshcherov V.S., Grigoryev V.M., 2002, Solar Phys., 209, 217

Gingerich O., Noyes R.W., Kalkofen W., Cuny Y., 1971, Solar Phys., 18, 347

Ruiz Cobo R., del Toro Iniesta J.C., 1992, ApJ, 398, 375

Sánchez Almeida J., Martínez González M., 2011, in Kuhn J.R., Berdyugina S.V., Harrington D.M., Keil S., Lin H., Rimmele T., Trujillo Bueno J. eds, Solar Polarization 6, ASP Conf. Ser., 437, p. 451

Solanki S.K., Brigljevič V., 1992, A&A, 262, L26.

Stenflo J.O., 2010, A&A, 517, A37

Ulrich R.K., Bertello L., Boyden J.E., Webster L., 2009, Solar Phys., 255, 53