COMPARATIVE STUDY OF SPECTRAL LINES WITH DIFFERENT LANDÉ FACTORS OBSERVED IN SUNSPOTS

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We analyze the spectra of two sunspots of July 8, 2015 and September 5, 2021 which were observed with the ATsU-5 solar telescope of the Main Astronomical Observatory of the National Academy of Sciences of Ukraine. The main goal of the study was to search for signs of superstrong magnetic fields in the sunspots ($> 10^3$ G), taking into account the fact that such magnetic fields can have mixed magnetic polarity. An SBIG ST-8300 CCD camera was used to record a spectral interval of about 8 Å near the Fe I 5434.5 Å line, where six metal lines with effective Landé factors g_{eff} from -0.014 to 2.14 are located. Also, FeI 5397.1 line with $g_{\text{eff}} = 1.426$ was studied too for the second sunspot. In the first spot, we found a splitting of the $I \pm V$ profiles in the FeI 5434.5 line, corresponding to a magnetic field with a strength of ≈ 25 kG, which has the opposite magnetic polarity with respect to the "kilogaussian" magnetic field (≈ 2 kG) determined from lines with large Landé factors. A detailed comparison of the spectral widths in the Stokes I profiles of two lines of the 15th iron multiplet, FeI 5434.5 and 5397.1 Å showed that their additional widening (local peaks of splitting) sometimes occurs at different places on the Sun. Considering that these lines have almost the same temperature sensitivity and formation height in the atmosphere, it is unlikely that this is a non-magnetic effect due to variations in thermodynamic conditions and the velocity field. Regarding the possible influence of spectral blends, the paradox is that it is the more "clean" line Fe I 5434.5 that demonstrates the most incomprehensible splitting peaks. This strengthens the assumption that the observed splitting peaks are of a magnetic nature. But then, if we assume that the additional widening of the 5434.5 line is due to the magnetic field, then its value should be $\sim 10^5$ G. The semi-empirical model for the first sunspot was built using the so-called Tikhonov stabilizers, which modify the objective function to ensure the smoothness and stability of the solutions of the inverse problem. This model has an anomalous feature, namely, the maximum of micro-turbulent velocities in the region of the temperature minimum, i. e. where the minimum of these velocities is present in the model of a quiet photosphere. Perhaps this feature indicates very strong magnetic fields in this sunspot. On the whole, we cannot draw a final conclusion about the existence of the abovementioned superstrong magnetic fields in the sunspots, but we draw attention to interesting and mysterious effects in the line profiles, which require additional studies.

Key words: Sun, solar activity, sunspots, magnetic fields, the Zeeman effect, super-strong magnetic fields.

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INTRODUCTION

Sunspots are convenient objects on the Sun for measuring magnetic fields in them. They have a slow evolution and significant size, sometimes up to 100 Mm [1,2], which is much higher than the spatial resolution of modern solar telescopes. The magnetic field strength in the umbra of developed sunspots usually reaches 2–3 kG, and sometimes even 4-6 kG [3–6].

With such a strong magnetic field, a full Zeeman splitting can be observed in some narrow lines of iron with large Landé factors ($g = 2.5 - 3$), which allows one to reliably measure the modulus of the magnetic field strength B, regardless of the orientation of the lines of force, scattered light or instrumental polarization. It is also important that the above "kilogaussian" magnetic fields in sunspots are observed with the filling factor f close to unity ($f \approx 1$). Due to this, the picture of the Zeeman effect is very contrasting and allows one to achieve high accuracy of measurements, up to several tens of gauss [7].

Sunspots contain multiple small-scale structures in the umbra and in the penumbra. Very small-scale (spatially inresolved) structures can contain especially strong magnetic fields. Weak spectral effects were detected in the spectra of sunspots, which indicate magnetic fields with an intensity of 7–7.5 kG [8] to ≈ 8 kG [9,10]. The authors of the first work found indications of the existence of such very strong magnetic fields in the penumbra of the sunspot, where matter descends at high speeds, 20 km s^{-1}. As for magnetic fields with intensity of about 8 kG, evidence of their presence was found in small-scale areas of umbra of large sunspots, where there was a rise of matter at speeds of 2–3 km s^{-1}. The filling factor of such sections is relatively small, $f \leq 0.3$. Recently, Durán *et al.* [11] measured magnetic fields up to 8.2 kG in the light bridge in a sunspot where the filling factor was close to one.

Perhaps, even stronger magnetic fields exist in sunspots exceeding 7–8 kG [12]. Acad. Severny first suggested that local magnetic fields in sunspots can reach 50 kG [13]. The following methodological points are important for their detection and study.

(1) The use of spectral lines with large Landé factors automatically limits the range of the registered magnetic field [14]. If even stronger magnetic fields do exist, they must be manifested in the spectrum by very strongly splitted Zeeman sigma components, which are difficult to detect in the spectrum of sunspots for two reasons. First, such spectral components may go beyond the registered range of the spectral monochromator. For monochromators based on the Fabry–Perot filters, these are just a few angströms (see, for example, [15]). Second, intense molecular lines appear in the spectra of sunspot umbras, which can greatly "noise" the picture of the Zeeman effect, especially with small filling factors. In addition, weak Zeeman sigma components can fall on neighboring solar lines (blends), where they are also difficult to detect.

(2) Extremely strong magnetic fields can be very tangled, with close (spatially unresolved) contact of opposite magnetic polarities. That is, the situation can be similar to quiet regions where entangled magnetic fields contain large hidden magnetic energy [16]. In this case, there may be no characteristic polarization in the Stokes parameters Q, U and V, typical of the Zeeman effect. However, even in this case, it is possible to diagnose such magnetic fields by the Stokes profile I, i. e. by the integral intensity, taken into account that these profiles should be expanded, and the magnitude of this expansion should be the greater, the greater, the Landé factor is. Therefore, to detect and study strong mixed-polarity magnetic fields, it is necessary to compare the observations in the several lines with various Landé factors, including spectral lines with very low sensitivity to the Zeeman effect.

(3) With existing methods of interpreting observations, the expansion of spectral lines by very strong mixed-polarity magnetic fields can be mistaken for the effect of turbulent velocities [17]. A characteristic feature of this may be the atypical behavior of these velocities, for example, their atypical relationship with thermal velocities or anomalous altitude profile of turbulent velocities.

In the study presented below, we take into account all the above points (1), (2) and (3). The aim of our work is to estimate the local magnetic field in the sunspots based on the comparison of the Stokes I for spectral lines with significantly different Landé factors. A specific task of our study is a comparative study of changes in the profile of the Fe I 5434.5 line and other spectral lines in the transition from the photosphere to the sunspot. In our previous paper [12], we found, in particular, that the FeI 5434.5 line expands sharply in some places of the sunspot and its surroundings, and this effect has no analogues in other spectral lines. One of the reasons for this expansion could be the presence of particularly strong ($\sim 10^5$ G) and spatially unresolved magnetic fields of mixed magnetic polarity. It this paper, we are trying to test this preliminary conclusion using new observational data.

