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High-resolution observations of solar magnetic fields and the magnetic structure of sunspots

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A simple method for observation of two-dimensional magnetic fields without the polarization optics (i.e., without the separation of polarities) is put forward. It is based on the registration of images with a sufficiently narrow bandwidth in the center of a magnetosensitive line.

Keywords: Methods: observational – Sun: magnetic fields – sunspots

1 The method of measurements

Starting from the works by Babcock & Babcock (1952); Babcock (1953), the magnetic fields of the Sun are usually observed by magnetographs based on Zeeman effect. Such observations are quite difficult, require expensive equipment and experienced observers. On the other hand, the forecast and study of the solar flares requires us to get the magnetograms quickly and with a high resolution, which can be hardly done by the usual magnetographs.

Our attempts to develop the fast high-resolution methods of observation of the magnetic fields, which is necessary to solve many problems of solar physics, led us to the following simple suggestion (Fig. 1): The center of a magnetosensitive line, e.g., FeI 6302.5 Å, is positioned to the exit slit of a spectroheliograph or a narrow-band filter, whose bandwidth approximately corresponds to the half-width of the line or even can be somewhat less (in the case of sufficient sensitivity). So, the magnetized regions in the resulting spectroheliogram will be brighter than unperturbed ones by the quantity proportional to the area shaded in Fig. 1; the excessive brightness in the first approximation being proportional to the magnetic field intensity.

Of course, the corresponding polarities cannot be distinguished. However, in the case of sufficiently high resolution, we can see all magnetic nodes. Moreover, the possibility of high resolution turns out to be enhanced because there are no additional polarization optics and the respective defects, as well as the corresponding decrease in exposition.

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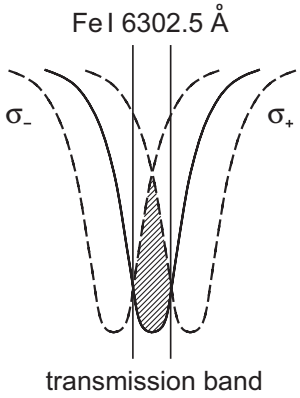


Figure 1 Scheme of obtaining a two-dimensional distribution of the magnetic field.

2 Observational results

Especially valuable and interesting information can be obtained when our method is applied to the sunspots (see the photographs below). These images demonstrate an unusual distribution of brightness in the penumbra, namely, its peripheral regions possess substantially less brightness than the regions immediately near the nucleus (umbra); and the gradient of brightness increases very much at the nucleus–penumbra boundary. This is evidently a consequence of the geometric effect in the magnetic field observations: the brightness is enhanced in the sunspot umbra and neighboring regions – where the field lines are directed approximately along the line of sight – just due to the absence or relative weakness of the π-component. This is also the reason why the penumbra near the center becomes lighter when it approaches the limb; while the penumbra near the limb, darker. Therefore, we get an extra opportunity to study the structure of the magnetic field in the sunspot under consideration. This is especially valuable for the complex sunspots and their groups, which produce the most part of flares.

The image presented in Fig. 2 was obtained in FeI 6302.5 Å line by CCD spectroheliograph installed in the solar tower telescope of Sternberg Astronomical Institute in Moscow on 07.07.2014 (Nikulin, 2000, 2001), whose bandwidth was 0.1–0.2 Å. So, the best images have better resolution than MDI.

The main advantages of this method are the simplicity (because it requires actually to obtain just an ordinary spectroheliogram or filtergram), the maximum resolution (due to the absence of polarization optics), the two-dimensional pattern of magnetic field, the possibility to estimate geometry of the field in sunspots, and its applicability even for the weak fields. The main disadvantage is the impossibility to separate the polarities. However, this can be partially compensated if the images by MDI or other magnetographs are used. Besides, a sufficiently accurate positioning of the spectral slit to the center of the magnetosensitive line is required.

