DOI: 10.17617/2.3213520
Proceedings of the 9th Solar Polarization Workshop SPW9
A workshop held in Göttingen, Germany, from August 26 to August 30, 2019
Achim Gandorfer, Andreas Lagg, Kerstin Raab (eds.)

Large-scale solar magnetic fields from observations in the visible and infrared spectral lines and some space weather issues

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Abstract. In the wide range of spatial scales of solar magnetic fields the large-scale ones (corresponding to a spatial resolution from several arc-minutes up to the whole Sun as a star) play a significant role due to two main reasons: (1) They allow to investigate the spatial structure and time evolution of the global solar magnetism. (2) They play the dominant role in the formation of coronal structures and space weather conditions. However, those fields are very weak, and their observation and the interpretation of those measurements are a challenging problem of modern solar physics. One possible way to improve the reliability of such a valuable source of information is to use observations taken in different spectral lines. Especially promising are measurements in the infrared spectral domain because of the increased sensitivity to weak magnetic fields. Since April 2010, regular full-disk observations of solar magnetic fields in three infrared spectral lines (Fe I 1564.8 nm, Si I 1082.7 nm, He I 1083.0 nm) have started with the infrared spectro-polarimeter (IRmag) on the Solar Flare Telescope at the Mitaka headquarters of the National Astronomical Observatory of Japan (NAOJ). Here we analyze such observations in view of their application to large-scale magnetic field measurements by comparing with observations in visible lines, provided by other observatories, and in the context of some space weather problems.

1 Introduction

The actual problems of modern solar physics in connection with solar-terrestrial physics are not only related to the search for mechanisms of coronal heating, but also about the intrinsic nature of coronal magnetic fields. Direct measurements of coronal magnetic fields are very limited at the present time, but since the fields are anchored in the photosphere, an important way to study them is modelling, based on observations of the photospheric magnetic field.

However, measurements of magnetic fields in the photosphere, which are taken in different spectral lines and/or observatories show (often significantly) different results. It is important to note, that these differences are not constant across the solar disk, but depend on the position on the disk (mainly following the center-to-limb variation CLV). Many papers (see, *e.g.* a recent paper by Demidov et al. (2018) and references therein) are devoted to the discussion of observations in different spectral lines and observatories. Observations in different spectral lines (due to their different sensitivity to magnetic field, plasma density, and temperature) are a powerful tool to investigate the properties of magnetic flux tubes. They are also important in the context of space weather, since any differences in magnetograms and synoptic maps, which are observed in different spectral lines, have a direct effect on the results of the calculation of the interplanetary magnetic field. One well-known example of such a kind of problems, which has a long history (Wang & Sheeley 1995), is the existence of a significant difference (by factor two or even more) between the observed strength of the interplanetary magnetic field near the Earth orbit, and the calculated value based on the use of data from the Wilcox solar observatory (WSO). This problem was one of the reasons for many attempts to make a revision of WSO magnetograms (Ulrich (1992), Wang & Sheeley (1995), *etc*) in order to take into account the saturation of the Fe I 525.02 nm line in strong magnetic fields. The correction factor for observations in this line at WSO (and at Mount Wilson observatory) has the form

$$K = 4.5 - 2.5 sin^2(r), \tag{1}$$

where r is the heliocentric angle from disk center. Later this equation was slightly modified (Ulrich et al. (2009)). However, some authors (Svalgaard et al. (1978), Demidov & Balthasar (2009), Demidov & Balthasar (2012)) object against such a correction of measurements in the Fe I 525.02 nm line.

This means that the problem is not solved yet, and new observations of solar magnetic fields in different spectral lines are useful and welcome. Thankfully, since April 2010 regular full-disk solar magnetic field observations in three infrared spectral lines (Fe I 1564.8 nm, Si I 1082.7 nm, He I 1083.0 nm) have started with the infrared spectro-polarimeter (IRmag) at the Mitaka headquarters of the National Astronomical Observatory of Japan (NAOJ) (Sakurai et al. 2018). Naturally, it is interesting to analyze such new observations in view of their application to the large-scale magnetic field, and to compare them with observations taken in visible lines, which are provided by other observatories. It is also worth to consider some aspects of space weather issues, which are related to the use of the new data set.

2 Comparison of Large-scale Solar Magnetic Fields, Observed in Infrared (IRmag) and Visible (GONG, SDO/HMI, STOP) Spectral Lines

The comparison of IRmag magnetograms taken in three spectral lines, observed simultaneously or quasi-simultaneously, has shown a perfect coincidence between each other (with correlation coefficients close to unity), but with regression coefficients ranging from 2 to 6 depending on the chosen combination of lines. These systematic differences can be caused by different formation depths of the respective spectral lines and/or by peculiarities of the calibration.