We are carefully considering the possibility of the existence of such superstrong magnetic fields in sunspots, precisely because evidence has recently been obtained in favor of such fields in a limb flare at heights of 5–30 Mm [18], i. e. at the level of the lower solar corona. If such superstrong magnetic fields can exist in the lower solar corona, then they can definitely exist in sunspots at a much deeper level in the Sun's atmosphere. It is important to note that a theoretical paper [19] has just been published in which a new class of force-free solutions for a horizontal magnetic filament with a circular cross-section is found, in which the magnetic field strength on the axis significantly (up to 2–3 orders of magnitude and more) exceeds the strength of the longitudinal external field that keeps the rope from lateral expansion. That is, this means that if the external magnetic field in sunspots is 10^3 G, then on the axis of the corresponding small-scale structures embedded in the sunspot umbra, it can be 2–3 orders of magnitude stronger, i. e. $10^5 - 10^6$ G. Of course, this theoretical prediction requires careful observational verification.

I. OBSERVATIONS AND SELECTED SPECTRAL LINES

Observational material for our study was obtained using horizontal solar telescope ATsU-5 of the Main Astronomical Observatory of the National Academy of Science of Ukraine. The telescope is well tested and has a half-width of the instrumental profile of 19–21 mÅ[20]. Regarding the spatial resolution, it is determined on the instrument not by its aperture, which could theoretically provide a subsecond resolution, but by seeing the image. This vibration, depending on the time and day of observations, can reach 5–6 arcsec. However, the spectra obtained actually have such fine details that can only occur if the actual spatial resolution is about 1–2 arcsec (see Fig. 2 below, for instance). During the observations, the spectra of sunspots and surrounding areas were recorded using an SBIG ST-8300 CCD camera. To obtain the spectra $I + V$ and $I - V$, a polarization mosaic by Skomorovsky [21] and a quarter-wave plate were used; both of these elements were placed in front of the entrance slit of the spectrograph. Some other features of such observations on ATsU-5 as well their processing were described in paper [12].

In this paper, we analyze in detail the observations of the leading sunspot in the active region NOAA 2381 of July 8, 2015, which was located at a distance $\rho/R = 0.25$, $\mu = 0.97$ from the center of the disk (in our previous paper [12] we analyzed the sunspot of August 25, 2015). The parameters of ρ, R and μ mean the observed distance from the center of the solar disk, the observed solar radius and the cosine of the heliocentric angle, respectively. The diameter of the penumbra of this spot was about 30

Mm; the spot was irregular in shape, especially its umbra (Fig. 1).

$I \pm V$ spectra were recorded with two-seconds expositions at 7:15:07 and 7:29:06 UT, accordingly. During the exposures, the entrance slit of the spectrograph crossed the spot in the north-south direction on the disk, as is shown in Fig. 1.

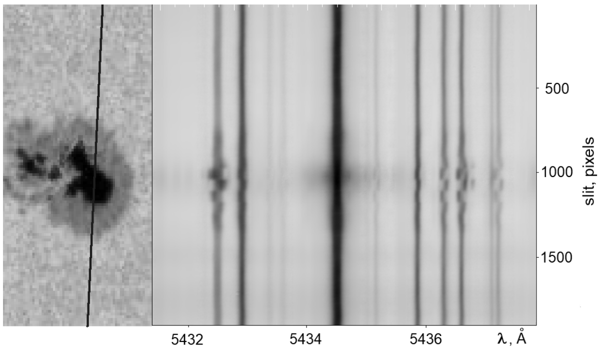

Fig. 1. The sunspot of July 8, 2015 in white light according to the SOHO data (left) and the normalized spectrum obtained with the ATsU-5, which is analyzed in this paper (right)

The $I \pm V$ spectra were recorded in the wavelength range about 8 Å around the Fe I 5434.5 Å line. The list of suitable spectral lines which are located in this range is presented in Table 1. In this Table, Landé factors for lines Nos. 3 and 5–6 correspond to empirically determined values, according to papers [22,23]; for other lines, these factors are theoretical for the case of the LS coupling. Other parameters of spectral lines are taken from multiplet tables by Moore [24]. In addition, we later added spectral line Fe I 5397.1 to our analysis to determine the nature of the subtle effects in line 5434.5. These two lines were studied only in the second sunspot, on September 5, 2021.

As can be seen from Fig. 1, lines Nos. 1, 5, 6 ($g_{\text{eff}} = 1.44 - 2.14$) have a significant Zeeman splitting, whereas in lines Nos. 2 and 4 ($g_{\text{eff}} = 0.5 - 0.66$) it is almost invisible. In line No. 3 with a very small Landé factor ($g_{\text{eff}} = -0.014$), this splitting is not visible at all, but here another effect attracts attention, namely: noticeably strengthened wings in the middle part of the sunspot. It should be noted that the spectrum image presented in Fig. 1 was "cleaned" by special computer programs in such a way as to equalize the level of intensity in and outside the spot, as well as to remove from the spectrum the bands corresponding to the boundaries of the polarization mosaic bands. This equalization of intensities was performed on those parts of the spectrum where there are no Fraunhofer lines. In this regard, the clearly visible effect of strengthening the wings of the line Fe I 5434.527 Å should be considered as real. This conclusion is also confirmed by the data for the second sunspot on 5 September 2021.

No.	**Element and multiplet number**	**λ, Å**	EP, eV	g_{eff}
1	Mn I – 1	5432.548	0.00	2.143
2	Fe I – 1143	5432.950	4.43	0.666
3	Fe I – 15	5434.527	1.01	−0.014
4	Ni I – 70	5435.871	1.98	0.500
5	Fe I – 1161	5436.299	4.37	1.440
6	Fe I – 113	5436.594	2.27	1.816
7	Fe I – 15	5397.141	0.91	1.426

Table 1. Selected magnetosensitive lines which were used for magnetic field measurements in the sunspot

II. EFFECTIVE MAGNETIC FIELD B_{eff}

Effective magnetic field B_{eff} was measured using the method of 'centers of gravity' of $I + V$ and $I - V$ profiles [25]. The difference between the positions of these profiles in a spectrum was considered to be $2\Delta\lambda_H$, i. e. double Zeeman splitting. It is necessary to note that it is correct for a pure longitudinal field only when angle γ between the field line and the line of sight is 0° or 180°. In other cases, the measured splitting should be smaller than the real one, and the determined magnetic field strength is expected to be reduced in comparison with the actual magnetic field value. In order to reduce the influence of noise fluctuations in the far wings of the lines, only central parts of the profiles were taken into account where distances from the line center did not exceed the half-width of the spectral line.

Figure 2 shows, for illustration, the distribution of spectral positions of lines Nos. 1 and 3 (from the list of Table 1) along the direction of the entrance slit of the spectrograph for two orientations of the quarter-wave plate. These spectral positions are calibrated in gauss (G) on an ordinate axis and presented by two curves which correspond to angles +45° and −45° of the quarter-wave plate axis relatively to the optical axis of the polarization mosaic. Along the horizontal axis on Figure, the horizontal coordinates of corresponding places on the Sun are given in numbers of pixels (slit, pxl). We will denote this parameter in the short form as S below. Borders of the bands of the polarization mosaic are shown by vertical stroke lines. For our observations, the width of one mosaic strip corresponds to 3.34 Mm on the Sun. The noisy curve $(I + V)$ shows the actual noise of the measured signal.