Of course, the brightness of many spectral lines is correlated with the magnetic field. However, we should mention that, for example, the observations in CaII K3 line

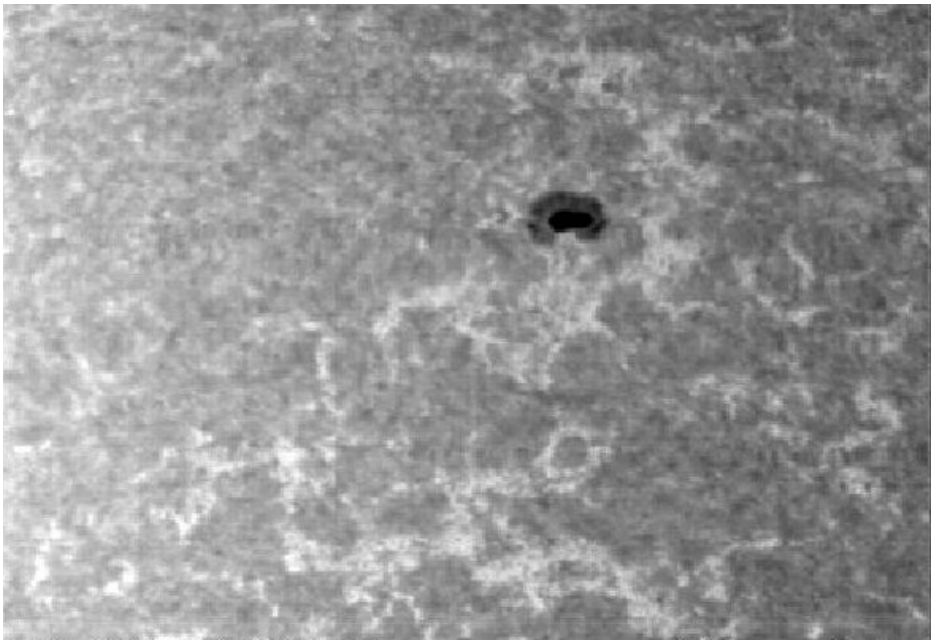


Figure 2 Magnetogram on 07.07.2014 in the line FeI 6302.5 Å. Brightness of the penumbra is enhanced on the side opposite to the limb.

give the effect comprising the thermal and Doppler components; while the magnetic effect in our method results just from Zeeman splitting and, therefore, the brightness in faculae is immediately related to the magnetic field. On the other hand, as was already mentioned above, the relation between the brightness and magnetic field in sunspots is more complex.

Despite the attractive features of observations in the lines of neutral iron 5250.2 and 6302.5 Å (a large Lande factor and a convenient spectral range at high sensitivity of photodetectors), we should probably seek for other lines – which possess a sufficient optical thickness and Lande factor at high excitation potential – for observation of the magnetic field variations in flares by this method. The suitable candidates seem to be the infrared lines of ionized calcium, helium 10 830 Å, FeII 4713 Å, FeII 4924 Å, HeII 4686 Å, H_β 4861 Å, and some others.

As was pointed out by Robinson (1980), Zeeman measurements in the case of stellar sources give only the residual fields, because the elements of opposite polarity compensate each other. The same effect takes place in the solar measurements with insufficient resolution. So, a high resolution is necessary for Zeeman measurements of the fine magnetic structures.

An extremely bright inner penumbra is observed in the image of line FeI 6302 Å, obtained on 08.07.2014 (Fig. 3). However, it is not bright everywhere but just at the umbra–penumbra boundary and the light bridge in the southern double sunspot. An umbra of the inner small sunspot at the western edge of the large spot is also surrounded by a bright strip.

