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On the Manifestation of Magnetic Flux Tubes in Observations of the Mean and Background Magnetic Fields of the Sun

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Abstract. Some recent results suggest that the fine-structured organization of solar magnetism is not quite correctly taken into account in observations of large-scale magnetic fields (LSMF). A good diagnostic tool for magnetic elements with kilogauss fields is the strength ratio method (SRM) where results of observations in lines with a different sensitivity to the magnetic field are compared. This paper presents the results obtained by applying the SRM method to observations of the solar mean (SMMF) and background magnetic fields (BMF). The subject of analysis includes SMMF and BMF observations made in different spectral lines during 1994 - 1997 at the STOP telescope of the Sayan observatory. It is shown that the influence of strong kilogauss fields appears to be important even in SMMF observations. BMF shows a certain dependence of results on the type of the object observed (active region or quiet photosphere). It is noticed that the influence of magnetic tubes can account (at least partially) for systematic differences in LSMF observations at different observatories.

1. Introduction

When measuring magnetic fields on stars, including the Sun, one is led to use not direct (as in laboratory physics or, for example, from spacecraft) but indirect methods to analyze the specific characteristics of electromagnetic radiation. The methods most generally employed are those based on the Zeeman effect, the splitting in a magnetic field of some spectral lines and the polarization of the splitting components. In the case of weak fields (in the sense that the magnitude of the Zeeman splitting is much less than the spectral line width), which is undoubtedly true for the solar mean (SMMF) and background (BMF) magnetic fields, the splitting can not be directly recorded. In this case magnetic field diagnostics are based on polarimetric measurements in spectral lines. However, the problem of interpreting such measurements is relatively simple if only the fields themselves and the medium in which they reside are sufficiently homogeneous. In the presence of gradients of magnetic and thermodynamic parameters, both in the line of sight and in the aperture of observation, the problem becomes much more involved.

The solar atmosphere is extremely inhomogeneous, both in depth and across the surface. The spatial distribution of solar magnetic fields is also far from isotropic. Moreover, it is currently almost universally accepted that most of the magnetic flux outside sunspots (90 percent as a minimum Stenflo (1973) is concentrated in so-called magnetic flux tubes with strengths of 0.1-0.2 T (1000-2000 G). The latest detailed reviews of such tubes may be found in, for example, Solanki (1993) and Muller (1994). Only with the recent advent of speckle polarimetry methods in solar research did there appear first indications of a direct registration of such tubes (Muller 1994; Keller 1992). However, much progress in the study of the origin of solar magnetism in general and of magnetic tube parameters in particular was made earlier with the use of indirect methods without the need for high spatial resolution. A particularly advantageous technique is the so-called line-ratio method (LRM) where results of identical measurements are compared, which are made in different spectral lines or in different parts of the contour of a single line. Depending on the ratio of measured parameters (we Designate this ratio as K) and on the type of line, in terms of certain models it is possible to derive much valuable information about the properties of unresolved details in the aperture of observations. In magnetographic measurements, a particular case of LRM is the strength-ratio method (SRM), where magnetic field strength measurements are compared, which are obtained in lines with different magnetic sensitivity (with different Landéfactors g). It is desirable that the difference in g be the only substantial difference in parameters of a particular pair of lines. A classical paper (Stenflo 1973) gave a justification to the SRM and impetus to its widespread use. The result obtained in the cited reference on a substantial difference of the value of K from unity for the pair of the lines λ 525.0 nm Fe I and λ 524.7 nm F eI was impressive evidence that strong, kilogauss fields exist even in a quiet solar atmosphere.

It should be noted that numerical simulation techniques for observed Stokes parameters in terms of two- or even three-component models have been increasingly accepted in recent years as applied to problems of diagnosing solar magnetic fields (Stenflo 1994; Bernasconi & Solanki 1996). However, the utilization of a "classical" SRM method remains very advantageous as before, and in some cases it is still indispensable. This statement refers in particular to observations of large-scale magnetic fields (LSMF) on the Sun, i.e. the BMF and SMMF. Observations of such fields have been and are of high priority, but corresponding Stokes-meter data are still unavailable (among other things, because of serious technical difficulties arising when recording extremely small degrees of polarization). The only current known example of the application of the SRM method to BMF observations is the paper by Shrauner & Scherrer (1994). It reports results derived by comparing magnetograms from the J.Wilcox Solar observatory (WSO) taken both in the usually-used lines Fe I 525.0 nm ($g = 3$) and Fe I 524.7 nm ($g = 2$).