One can see for line No. 1 the following main well-visible effects by the first line: (a) periodical deviations of the line position when transiting from a given band of mosaic to the next one, and (b) discrete change of the sign of deviation to the opposite sign for different orientations of the quarter-wave plate. In particular, such effects demonstrate the magnetic nature of these manifestations.

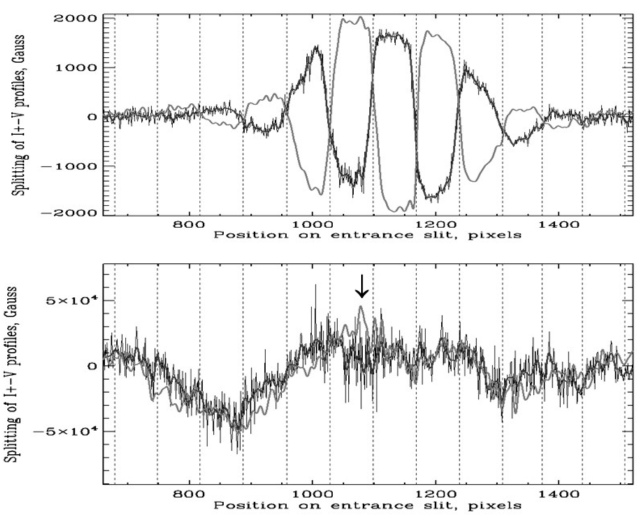

Fig. 2. Distribution for of spectral positions of lines No. 1 (above) and 3 (botton) along the direction of the entrance slit of the spectrograph the sunspot on July 8, 2015 for two orientations of the quarter-wave plate (see the Text)

In order to determine the magnitude of the measured magnetic field using these graphs, it is necessary to take half of the difference of the line position corresponding to the different orientation of the quarter-wave plate for each specific strip of the mosaic. For example, in Fig. 2 in the abscissa interval $S = 1100 - 1170$, the line positions correspond to values of $+1600$ G and -1900 G. Subtracting the second value from the first one and taking half, we have an average field in this strip, equal to 1750 G. In the physical sense, this value is intermediate between the longitudinal component $B_{\mathrm{LOS}} \equiv B_{||} = B\cos(\gamma)$ and the modulus of the magnetic field B, since the observed splitting of Zeeman's π and σ components is not complete (this is clearly seen in Fig. 1). That is, it can be expected that in some places in the spot, the modulus of the magnetic field was greater than ≈ 1.8 kG.

A similar examination of line No. 3 with a very small Landé factor (-0.014) shows that in some places of the sunspot it also has a very weak spectral splitting. The strongest effect of this kind is marked by an arrow in the bottom panel of Fig. 2. If we interpret this spectral splitting as a manifestation of the Zeeman effect, then the corresponding field strengths should be approximately 25 kG. The second important conclusion from these data is that the magnetic polarity of this superstrong field should be opposite to the polarity of the magnetic field with a strength of about 2 kG measured by line No. 1 (see above). That is, this means that small-scale inclusions with fields of 10^4 G range and opposite magnetic polarity were embedded in the background kG field.

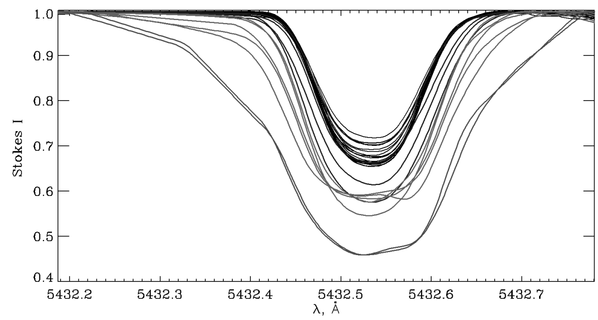

Fig. 3. Stokes I for line Mn I 5432.548 ($g_{\mathrm{eff}} = 2.143$) at different places of active region NOAA 2381 (July 8, 2015), which is displayed on Fig. 1

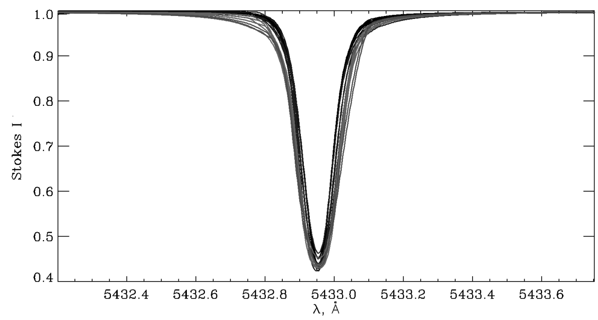

Fig. 4. Same as in Fig. 3, but for the line FeI 5432.950 ($g_{\mathrm{eff}} = 0.666$)

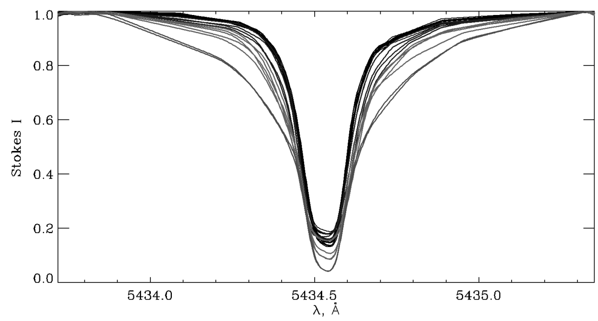

Fig. 5. Same as in Figs. 3 and 4, but for the Fe I 5434.527 Å ($g_{\mathrm{eff}} = -0.014$)

At first glance, this conclusion seems unreliable, but it should be taken into account that a similar case was observed also in another sunspot, namely August 25, 2015, which was studied in paper [12]. This follows from a comparison of Figs. 3 and 4 in the above paper, where one can see that for the same places in the sunspot the sign of the splitting of the $I+V$ and $I-V$ profiles in line No. 1 is the same as in line No. 3. But since line No. 3 has a negative Landé factor (-0.014), it means that the corresponding polarity of the superstrong magnetic field is opposite to the polarity of the weaker "kilogauss" field.

In addition, a close contact of strong magnetic fields of opposite polarity is expected theoretically too, more precisely in the linear force-free model by Solov'ev and Lozitsky [26]. According to this model, magnetic fields can reach $\sim 10^4$ G in the central part of small-scale (spatially unresolved) force-free ropes, and these central parts are surrounded by a periphery with weaker magnetic fields of opposite magnetic polarities.