Such a high correlation can hardly be expected from a comparison of measurements made with different instruments. But it is interesting to know exactly, to which degree of compliance the IRmag data match with others. The results of a comparison of an IRmag magnetogram taken in the Si line with one from SDO/HMI, and of an IRmag magnetogram taken in the Fe line with one from GONG (Ni I 676.8 nm line) are shown in Fig.1, in the left and the right panels, respectively (observations taken on January 15, 2013). We see that - with rather good correlation (ρ = 0.91) - SDO/HMI shows magnetic field strengths almost two times weaker than IRmag (R = 0.52). For the GONG and IRmag data in the Fe line we have (ρ = 0.74) and very similar ($R \approx 1.0$) values of the field strength.

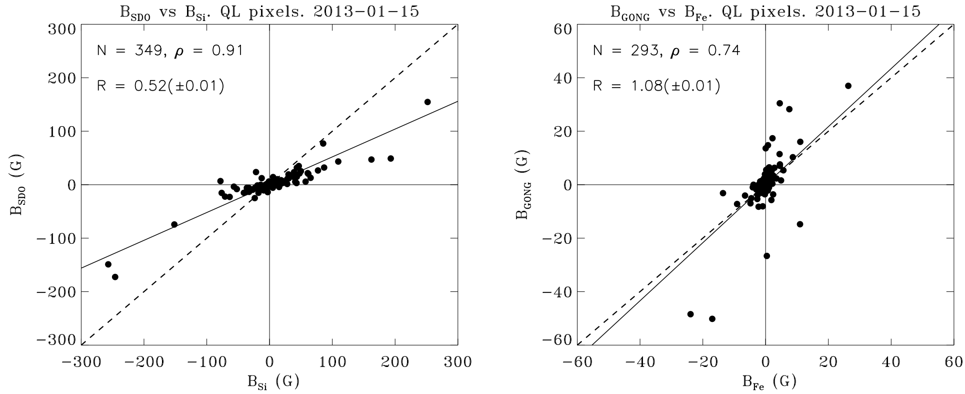

Figure 1. Scatter plots for the IRmag magnetogram in Si I 1082.7 nm line, and a co-temporal SDO/HMI (line Fe I 617.3 nm) magnetogram (left panel), and for the IRmag magnetogram in Fe I 1564.8 nm line, and the GONG (line Ni I 676.8 nm) magnetogram (righ panel). Observations of January 15, 2013. N - number pairs of points (pixels), ρ - correlation coefficient, R - coefficient of linear regression (*solid line*). The *dashed line* marks the case $R = 1.0$.

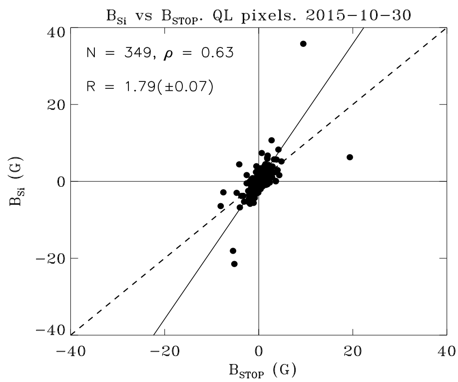

Figure 2. Scatter plot for the IRmag magnetogram in Si I 1082.7 nm line and the STOP magnetogram in the Fe I 525.02 nm line. Observations from October 30, 2013. N - number pairs of points (pixels), ρ - correlation coefficient, R - coefficient of linear regression (*solid line*). The *dashed line* corresponds to the case $R = 1.0$.

We also compared the IRmag data with magnetograms from other sources of observations in visible light. For a comparison with STOP (spectral line Fe I 525.02 nm) in particular, another day (October 30, 2013) was chosen, with much weaker magnetic fields on the solar disk. The results of the comparison of the STOP magnetogram with the IRmag magnetogram taken in the Si line are shown in Fig.2.

The close, but still different times of observation, and the differences in the two instruments have an impact here, and the discrepancy of the measurements (scattering of points) is rather big ($\rho = 0.63$, $R \approx 1.8$). But what is important to note is that the observed magnetic field strengths in the IRmag infrared line (Si I 1082.7 nm) are stronger by a factor of ≈ 2.0

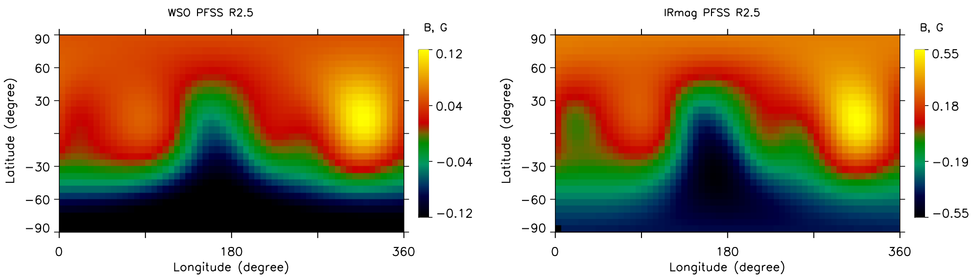

Figure 3. Distribution of magnetic field on the source surface, as calculated from WSO (*left panel*) and Mitaka (*right panel*) synoptic maps for Carrington Rotation 2164 under the approximation of a radial solar magnetic field and using a PFSS model.

than in the visible spectral lines.

