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Estimation of the flux tube diameters outside sunspots using Hinode observations. Preliminary results

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Indirect estimations of diameters of the smallest flux tubes outside sunspots are made using SOT/Hinode observations of FeI 6301.5 and 6302.5 lines. These estimations are based on the comparison of measured effective magnetic field strength $B_{\rm eff}$ in named lines. It is shown that $B_{\rm eff}(6301.5)/B_{\rm eff}(6302.5) \approx 1.3$ in the range $B_{\rm eff} = 40$–300 G, and $B_{\rm eff}(6301.5)/B_{\rm eff}(6302.5) \approx 1.0$ for $B_{\rm eff} \leq 10$–20 G. The first case corresponds to the two-component magnetic field with kG flux tubes and weak background field, whereas the second one corresponds to background field without flux tubes. Assuming that the field range $B_{\rm eff} = 10$–40 G corresponds to the case with only one flux tube in each pixel, the flux tube diameters should be 15–30 km. Possible influence of the brightness contrast and the Zeeman saturation could change this estimation by approximately 20%.

Key words: Sun: magnetic fields, photosphere

INTRODUCTION

The problem of true sizes of the smallest discrete flux tubes outside sunspots is far from being solved. It is well known that sunspots are the largest structures on the Sun with the strongest magnetic fields. Their diameters, typically, are 5–100 Mm, and magnetic field strengths are in the range 2–3 kG, sometimes reaching 4–5 kG [1, 5, 14]. Solar pores (i. e. small sunspots without penumbra) have diameters, typically, 1–3 Mm and magnetic field of 1.5-2 kG. Similar values of field strength are found in spatially unresolved magnetic flux tubes using line-ratio method; true flux tube diameters have been estimated in the range 100–300 km (e. g., [15]). Such estimations have been obtained using the magnetographic observations with direct resolution 1700 km, assuming negligible contribution of background field. Similar method and assumptions have been used by Wiehr [17]. Assuming that field $B_{\rm eff} = 2$ G corresponds to a single flux tube within the aperture of 2400 km, he estimated their diameters to be around $d_{\rm min} = 62$ km.

It is necessary to note, that both assumptions (about negligible contribution of background field and $B_{\rm eff} = 2$ G) are too rough. Lozitsky [7, 8], Gordovskyy & Lozitsky [4] have shown that the best interpretation of measurements made in about ten spectral lines with very different Lande factors from [3, 6] can be given using the two-component model with non-zero background field. Similar conclusions have been made in [9, 12] based on magnetographic observations of quiet regions in 5250.2 and 5247.1 lines. They showed that the magnetic field strength in flux tubes, $B_{\rm ft}$, is 1.5–2.2 kG, while the strength of the background field, $B_{\rm backgr}$, and the filling factor of flux tubes, f, are related via simple formula: $B_{\rm backgr}/f \approx 1$ kG. Therefore, $d_{\rm min} = 40$–50 km, assuming $B_{\rm eff} = 4$ G and size of 1 Mm of enter aperture for direct observations.

In reality, the assumption that $B_{\rm eff} = 4$ G corresponds to one flux tube per pixel (or aperture) is rather questionable. In the studies discussed above, $B_{\rm eff} = 4$ G is supposed to exceed the noise level of the magnetograph. However, the noise level depends on various instrumental parameters, for instance, the integration time. Therefore, the use of specific spectral manifestations would provide more reliable tool for spatially unresolved field diagnostics. In the line-ratio method, $B_{\rm eff}(5247.1)/B_{\rm eff}(5250.2) > 1$ (or $B_{\rm eff}(6301.5)/B_{\rm eff}(6302.5) > 1$) corresponds to the two-component magnetic field — with kG flux tubes and weak background field. On the contrary, in case of $B_{\rm eff}(5247.1)/B_{\rm eff}(5250.2) = 1$ and $B_{\rm eff}(6301.5)/B_{\rm eff}(6302.5) = 1$, the field should be nearly uniform. Obviously, a single flux tube per pixel should be a transitional case between $B_{\rm eff}(6301.5)/B_{\rm eff}(6302.5) > 1$ and $B_{\rm eff}(6301.5)/B_{\rm eff}(6302.5) = 1$; additional flux tubes would further change this ratio. This idea is used in the present work to estimate sizes of flux tubes using Hinode spectropolarimetric observations.