III. STOKES I

On the basis of the observed profiles $I+V$ and $I-V$, Stokes I profiles were calculated. In Figs. 3–5, these profiles are compared for some spectral lines for that section of active region NOAA 2381, which is displayed in Fig. 1. Some angularity of the line profiles is explained by the fact that the parasitic blends in the wings of the lines were removed using the method of linear envelopes. It can be seen from Fig. 3 that line No. 1 with a high magnetic sensitivity changes significantly from the quiet photosphere to the sunspot. In this Figure and in Figs. 5–6, the narrowest profiles belong to the photosphere outside the sunspot, the wider ones to the sunspot penumbra, and the widest ones to the sunspot umbra.

From Fig. 3 it can be seen that not only the half-width of line No. 1 increases in the spot, but also the depth, i. e. in general — the equivalent line width. This is an expected effect for a line with a large Landé factor and a low excitation potential of the lower term ($EP = 0.00$ eV) — such lines always amplify in sunspots. In contrast, the Fe I 5432.950 line with a small Landé factor ($g_{\text{eff}} = 0.666$) hardly changes from photosphere to a sunspot (Fig. 4); similar changes occur in Ni I 5435.871 Å line ($g_{\text{eff}} = 0.500$).

Interestingly, the Fe I 5434.527 Å line with the almost zero Landé factor also changes markedly during the transition from the photosphere to the sunspot (Fig. 5). The corresponding change concerns, mainly, its wings, which become much wider and more intense in the sunspot umbra. The central depth of this line also increases in the spot, but less than the intensity of its wings. This amplification of the wings is visible, as was noted above, even from the two-dimensional image of the spectrum of the sunspot (Fig. 1).

One of the reasons for this effect may be that the pressure in the sunspot at the level of $\tau_5 = 1$ is higher than in the photosphere. According to Maltby *et al.* [27], the total pressure (gas + turbulent motions) in the photosphere model is 1.211×10^5 dyn/cm^2, while in a sunspot (model M) it is 2.685×10^5 dyn/cm^2, i. e. 2.22 times higher. According to the calculations by Dr. Mykola Gordovskyy, performed at our request using the NICOLE code [28], it is the pressure that significantly affects the expansion of the profile of the line Fe I 5434.5.

Another reason for the significant amplification of the wings of the Fe I 5434.527 Å line in the sunspot umbra may be a significant increase in turbulent velocities. This issue will be considered in detail below (see section 9 below).

IV. FULL WIDTH AT HALF MAXIMUM, FWHM

It is interesting to compare the quantitative changes in line profiles from photosphere to different parts of the sunspot versus the intensity in the spectral continuum. The data on the continuum are shown in Fig. 6, where the horizontal axis presents the position on the Sun in pixels, and the vertical axis — the relative intensities. Each point on the graph represents the average value for one strip of polarized mosaic; the points on the graph are shown with a step of 3.34 Mm on the Sun. It is seen that the intensity in the continuum is reduced in the sunspot umbra by about 4 times; the horizontal coordinates of 1050–1150 correspond to the sunspot umbra, while the coordinates of approximately 800–900 and 1300–1400 — the penumbra of the spot. The surrounding photosphere corresponds to numbers of pixels from 0 to 500 and from 1500 to 2000.

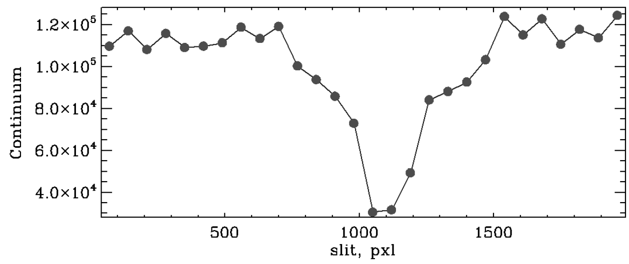

Fig. 6. Variations in the intensity in the spectral continuum (in arbitrary units) along the direction of the entrance slit of the spectrograph for the case presented in Fig. 1

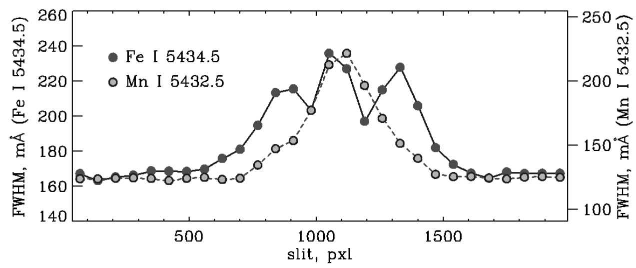

Fig. 7. Variations in the full width at half maximum, FWHM, of line No. 1 (Mn I 5432.548 Å, $g_{\text{eff}} = 2.143$) and line No. 3 (Fe I 5434.527 Å, $g_{\text{eff}} = -0.014$) along the direction of the entrance slit of the spectrograph

From Fig. 7 it follows that the FWHM of line No. 1 increases very significantly in the sunspot umbra — from 125 to 230 mÅ, i. e. 1.84 times. This increase anticorrelates closely with the intensity in the spectral continuum: the line width is greater the lower the intensity in the spectral continuum. Obviously, the main factor in this expansion is the magnetic field, i. e. the Zeeman splitting, which should be maximum in the sunspot umbra.

Let us estimate this effect. For the Mn I 5432.548 Å line, taking into account its Landé factor, the relationship between the Zeeman splitting $\Delta\lambda_H$ and the magnetic field B is as follows

$$\Delta\lambda_H = 2.95 \times 10^{-5} B, \quad (1)$$

where the Zeeman splitting $\Delta\lambda_H$ is expressed in ångströms (Å), and the magnetic field B is expressed in gauss (G). For an approximate theoretical estimate of the broadening of the line profiles, the Unno theory [29] was used. Fig. 8 shows the theoretical dependences for the longitudinal ($\gamma = 0°$) and transverse ($\gamma = 90°$) fields and for the absorption coefficient $\eta_0 = 2.5$.

In this Figure, the following parameters are presented: $\Delta\lambda_{1/2} \equiv$ FWHM, $v_H = \Delta\lambda_H/\Delta\lambda_D$. It can be seen from the Figure that for $v_H \leq 0.8$ the dependences for $\gamma = 0°$ and $90°$ are close to each other, but for $v_H > 0.8$ they gradually diverge from each other. Based on these dependences and on the observed expansion of the Mn I 5432.548 line in the sunspot (by a factor of 1.84), we obtained $B = 1.92$ kG for $\gamma = 0°$ and $B = 2.95$ kG for $\gamma = 90°$. These values should be compared with $B_{\text{eff}} = 1.75$ kG (see Section 3 above), which was obtained directly from the splitting of the $I \pm V$ profiles. As long as we can expect for this line $B_{\text{LOS}} \leq B_{\text{eff}} \leq B$ in the case of a homogeneous (one-component) field, the observed broadening is quite explainable from the point of view of the dominance of the Zeeman effect in it.

If a similar consideration is applied to line No. 4 with $g_{\text{eff}} = 0.500$, then for it we have the theoretical value of the magnetic field intensity $B \approx 2.5 - 2.7$ kG versus the value $B_{\text{eff}} \approx 1.6$ kG measured directly from the splitting of the $I \pm V$ profiles. This difference is also quite understandable, given that the FWHM method of the Stokes I profiles gives the modulus of the magnetic field strength, while the B_{eff} value presents the longitudinal component B_{LOS} (for lines with small Landé factors).