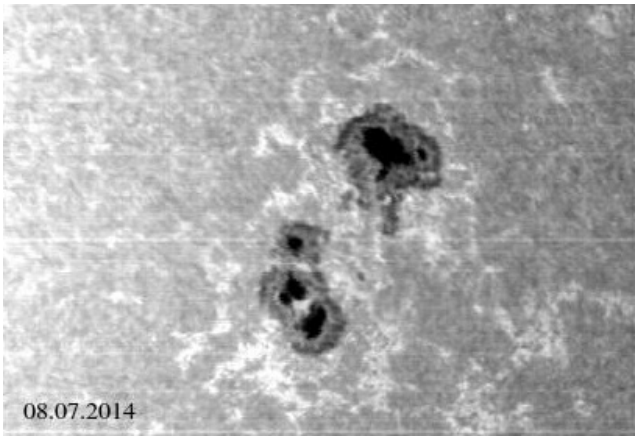


Figure 3 The active region on 08.07.2014 in the center of line 6302.5 Å.

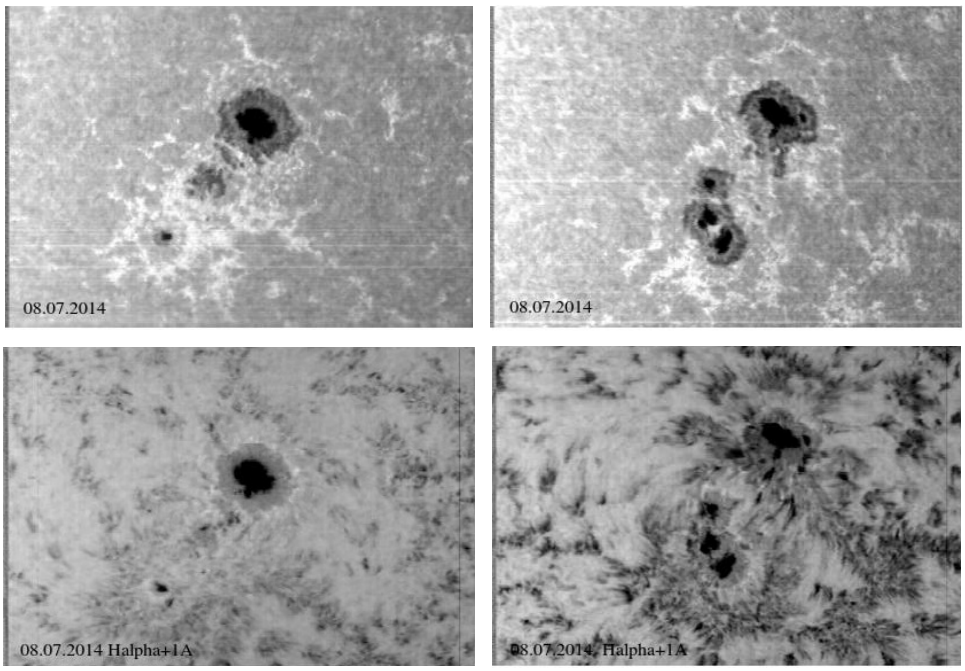


Figure 4 Comparison of brightness distribution in the penumbra in FeI 6302.5 Å (top row) and $H_\alpha + 1.0$ Å (bottom row).

As is seen in Fig. 4 (right-hand column), the eastern sunspot (bottom row) is separated by a light bridge where the magnetic field seems to be enhanced, because the bridge does not possess an excessive brightness in the image of the same sunspot in the wing of H_α line.