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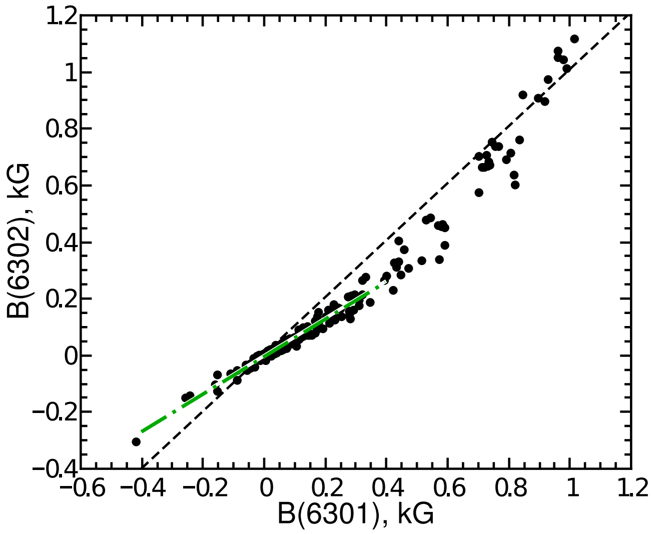

Fig. 1: $B_{\text{eff}}(6302.5)$ vs. $B_{\text{eff}}(6301.5)$ outside sunspots measured using the splitting of centres-of-mass of I+V and I−V Stokes profiles. Dashed black line corresponds to $B_{\text{eff}}(6301.5) = B_{\text{eff}}(6302.5)$. Dashed-dotted line corresponds to the linear fit between −400 and 400 G.

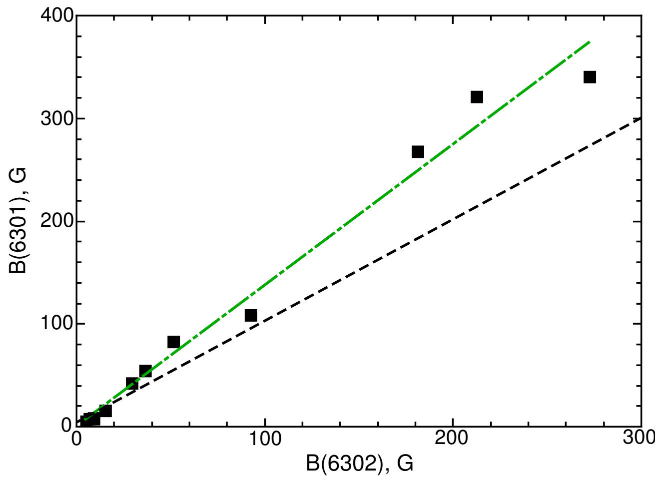

Fig. 2: $B_{\text{eff}}(6301.5)$ vs. $B_{\text{eff}}(6302.5)$ outside sunspots measured using the bisector splitting of $I \pm V$ profiles. Dashed black line corresponds to $B_{\text{eff}}(6301.5) = B_{\text{eff}}(6302.5)$. Dashed-dotted line corresponds to the linear fit between −400 and 400 G.

OBSERVATIONS

Space observatory Hinode (Dawn in Japanese) was launched on September 23, 2006. The main objective of Hinode is high-precision measurements of small changes in the intensity of the solar magnetic fields. The observatory has three scientific instruments: the Solar Optical Telescope (SOT), the EUV Imaging Spectrometer (EIS), and the X-Ray Telescope (XRT) (see [16]). The diameter of the primary mirror of the telescope is 50 cm, which provides direct diffraction limit of the spatial resolution at the level of 0.32 arcsec = 230 km on the Sun in the red spectral region (λ=6302 Å). Decomposition of sunlight into a spectrum was made by Fabry-Perot interferometer. The equipment of Hinode allow observations of the Sun in 10 spectral lines, including Mg I 5172.7 Å, Fe I 5247.1, 5250.2, 5250.6, 5576.1 Å, Na I 5896 Å, Fe I 6301.5, 6302.5 Å, Ti I 6303.8 Å, Hα 6563 Å. In the spectropolarimetric mode (receiving distributions of Stokes parameters I, Q, U, V over the line profile) spectral resolution is about 90 m Å at 6300 Å. In this work we analyse non-sunspot magnetic field measurements in area of three active regions: 29 January 2015, 8 April 2015 and 9 May 2015, NOAA 2268, 2320 and 2339, respectively.