The observed variations in the FWHM parameter for line No. 3 have the following main effects (Fig. 7): (a) significant line broadening from 165 mÅin the photosphere to about 235 mÅin the sunspot, i. e. by more than 40%, and (b) three maxima of the FWHM parameter, one of which rests on the umbra of the sunspot, and the other two — on its penumbra. The latter effect seems especially strange and will be discussed in detail below.

In order to considering the Zeeman splitting, the following gauge formula should be used for line No. 3 for linking the Zeeman splitting and the magnetic field strength:

$$\Delta\lambda_H = 1.93 \times 10^{-7} B. \quad (2)$$

For another line of the 15th multiplet of iron, FeI 5397.14 ($g_{\text{eff}} = 1.426$), the corresponding formula is as follows:

$$\Delta\lambda_H = 1.94 \times 10^{-5} B. \quad (3)$$

That is, at the same magnetic field, the 5397.14 line splits approximately 100 times more strongly than the 5434.5 line.

From the dependences presented in Fig. 8 it follows that at a magnetic field $B = 3000$ G, the half-width of the Fe I 5397.1 line should increase by 11%, while the Fe I 5434.5 line should increase by 0.1% only. Thus, the increase in the half-width of the Fe I 5434.5 line presented in Fig. 7 is probably purely non-magnetic. If it is attributed to the magnetic field (which in this case is far from obvious), then the corresponding magnitude of the magnetic field should be 10^5 G.

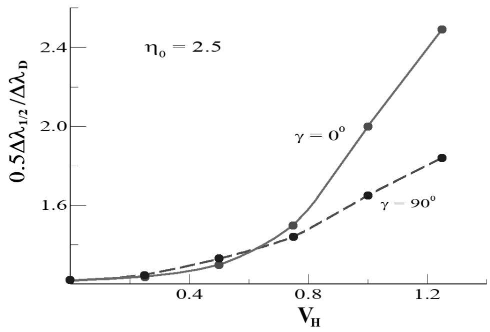

Fig. 8. Theoretical dependence of FWHM $\equiv \Delta\lambda_{1/2}$ versus relative Zeeman splitting $v_H = \Delta\lambda_H/\Delta\lambda_D$ (see the Text)

V. LINE WIDTH AT DIFFERENT DEPTHS, FW025 AND FW075

In order to develop diagnostic tests to search for particularly strong magnetic fields, the following parameters were also considered: FW025, the full line width at a depth of 25% of the maximum, and FW075, the full line width at a profile depth of 75% of the maximum. Changes of these parameters along the direction of the entrance slit are shown in Figs. 9–11.

Figure 9 shows that the parameter FW075 for line 5434.5 has two clear maxima in the region of the penumbra of the sunspot, while in the sunspot umbra this parameter has almost the same value as outside the spot, in the photosphere. On the contrary, the parameter FW025 has only one high maximum in the umbra of the sunspot, while on the border of "umbra–penumbra" its changes are close to the plateau type. In other words, the deepest sections of the line profile expand most strongly in the penumbra of a sunspot, while in the sunspot umbra the greatest expansion is observed in the line wings.

Interestingly, almost nothing of this kind is observed in the line with a large Landé factor (Fig. 10). More precisely, in such a line one clear maximum is observed in the sunspot umbra. True, for the deep parts of the profile it is wider than for the narrower parts of the profile.

As for the lines with the Landé factor in the range 0.5–0.67, the relative expansion of the profile is almost the same here at different depths of the profile both for the umbra and penumbra of the sunspot (Fig. 11). The corresponding distributions along the direction of the entrance slit of the instrument closely resemble a plateau or a slightly inclined plateau. More exactly, the local peak of this plateau is localized, likely, in the sunspot penumbra ($S \approx 1300$).

Line, Å	$g_{\rm eff}$	**[FW075]**	**[FW025]**	**[FW075]/[FW025]**
FeI 5434. 527	–0.014	1.35	2.08	0.65
NiI 5435.871	0.500	1.20	1.12	1.07
MnI 5432.548	2.143	1.83	2.25	0.81

Table 2. The maximum changes of the line widths upon transition from photosphere to the sunspot umbra for the sunspot of July 8, 2015

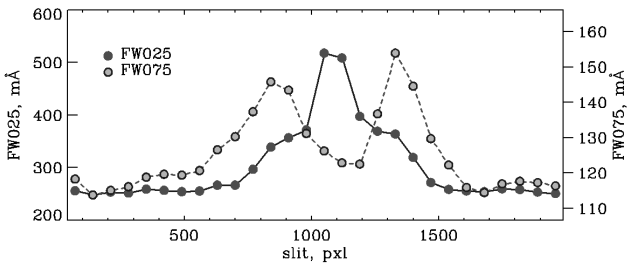

Fig. 9. Comparison for Fe I 5434.5 Å ($g_{\rm eff} = -0.014$) of the full line width at a depth of 25% (FW025) and 75% (FW075) of the maximum for different places on the Sun along the direction of the entrance slit. Here, the maximum expansion is 1.34 (FW075) and 2.08 (FW025) in units of the surrounding photosphere and relates to the sunspot penumbra

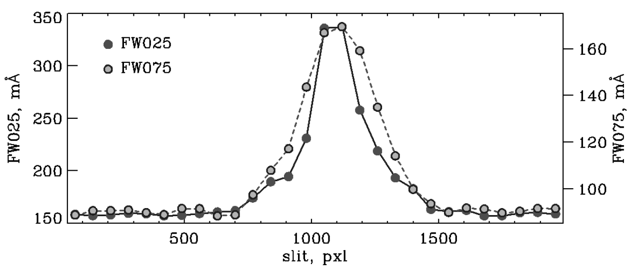

Fig. 10. The same as in Fig. 9 but for Mn I 5432.548 Å line ($g_{\rm eff} = 2.143$). Here, the maximum expansion is 2.25 (FW025) and 1.83 (FW075) in units of the surrounding photosphere and relates to the sunspot umbra

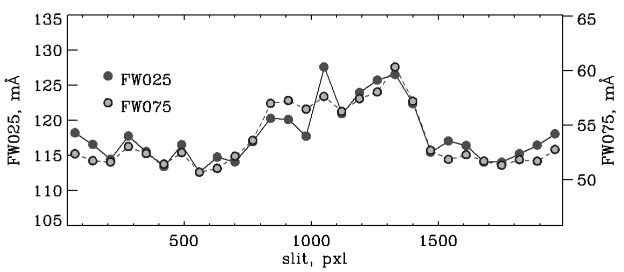

Fig. 11. The same as in Figs. 9 and 10 but for Ni I 5435.871 Å ($g_{\rm eff} = 0.50$). Here, the maximum expansion is 1.20 (FW025) and 1.12 (FW075) in units of the surrounding photosphere and relates to the sunspot penumbra

Obviously, it is difficult to explain this by purely non-magnetic factors. It is known that in the penumbra of a sunspot the temperature is much higher than in the umbra, and it is closer to the temperature of the surrounding photosphere (≈ 5500 K). According to direct measurements, the magnetic field strength in the penumbra of the spot is also lower than in the sunspot umbra. The picture of radial velocities due to the Evershed effect is such in the penumbra of the spot that these velocities are mainly horizontal relative to the surface of the Sun and, therefore, transverse, if we observe the sunspot near the center of the solar disk [1]. Such velocities should not significantly expand the profile of the spectral line. In any case, a similar effect is not observed in line No. 1 (Fig. 10).