In the next section we will show that the same conclusion is true not only for separate magnetograms, but also for synoptic maps and other parameters based on them.

3 Similarity and Differences of IRmag and Other Data on the Coronal Level

One important application of full-disk observations of solar magnetic fields is their use for calculations - using different model assumptions - of the corona near the Sun and the heliosphere up to the orbit of Earth and beyond. Despite the fact that various very complicated 3D MHD models for such calculations have been developed, the rather old and relatively simple PFSS model (potential field source surface) is still widely used and provides good results for space weather applications. Synoptic maps of photospheric magnetic fields from different instruments are used as inner boundaries for such simulations. One of the main parameters, which influence the outcome of a PFSS model, is the distribution of magnetic fields on the source surface, and it is interesting to see how our IRmag data compare to the other ones under this aspect.

For this purpose Fig. 4 presents the distributions of magnetic fields on the source surface for the WSO (left panel) and IRmag (right panel) cases. We see that both pictures look quite similar, but there are some differences in the behavior of the current sheets, and, what is more important, in the values of field strength.

To illustrate the similarity and the differences in the distributions of B_r on the source surface in more details, the region close to the solar equator (which is the most important from the point of view of effects on the Earth) was chosen. Fig. 4 shows the longitude distribution of B_r for the IRmag, WSO, and STOP cases. It is obvious, that all three curves show similar behaviour, but their amplitudes differ significantly.

This is supported by a quantitative analysis, which is presented in Fig. 5, where scatter plots, correlation and regression coefficients for corresponding combinations of curves are shown. It is interesting to note that the STOP data show source surface magnetic fields which are two times stronger that those seen with WSO. For the IRmag case this factor is even higher, close to the coefficient given in equation (1), and it is equal to ≈ 5.

One important conclusion that could be drawn from this study is that observations in

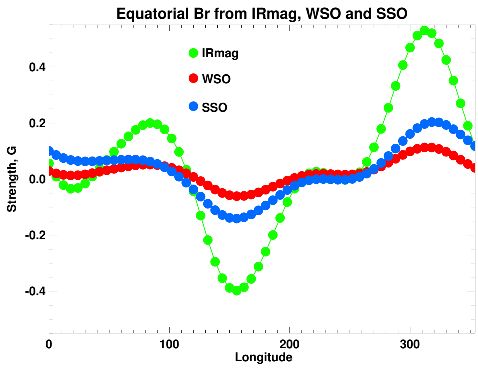

Figure 4. Longitude distributions of open magnetic field (B_r) on the source surface (for IRmag and WSO see Fig. 3), plotted for latitudes near the solar equator.

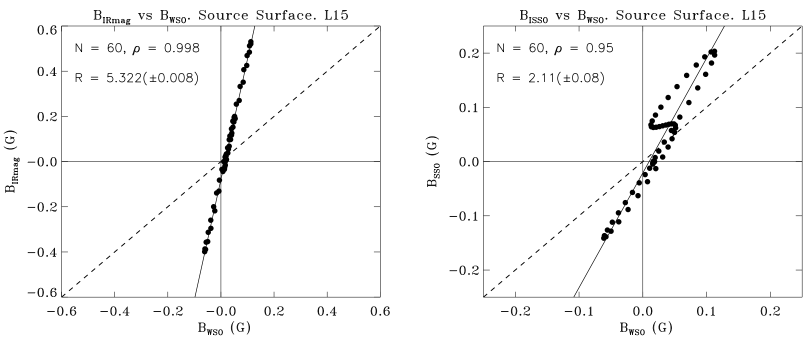

Figure 5. Quantitative comparison of the curves presented in Fig. 4. N - number pairs of points (pixels), ρ - correlation coefficient, R - coefficient of linear regression (*solid line*). The *dashed line* corresponds to the case $R = 1.0$.

the infrared Si I 1082.7 nm spectral line, which was mainly used here, provide magnetic field strengths on the level of the photosphere and in the corona (2.5 solar radii), which are significantly (by factor 2–5) stronger than observations from the other instruments in visible lines. This fact may have a great impact for many space weather aspects.

Acknowledgements. Part of this work was achieved using the grant of Visiting Joint Research supported by the Research Coordination Committee NAOJ. MLD is grateful to the SPW9 SOC and LOC for financial support (waiving the conference fee) for attending the meeting. The work was perfomed with budgetary funding of Basic Research programe II.16. The SDO/HMI, GONG, WSO magnetograms used are taken from *http://jsoc.stanford.edu*, *http://gong.nso.edu*, *http://wso.stanford.edu*. Some PFFS codes used here adopted from package available at SSW and provided by M.L.DeRosa (see http:/www.lmsal.com/~derosa/pfsspack). The authors acknowledge the anonymous referee for comments that helped to improve this paper.

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