As it was explained above, for determination of the flux tube size the dependence $B_{\text{eff}}(6301.5)$ vs. $B_{\text{eff}}(6302.5)$ should be considered. Two examples of such dependence for non-sunspot fields based on Hinode data are given in Figs. 1,2. In these Figures, dashed-dotted line presents ratio $B_{\text{eff}}(6301.5)/B_{\text{eff}}(6302.5) = 1.3$, whereas cross-hatching line — $B_{\text{eff}}(6301.5)/B_{\text{eff}}(6302.5) = 1.0$. Two methods were used for B_{eff} determination. First is traditional “centre of gravity” method that applies to $I + V$ and $I - V$ profiles. This method includes the central parts of profiles which have the maximum intensity. Second method bases on determination of splitting of bisectors of the same profiles, excluding line core and far wings where gradient of intensity, $\mathrm{d}I/\mathrm{d}\lambda$, is low. From Fig. 1 it follows that ratio $B_{\text{eff}}(6301.5)/B_{\text{eff}}(6302.5) = 1.3$ begins from about 10 G. So, we can suppose that minimal effective magnetic field, which correspond to the presence of only one flux tube inside aperture, $B_{\text{eff,min}}$, is about 10 G. From Fig.2 we can see that ratio $B_{\text{eff}}(6301.5)/B_{\text{eff}}(6302.5) = 1.3$ is actual in field range B_{eff} = 40–300 G, whereas $B_{\text{eff}}(6301.5)/B_{\text{eff}}(6302.5) = 1$ — for $B_{\text{eff}} \approx 20$ G. Thus, in field range between 40 and 10 G we can expect transition from two- to mono-component magnetic field structure. In the next section the use of this diagnostic peculiarity for estimation of flux tube diameter is described.

INTERPRETATION OF THE DATA

We assume that the measured effective magnetic field B_{eff} represents the magnetic flux going through each pixel. It is valid for lines with low magnetic sensitivity, which does not experience the effect of magnetic saturation. (The effect of magnetic saturation is the loss of the measured magnetographic signal in very strong fields (kG range). It appears when spectral line components corresponding to the strong field move outside the analysed spectral range.) In addition, we believe that the magnetic field is longitudinal (has only the line-of-sight component) and two-component everywhere, i. e. consists of unresolved flux tubes with strength B_0 on their axes and background field with strength $B_{\rm backgr}$. Therefore,

$$B_{\rm eff} = (1-f)B_{\rm backgr} + fkB_0, \quad (1)$$

where f is a filling factor for flux tubes and k is the factor that takes into account the radial distribution of magnetic field $B(x)$ in fluxtube ($k = 1$ corresponds to a rectangular profile and $k < 1$ corresponds to non-rectangular profiles, i. e. similar to those observed in sunspots). According to [9], the profile $B(x)$ for flux tubes in quiet regions on the Sun is approximately the same as in solar pores, and can be approximated by the expression

$$B(x) = B_0\left(1 - x^4\right), \quad |x| \le 1, \quad (2)$$

where x is the relative distance from the flux tubes axis, $x = r/r_0$, r is linear distance from the tube axis, r_0 is the tube radius. In case of profile (2), $k = 2/3$. Let us transform the expression (1), taking into account that $B_{\rm backgr} \ll kB_0$:

$$f \approx \frac{B_{\rm eff}}{B_{\rm backgr}/f + kB_0},$$

where $B_{\rm backgr}/f \approx 1\,{\rm kG}$ [9]. Then, assuming that one flux tube with diameter d is inside instrument's aperture, after simple transformations we obtain:

$$d = 2\sqrt{\frac{f_{\min}S_0}{\pi}} \approx 2\sqrt{\frac{B_{\rm eff,min}S_0}{\pi\left(B_{backgr}/f + kB_0\right)}}, \quad (3)$$

where $f_{\min}$ and $B_{\rm eff,min}$ are minimal filling factor and the effective magnetic field, respectively. These values correspond to the presence of only one flux tube inside aperture. S_0 is equivalent area of the input aperture for direct observations. Taking into account that direct resolution for SOT/Hinode is 230 km, we have $S_0 = 4.15 \cdot 10^4\,{\rm km}^2$, assuming a circular entrance aperture of the instrument. As it was explained above, $B_{\rm eff,min} = 10$–40 G. Also, taking into account the estimation of B_0 in [9, 10], we will suppose $B_0 = 2.2$–2.3 kG. Substitution of these parameters into (3) gives the following estimations:

$d \approx 14.5$ km for $B_{\rm eff,min} = 10$ G,
$d \approx 20.5$ km for $B_{\rm eff,min} = 20$ G,
$d \approx 29$ km for $B_{\rm eff,min} = 40$ G.

Thus, despite the magnitude of the uncertainty $B_{\rm eff,min}$, values of d hit in the relatively narrow range, approximately 15–30 km. These values are smaller than similar estimations obtained earlier in [9, 17], so, it is necessary to consider other effects that may change the value of d.