Table 2 compares the maximum change in the line widths during the transition from the photosphere to the sunspot umbra. The maximum change at the shallow level of the profiles is indicated by [FW025], and the maximum change at the deep level is indicated by [FW075]. It can be seen that both parameters change very significantly, by tens of percents, and sometimes even more than 100%. There are interesting results of comparing the ratio [FW075] / [FW025] for the lines with very different Landé factors. It is seen that this ratio is less than one for lines with $g_{\rm eff} = -0.014$ and 2.143, but more than unity for a line with intermediate $g_{\rm eff} = 0.500$. In addition, this ratio for lines Ni I 5435.871 Å and Mn I 5432.548 Å differs from unity by 7–19%, while for line FeI 5434. 527 Å is much higher — by 35%. What can this mean?

It is important to note that according to the criterion of the ratio [FW075] / [FW025], line Fe I 5434.527 Å behaves similarly to line Mn I 5432.548 Å — in both lines this ratio is less than one. However, in the Mn I 5432.548 Å line, this value is due to its large Zeeman splitting caused by magnetic fields of the "kilogauss" range. In this case, the Zeeman σ components fall into the far wings of the line in the Stokes I profile, expanding this profile there. We can assume that the situation is similar with the Fe I 5434.527 Å line. In this case, the magnetic field must be of such a strength that the corresponding σ components of the Zeeman splitting fall into the wings of the line and there expand its profile.

Thus, it seems possible to explain our results by the assumption that the sunspot has a two-component magnetic field: (a) a background "kilogauss" field with a large filling factor which gives a well visible Zeeman splitting in a spectral line with large Landé factor (2.143), but a very small (unregistered) splitting in the line with Landé factor -0.014, and (b) a very strong magnetic field with a small filling factor, which does not make visible effects of splitting in the line profile with the Landé factor 2.143 (due to the too large Zeeman splitting in this line), however, it gives such a splitting of the Zeeman σ components in the line with the Landé factor -0.014 that they amplify the wings of the Fe I 5434.527 Å .

An indirect sign of the Zeeman nature of the difference between the profiles of line No. 3 in the spot and the photosphere is that this difference is symmetrical relative to the center of the line (Fig. 5). This should be the case when another splitting pattern corresponding to extremely strong fields is superimposed on the main splitting pattern corresponding to kG fields. Since both sigma components of the Zeeman splitting should have the same intensity in the Stokes I profile, we should observe the same intensity of the "violet" and "red" wings of the line. This is exactly what is observed both for line No. 1 and for line No. 3 (Figs. 3 and 5).

Another conclusion follows itself from the examination of Fig. 9. We can see that deep parts of the profile (i. e. those which are closer to the center of line No. 3, see parameter FW075) expand more in the sunspot penumbra, whereas the shallow part of the profile (i. e. more distant from the center of line No. 3, see parameter FW025) expands more in the sunspot umbra. Taking into account this circumstace, we can expect that the superstrong magnetic field (perhaps, of $\sim 10^5$ G level) is stronger in the sunspot umbra and weaker in the sunspot penumbra. Thus, it seems likely that both the "kilogauss" and the superstrong magnetic fields can have the following common feature: they are the strongest in the sunspot umbra and somewhat weaker in sunspot penumbra. Of course, for more rigorous conclusions on this issue, model calculations of line profiles for realistic sunspot models are required; we plan to do such calculations in the future as an additional study.

Since lines Nos. 1–6 of Table 1 have very different depths and temperature sensitivities, the most convincing test (a kind of "experimentum crucis") should be using a spectral line that is as similar as possible to line Fe I 5434.5. Such a line is line Fe I 5397.1.

VI. COMPARISON OF Fe I 5434.5 AND Fe I 5397.1 LINES

Comparative characteristics of lines Fe I 5434.5 and Fe I 5397.1 are shown above in Table 1. One can see that these lines belong to one multiplet No. 15, have similar excitation potentials (1.01 and 0.91 eV, respectively), but very different Landé factors (-0.014 and 1.426, respectively). In addition to this Table, it should also be noted that the equivalent widths of these lines in the spectrum of the photosphere are close, 184 and 239 mÅ, respectively [30].

Comparison of the observed Stokes I profiles for both lines for the sunspot on September 5, 2021 (NOAA 2863) is presented in Fig. 12. The Figure shows that (a) the profiles of these lines are very similar in the photosphere and in the sunspot umbra, and (b) the changes in the profiles of both lines upon transition from the photosphere to the sunspot umra are very significant and have approximately the same value.

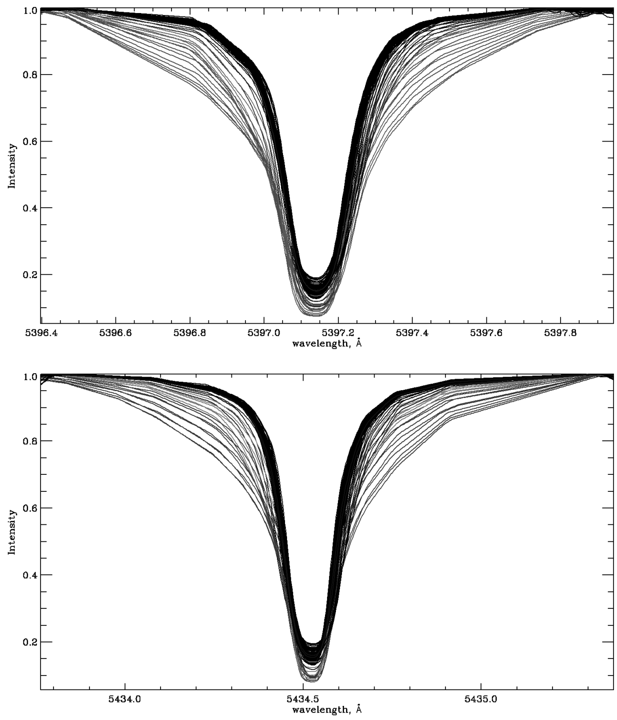

Fig. 12. Comparison for the sunspot on September 5, 2021 of the observed Stokes I profiles for lines Fe I 5397.1 (above) and Fe I 5434.5 (below) in the nearest photosphere (narrow profiles), the sunspot penumbra (profiles with moderate extension) and umbra (the most extended profiles)

Thus, we have a significant difference from the line FeI 5432.950 ($g_{\rm eff} = 0.666$), which upon transition from the photosphere to the sunspot rarely changes in depth and half-width (see Fig. 4 above). One can also see that the profiles of both lines in the sunspot are quite symmetrical, which can equally indicate both the Zeeman effect and the expansion by pressure. Therefore, new additional data are needed to differentiate these effects. For this purpose, let us compare parameters FW025 and FW075 in different parts of the sunspot and its environment (Figs. 13 and 14).