The present paper discusses the results of both BMF and SMMF observations in lines with different magnetic sensitivity obtained at the STOP telescope of the Sayan Solar observatory (SSO). It must be emphasized that, as applied to the SMMF, such results are reported for the first time.

2. Justification of the Current Importance of the Study

The question of the primary sources of the SMMF and BMF is by no means simple and is very important for a variety of reasons. For instance, this is important for a better understanding of the origin of stellar magnetism as one of the aspects of the currently central problem of solar-stellar analogues (Zwaan 1994). In addition, this is important for improving the accuracy of prediction of interplanetary parameters from solar data (that the situation with this problem is not quite O.K. is attested in particular by Wang & Sheeley (1988) and Zhao & Hoeksema (1995).

The relationship of the solar magnetic flux components concentrated in and outside active regions undergoes significant variations with the cycle of solar activity, and variations in total flux are relatively small in this case (Harvey 1994). In active regions, the magnetic flux is distributed largely between sunspots and faculae. The question of the spatial distribution of flux outside active regions is more complicated. It is known with high assurance that most of the flux (visible, we must emphasize) is concentrated in network elements on supergranulation cell boundaries. A relatively small remaining part (about 10 percent) of the magnetic flux in the form of weak-strength fields (less than 0.1 T) seems to reside inside the cells of network structure. Some aspects of the problems of recording and interpreting magnetic fields inside network elements are discussed in Keller et al. (1994). Since such fields, with a relatively small strength, occupy large areas (a large filling factor), they are able to affect observations considerably, especially in measurements with large spatial averaging. In this case (just the one occurring in SMMF and BMF observations) the contribution of strong but opposite-polarity magnetic tubes can be compensated, and the key role can be played by weak but appropriately spatially distributed fields.

3. Observations and Results

It happened that all preceding SMMF measurements and most BMF observations were carried out in the line λ 525.0 nm Fe I. The prime reason for choosing this line is the large value of the Landéfactor ($g = 3$), which permits weak magnetic fields to be recorded with greater confidence. In the context of present-day practice, however, the preferred use of this line cannot be recognized as fully successful. This line is highly temperature sensitive, and its profile undergoes significant variations depending on a particular solar feature and across the full solar disk (Demidov 1994). Therefore, it is of significant scientific interest to conduct SMMF and BMF observations in other spectral lines.

The question of choosing lines for such a kind of research is also of significant importance. An essentially ideal combination is the pair of the lines λ 525.0 nm Fe I (LEP = 0.12 eV, $g = 3$) and λ 524.7 nm Fe I (LEP = 0.09 eV, $g = 2$). The lower level excitation potentials and the Lande factors are in parentheses. As far as the SMMF is concerned, in this paper we analyze, in addition to this pair of the lines, also observations in the combination of the lines λ 525.0 nm Fe I and λ 513.7 nm NiI (LEP = 1.67 eV, g =1). Measurements in the three lines were made mainly at the STOP telescope of the SSO following a standard technique.

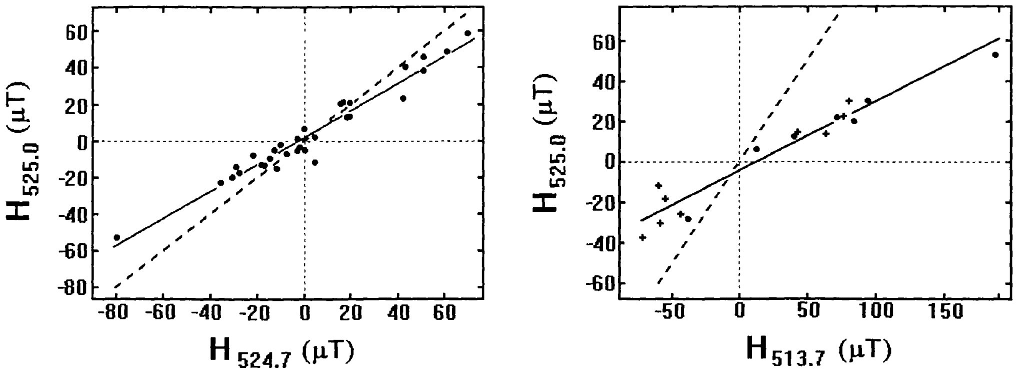

Figure 1. Comparison of SMMF measurements made in the line λ 525.0 nm Fe I and in the line λ 524.7 nm Fe I (left panel), and in the line λ 525.0 nm Fe I and in the line λ 513.7 nm NiI (right panel).