DISCUSSION

Similar to the equation (1), the intensity of circular polarization, Stokes V, can be written as:

$$V_{\rm obs} = (1-f)V_{\rm backgr} + fV_{\rm ft}. \quad (4)$$

In the weak-field approximation:

$$V = \frac{{\rm d}I}{{\rm d}\lambda}\Delta\lambda_H \propto I_c\frac{{\rm d}r_\lambda}{{\rm d}\lambda}B, \quad (5)$$

where I is the Stokes I parameter, $\Delta\lambda_H$ is the Zeeman splitting, $r_\lambda = I_\lambda/I_c$ is relative intensity, I_c is intensity in the nearest spectral continuum, B is the magnetic field. In principle, for non-sunspot magnetic fields, formula (5) is suitable for evaluating $V_{\rm obs}$ and $V_{\rm backgr}$, but not suitable for $V_{\rm ft}$. The main reason is that, due to Zeeman saturation, Stokes V increases slower than ${\rm d}r_\lambda/{\rm d}\lambda$. Let us introduce the factor accounting for Zeeman saturation, Z_s. Thus,

$$V_{\rm ft} \propto I_{c,{\rm ft}}\frac{{\rm d}r_\lambda}{{\rm d}\lambda}Z_sB_{\rm ft}, \quad (6)$$

where $Z_s \le 1$. From (6) it also follows, that $V_{\rm ft}$ depends on $I_{c,{\rm ft}}$, i. e. intensity of the spectral continuum in flux tubes. According to the observations in [2, 11] $I_{c,{\rm ft}}/I_{c,{\rm backgr}} > 1$, potentially, if we assume that flux tubes coincide with solar filigree or faculae knots, this ratio can be as high as 2. Now, let us introduce the parameter describing the flux tube continuum contrast, $K_{\rm ft}$, as $K_{\rm ft} = I_{c,{\rm ft}}/I_{c,{\rm backgr}}$. Obviously, as long as filling factor f is small for non-sunspot areas, $I_{c,{\rm obs}} \approx I_{c,{\rm backgr}}$. Our final assumption is:

$$\left(\frac{{\rm d}r_\lambda}{{\rm d}\lambda}\right)_{\rm obs} \approx \left(\frac{{\rm d}r_\lambda}{{\rm d}\lambda}\right)_{\rm backgr} \approx \left(\frac{{\rm d}r_\lambda}{{\rm d}\lambda}\right)_{\rm ft}.$$

After substituting these parameters into formula (4) and making elementary transformations, we get

$$B_{\rm obs} = (1-f)B_{\rm backgr} + fK_{\rm ft}Z_sB_{\rm ft}. \quad (7)$$

Assuming $B_{\rm obs} \equiv B_{\rm eff}$, formulas (4) and (7) yield the following expression:

$$d \approx 2\sqrt{\frac{B_{\rm eff,min}S_0}{\pi(B_{\rm backgr}/f + kK_{\rm ft}Z_sB_0)}}. \quad (8)$$

Let us compare the values of d for two cases: $K_{\rm ft} = 2$ and $K_{\rm ft} = 1$ assuming $Z_s = 1$; the corresponding diameters are d_2 and d_1, respectively. From (8) it is obvious that

$$\frac{d_2}{d_1} = \sqrt{\frac{B_{\rm backgr}/f + kB_0}{B_{\rm backgr}/f + 2kB_0}} \approx \sqrt{\frac{1000+1500}{1000+3000}} \approx 0.8.$$

Thus, two-fold enhancement of continuum contrast in flux tubes changes our estimations by only about 20%. True diameters of flux tubes in this case are

$$d_2 = 0.8 \times (14.5 - 29) \approx 12 - 23\,\text{km}.$$

Similar calculations show that significant Zeeman saturation of $Z_s = 0.5$ would result, on the contrary, in increasing of d by about 20%. Therefore, the increase of the continuum contrast and Zeeman saturation, have opposite effect on the value of d and, in the general, should not greatly affect our estimations. Hence, we can conclude that actual diameters of flux tubes should be, approximately, in range 15–30 km, i. e. much smaller that diffraction limit of the most modern solar instruments.

SUMMARY

For three active regions on the Sun we have made indirect estimations of diameters of the smallest flux tubes outside sunspots using SOT/Hinode polarimetric observations. These estimations are based on comparison of measured magnetic field strength B_{eff} in Fe I 6301.5 and 6302.5 lines. It is shown that $B_{\text{eff}}(6301.5)/B_{\text{eff}}(6302.5) \approx 1.3$ in the field range B_{eff} =40–300 G, and $B_{\text{eff}}(6301.5)/B_{\text{eff}}(6302.5) \approx 1.0$ for $B_eff \leq$ 10–20 G. First case corresponds to two-component magnetic field with kG flux tubes and weak background field, whereas the second one corresponds to one-component field without flux tubes. If we assume that only one flux tube exists in each pixel in the field range $B_{\text{eff}} =$ 10–40 G, then the diameters of flux tubes should be 20–30 km. Possible influence of the brightness contrast and the Zeeman saturation could change this estimation by about 20%. From our results it follows, that even in era of GREGOR telescope [13]), with 1.5 m aperture and about 80 km resolution, the smallest magnetic flux tubes might not be resolved spatially. Naturally, these smallest flux tubes cannot be resolved by other modern solar telescopes and, therefore, appropriate interpretation of such observations will require multi-component field models.

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