From these Figures one can see that the maximum of widening of the FeI 5397.1 line corresponds to the abscissa $S_{\max}(1) = 72 - 73$ for all three parameters, FWHM, FW025, and FW075. In addition to the specified strongest maximum, there is an even more or less obvious presence of another weaker maximum, which is localized at $S_{\max}(2) \approx 61$.

As for the FeI 5434.5 line, in the parameters FWHM and FW025 the strongest maximum corresponds to $S_{\max}(1) \approx 66$, while for FW075 the strongest maximum corresponds to the abscissa ≈ 53. In addition, for FW075 there are two more clear (but lower) maxima on $S_{\max}(2) \approx 80$ and $S_{\max}(3) \approx 109$. Notice, the diameter of the investigated sunspot was 19.5 Mm or 27 arcsec including the penumbra. Thus, *the peak at* $S_{\max}(3) \approx 109$ *was out of the sunspot and, therefore, its occurrence cannot be explained by an increase in the pressure in the sunspot.* Since, as noted above, both lines form almost at the same height in the solar atmosphere and have the same sensitivity to temperature, one would expect similar FW075 distributions for both lines.

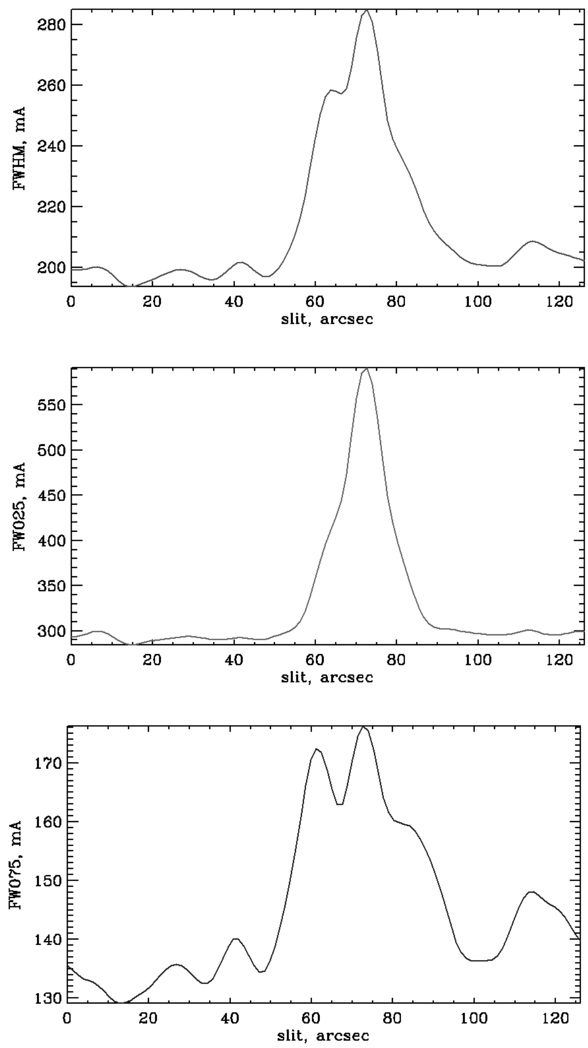

Fig. 13. Changes in FWHM, FW025, and FW075 parameters of the Fe I 5397.1 line in the area of the sunspot on September 5, 2021

More precisely, another effect is possible here, given that the parameters FWHM, FW025, and FW075 correspond to different heights in the solar atmosphere. Namely, information about the highest layers is reflected to the greatest extent by the FW075 parameter (i. e., the core of the line); about the slightly lower ones — by the FWHM parameter (middle wings), and about the deepest ones — by the FW025 parameter (far wings). Let us also take into account that the Fe I 5397.1 line has a larger equivalent width and a lower lower-term excitation potential than the Fe I 5434.5 line. This means that its core is generally formed in the solar atmosphere higher than that of the Fe I 5434.5 line. But then, taking into account the stratification of the solar atmosphere and the difference in physical conditions at its different levels, we can expect the strongest effects from the Fe I 5397.1 line, and not Fe I 5434.5.

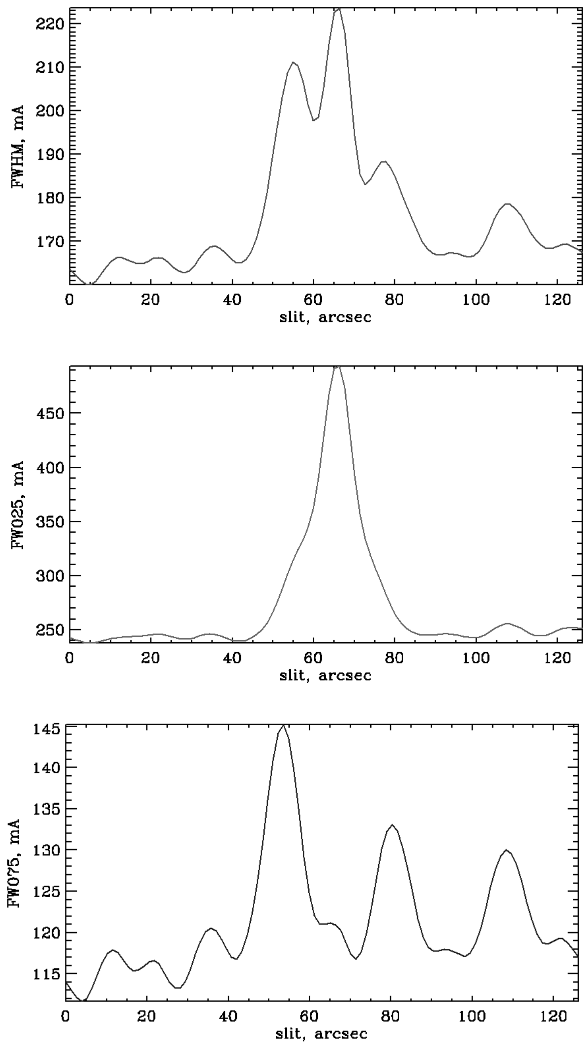

Fig. 14. The same as in Fig. 13, but for the FeI 5434.5 line

Since we have an opposite picture, it is permissible to assume that it is the magnetic field that plays a role here, since these lines have a significant difference in the Landé factor (about 100 times). However, as shown above, magnetic fields in the "kilogaussian" range expand the Fe I 5434.5 line by only 0.1%. Meanwhile, from Fig. 14 it follows that the incomprehensible widening of this line, according to the data on FW075, reaches about 10%. If this expansion is really due to a magnetic field, the value of this field should be about 2 orders of magnitude larger, i. e. about 10^5 G.