Results of comparison of the SMMF observations in these two combinations of the lines are shown in Fig. 1. All data presented in the left panel (number of observations N = 31) were obtained at the STOP. In the right panel (N = 16) circles correspond to the data obtained at the STOP, while crosses correspond to the observations when measurements in the line λ 525.0 nm Fe I were made at WSO. Noteworthy is a relatively small spread in points: the correlation coefficient in both cases is 0.97. Dashed slanting lines on these plots correspond to the case $K = 1$. Solid lines represent regression lines drawn through experimental points. The equations of linear regression have the form:

$$H_{525.0} = -2(\pm 1) + 0.74(\pm 0.03) * H_{524.7} \tag{1}$$

$$H_{525.0} = -5(\pm 2) + 0.34(\pm 0.02) * H_{513.7} \tag{2}$$

Thus, $K = 0.74$ for the combination of the lines λ 525.0 nm Fe I and λ 524.7 nm Fe I, and $K = 0.34$ for the combination of the lines λ 525.0 nm Fe I and λ 513.7 nm NiI. Interpretation of the right panel in Fig. 1 and equation (2) can be far short of unique because of a significant difference of other parameters of the lines besides the Landéfactors. Therefore, the fact of a significant difference from unity of the parameter K for the data on the left panel in Fig. 1 deserves special attention. This fact puts in doubt the validity of the weak field approximation for interpretation of SMMF measurements. Strong magnetic fields, concentrated in magnetic flux tubes, presumably have a substantial influence upon such observations.

We are coming now to the analysis of the background magnetic field observations in the λ 525.0 nm Fe I and λ 524.7 nm Fe I lines. The observations in both lines were carried out sequentially with a minimum possible difference in time (usually 1.5-2 hours). With 120" angular resolution, this makes it possible to eliminate most of the influence of the solar rotation and BMF time variations upon the results. An example of magnetograms taken in the two abovementioned lines on April 2, 1997, is given in Fig. 2. As would be expected,

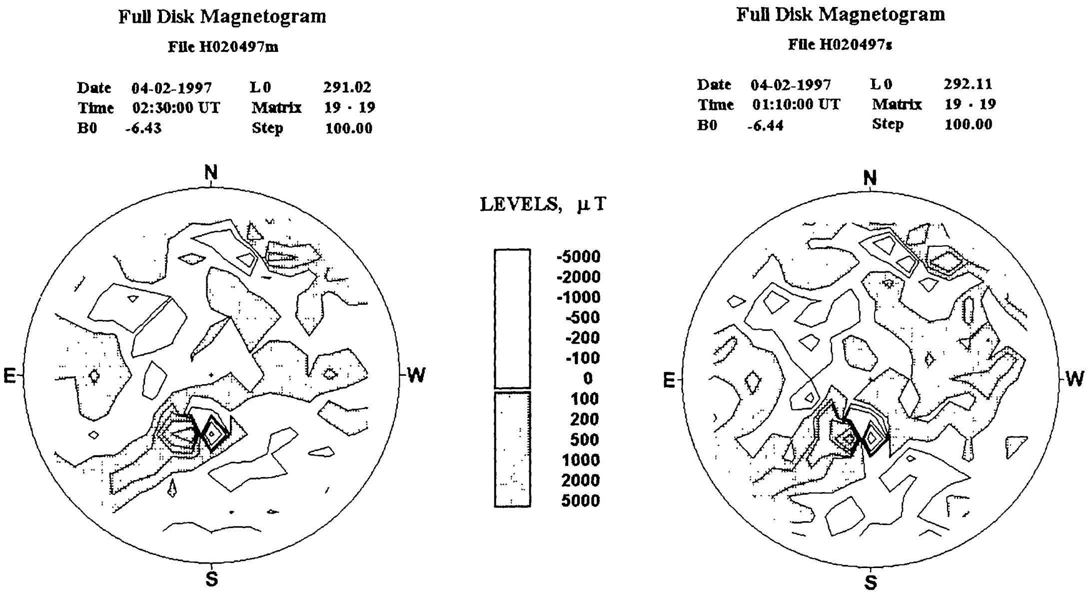

Figure 2. An example of magnetograms observed in two different spectral lines: in λ 525.0 nm Fe I (left) and in λ 524.7 nm Fe I (right).