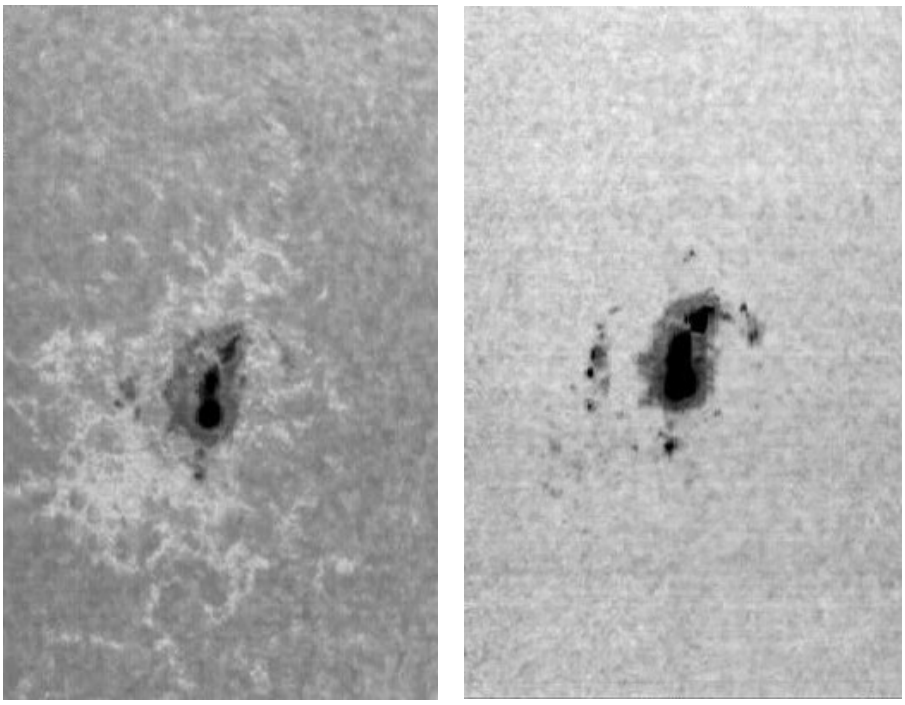


Figure 5 Comparison of brightness distribution in a sunspot in the line FeI 6302.5 Å (left-hand side) and in the neighboring continuum.

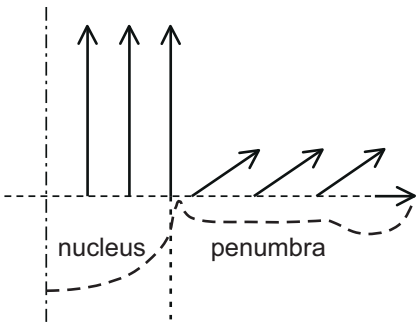


Figure 6 Sketch of direction of the magnetic field lines in a sunspot. Thick dashed line describes a behavior of the mean brightness along the sunspot radius in magnetograms.

The brightness is enhanced immediately at the umbra–penumbra boundary, especially around the small umbra in the tail. As is seen in Fig. 5 (left-hand side) taken on 11.09.2014, a junction between two nuclei is followed by the bright bridge, which is absent in the continuum (right-hand side).

From the analysis of the presented magnetograms, we can suggest the following scheme of the magnetic structure in a sunspot (Fig. 6): Sharp variation in the inclina-

tion of the magnetic field lines (from normal to the photosphere to the angle 30°–45°) seems to be observed at the nucleus–penumbra boundary; and they are further inclined up to the approximately horizontal direction at the penumbra–photosphere boundary.

We believe that this model is confirmed by the characteristic features of images of the active regions in the extreme ultraviolet lines of highly-ionized elements, where just the sunspot nucleus continues into corona in the form of one or few "trunks" of the loop, while the field lines associated with penumbra remain at the level of chromosphere (Fig. 6).

3 Conclusions

1. The suggested method for registration of two-dimensional distributions of solar magnetic fields is characterized by the simplicity (since it requires actually the usual spectroheliograms or filtergrams), the maximum geometric resolution (due to the absence of polarization optics), the possibility to estimate geometry of the field in sunspots, and applicability to the relatively weak magnetic fields (e.g., in faculae).
2. The main drawback is the impossibility to separate the polarities. This can be partially compensated by using the images from MDI or other magnetographs.
3. The peculiarities revealed in the behavior of brightness in the penumbra enable us to assume that inclination of the magnetic field lines changes sharply at the umbra–penumbra boundary and near the penumbra–photosphere boundary. This seems to be confirmed by ultraviolet images of the active regions in the lines of highly-ionized elements.

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