the two magnetograms are almost identical in general appearance. However, the accurate quantitative comparison of the strengths of these magnetograms presented in the left panel of Fig. 3, attests that a systematic difference exists. With the correlation coefficient $\rho = 0.93$ (N = 251), the equation of linear regression (calculated by the method of reduced major axis, RMA, represented in the figure by a slanting straight line, has the form:

$$H_{525.0} = -9(\pm 9) + 0.73(\pm 0.02) * H_{524.7} \qquad (3)$$

In addition to the magnetograms of April, 2, 1997, fifteen other pairs of magnetograms (sometimes incomplete) were being analyzed in this study. An examination of results reveals that: firstly, correlation coefficients vary from 0.58 to 0.98; and, secondly, values of the parameter K are not very stable (vary from 0.67 to 0.98). An example of a comparison of magnetograms, for which K is virtually unity, is shown in the right panel of Fig. 3. The correlation in this case $\rho = 0.72$ (the number of pairs of points N = 241), and the equation of linear regression has the form:

$$H_{525.0} = 7(\pm 10) + 0.95(\pm 0.04) * H_{524.7} \qquad (4)$$

Analysis of the cases where K is closer to 1 showed that values of strengths on such magnetograms are less. Nevertheless, the mean value of the parameter K for all the data analyzed (N = 3570) is 0.794 (± 0.008) and differs statistically significantly from unity. Because the level of solar activity changes with the solar

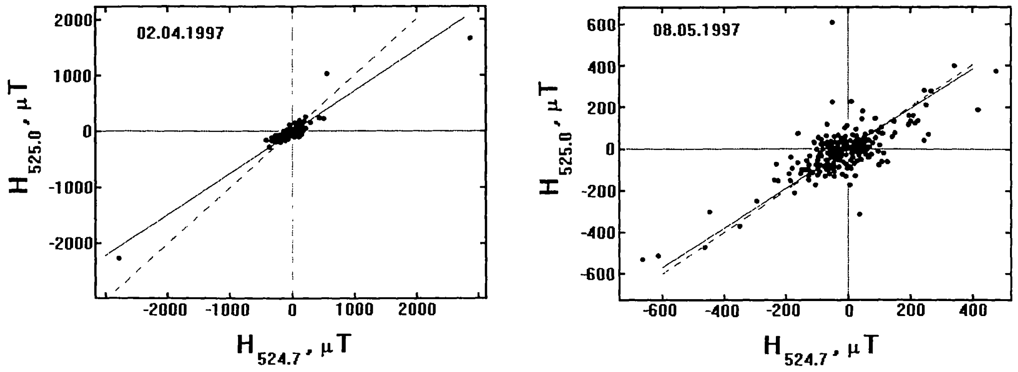

Figure 3. Left panel: scatter plot of background magnetic field observations in spectral lines λ 525.0 nm Fe I and in λ 524.7 nm Fe I. The slanting dashed line corresponds to $K = H_{525.0}/H_{524.7} = 1$, the slanting solid line is described by equation (3). The observation was made on April, 2, 1997. Right panel: the same for another day of observation, May, 8, 1997. The slanting solid line corresponds to equation (4).

cycle, it is possible to wait for variations of the K- parameter value. But new special observations and investigations are necessary.

4. Discussion and Conclusion

The question naturally arises of the degree of reliability of the above results. In actual truth, for example, observed strengths of the SMMF are very small, and their detection is nearly on the verge of technical capabilities. In this case numerous instrumental and procedural factors can have a very substantial distorting influence upon the data. Effects similar to those taken up in this paper, for example, can be introduced by the inadequately accurate allowance for the zero level displacement in the magnetograph. In this case the "strengths" recorded in different lines (among them non-magnetic lines) must be about the same (subject to an appropriate calibration). In effort to explore the possibility of such an effect, measurements in the non magnetic line λ 512.4 nm Fe I were made at the STOP in the mode entirely similar to SMMF measurements in magnetic lines. Results are presented in Fig. 4 (left panel). With the correlation coefficient $\rho = 0.17$ (N = 22), the equation of linear equation calculated by the RMA method (shown in Fig. 4 by a slanting straight line) has the form:

$$H_{512.4} = -4(\pm 4) + 0.30(\pm 0.06) * H_{525.0} \qquad (5)$$

Thus, it may be concluded that values of the "spurious" strength in a non-magnetic line are very small and are at the limit of measurement accuracy. That is, it is unlikely that the results presented above can be explained by purely instrumental effects.

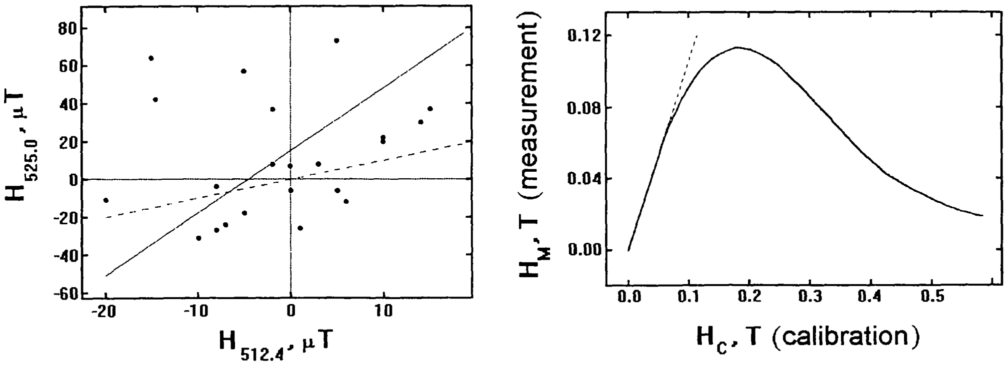

Figure 4. Left panel: scatter plot of SMMF observations in spectral lines λ 525.0 nm Fe I and in non magnetic line λ 512.4 nm Fe I. The slanting dashed line corresponds to $K = 1$, the slanting solid line is described by equation (5). Right panel: calibration curve for the STOP telescope at the Sayan observatory in the BMF observation mode for the λ 525.0 nm Fe I and for exit slits 5.6 pm wide separated by 3.2 pm. It will be recalled that at the WSO these dimensions are 7.8 pm and 1.8 pm, and at the Crimean observatory 5.5 pm and 7 pm, respectively.

A close agreement of the resulting value of the parameter K with values of $H_{525.0}/H_{524.7}$ reported in other publications for higher spatial resolution observations also argues for our dealing with an actual solar effect. Thus, in particular, in the reference cited above (Shrauner & Scherrer 1994), the value of K=0.858 was obtained for the background field observations at WSO. According to Frazier & Stenflo (1978) $K = 0.75$. Reasonably similar values of K are also reported in a summary published in Kostenko & Lozitsky (1996) (largely based on flare observations). It may will be that as new observational data from the STOP is accumulated, the value of the parameter K will be somewhat updated.

A possible consequence of the manifestation of strong magnetic fields in observations of large-scale magnetic fields, in particular of the SMMF, is a systematic difference in data from different observatories (see, for example, Kotov & Severny 1983; Grigoryev & Demidov 1987). The matter is that because of strong magnetic fields, as a consequence of the magnetograph signal saturation, different strengths will be recorded not only in observations in different lines with different sensitivity to the magnetic field but also in observations in different parts of the profile of the same line. Since the exit-slit parameters of the photometers at the observatories, the data from which were analyzed in the references cited above, are different, this does seem to be responsible for the existing differences in SMMF amplitudes. This conclusion is also supported by the fact that the SMMF observations at SSO and WSO during 1993-1997 (Demidov & Grigoryev, these proceedings), with actually the same parameters of the photometer slits (as a consequence with similar calibration curves), showed virtually no systematic differences. The calibration curve for the STOP telescope (in the BMF observations mode) is shown on the right panel in Fig. 4 of the present paper; for the WSO see Fig. 7 in Svalgaard et al. (1978). Keeping in mind these circumstances, it will be very interesting to compare, in addition to SMMF observations, BMF observations at SSO and WSO.

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Part 4. Photosphere through Chromosphere