Interestingly, another test based on the value of the [FW075]/[FW025] ratio (see above) for these two lines does not reveal anything suspicious in this respect. Namely, the value of the [FW075]/[FW025] parameter is equal to 0.64 for the FeI 5397.141 line and 0.63 for the FeI 5434.5. This small difference can be explained by the higher magnetic sensitivity of line FeI 5397.141.

On the whole, obviously, a search for the hidden presence of superstrong magnetic fields should be based on a thorough analysis of precisely those observational features that contain incomprehensible moments, and not those where there are no unexpected effects. It is these unexpected effects that should be attempted to be modeled in future studies. From this point of view, perhaps, the [FW075]/[FW025] ratio is not as informative and interesting as the dependences shown in Figs. 13 and 14. The reason for this is that the [FW075]/[FW025] ratio contains information only about two points on graphs like Fig. 13 and 14. On the contrary, these graphs themselves, containing many points (i. e., a lot of data) are more informative for our purpose. But modeling such a complex picture is obviously much more difficult than the [FW075]/[FW025] ratio itself. This may be the task of a separate study.

VII. SPECTRAL BLENDS

Obviously, another non-magnetic factor, the possible effect of blends on the profiles of the studied lines, can play a certain role. Here, not only the intensity of the blends is important, but also their distance from the centers of the studied lines. Apparently, we can assume that if this distance exceeds 1000 mÅ, then such blends can be ignored.

With this in mind, Table 3 compares data on blends according to Ch. Moore *et al.* [30], and Wiese and Martin [31]. This comparison reveals a significant difference not only in some wavelengths of the spectral lines, but also in their intensities. For example, the studied lines 5397.1 and 5434.5 according to the first source have equivalent widths of 239 and 184 mÅ, respectively, while according to the second source they have intensities of 300 and 100, respectively. This striking contradiction obviously indicates significant errors in the second source. As for our observations, they confirm exactly the first source, and not the second (see Fig. 12 above). Also from the Internet atlas of the solar spectrum (`http://bass2000.obspm.fr/solar_spect.php`) it follows that the data of Ch. Moore *et al.* [30] are more reliable.

If we rely on this source, as well as on the general form of the spectrum according to the above Internet atlas, then it is obvious that the Fe I 5434.5 line is much "cleaner" (i. e., less blended) than the 5397.1 line. As can be seen from the atlas of the solar spectrum, line Fe I 5397.1 has pronounced blends Nos. 1,2,3,4, and 6 from the list in Table 3, while line Fe I 5434.5 has only blends Nos. 11, 14 and 15. Although the most intense blends were "cut off" during the initial processing of the observational material, it cannot be guaranteed that this correction did not introduce some errors into the final results.

Conditional number	Wavelength,Å from [30]	Equivalent width, Å from [30]	Wavelength,Å from [31]	Intensity from [31]
1	5396.247	12	5396.33	29
2	5396.578	7.5	5396.60	17
3	5396.734	3	—	—-
4	5396.904	2.5	5397.09	85
5	5397.141	239	5397.127	300
6	5397.623	24	5397.64	150
7	5397.930	4	5397.87	11
8	5433.644	6.5	—	—
9	5433.938	1.5	—	—
10	5434.045	1	—-	—
11	5434.179	4	5434.18	40
12	5434.527	184	5434.523	100
13	5434.861	3	—	—
14	5435.039	3.5	5435.07	300
15	5435.183	8.5	5435.18	90
16	5435.587	4	5435.68	55

Table 3. Spectral blends near the studied lines

With regard to the reliability of the final results, the case of the absence of intense blends, apparently, is still better than the case of correcting the influence of such blends. In this regard, it is very indicative that it is the line Fe I 5397.1 (more blended) that has a better agreement between the distributions of the parameters FWHM, FW025, and FW075 (Fig. 13) than the more "clean" line Fe I 5434.5 (Fig. 14).

That is, it seems that the effects observed in Fig. 14 are difficult to explain not only by thermodynamic effects and effects in the velocity field, but also by spectral blends. This is what makes us suspect that the observed manifestations are, after all, of a magnetic nature. But then, as indicated above, the corresponding magnetic field (taking into account the negligibly small Landé factor of the Fe I 5434.5 line) should be about 10^5 G.

VIII. SEMI-EMPIRICAL MODEL OF SUNSPOT ON JULY 8, 2015

The semi-empirical model of the sunspot on July 8, 2015 was constructed by Prof. Myroslav Stodilka, our unforgettable colleague and friend, by solving the inverse problem of the non-equilibrium radiation transfer using the observational data of the FeI 5434.5 line. The inverse problem is one of the incorrect problems, because there are many solutions that satisfy the chosen criterion for finding solutions. The so-called Tikhonov stabilizers were used, which modify the objective function, to ensure the smoothness and stability of the solutions of the inverse problem [32, 33]. The constructed semi-empirical models of altitude stratification of temperature and microturbulent velocity are shown in Figs. 15 and 16. It can be seen that the temperature distribution with the height outside the spot is generally in good agreement with the MACKKL model [27]. In the penumbra of the sunspot and especially in the sunspot umbra, the temperature distribution also qualitatively resembles the model, but has a total downward shift to the region of lower temperatures.

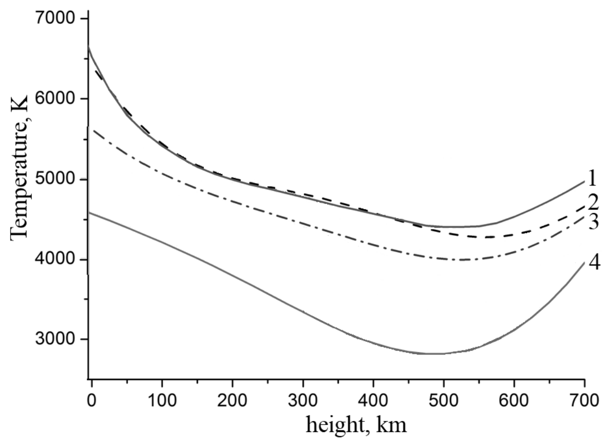

Fig. 15. Comparison of reproduced altitude dependences of temperature for different objects: 1 — quiet photosphere according to MACKKL model [27], 2 — photosphere outside the sunspot under study ($S = 350$), 3 — sunspot penumbra ($S = 1330$), 4 — sunspot umbra ($S = 1050$

The picture is completely different for micro-turbulent velocities (Fig. 16). Outside the sunspot, there is also a satisfactory agreement with the MACKKL model, but in the sunspot itself there are sharp differences from this model. In particular, in the sunspot penumbra the turbulent velocities have a wide maximum in the altitude range of $h = 300 - 500$ km, i. e. exactly in that range where there is a distinct minimum in the MACKKL model. Also, in the umbra of the sunspot, there is a significant difference from the quiet atmosphere, namely, a significantly large amplitude of changes in this parameter (from 0.1 to 1.5 km s^{-1}) in comparison with quiet photosphere. Moreover, in the models of sunspots E, M, and L, according to Maltby *et al.* [27], micro-turbulent velocities in the altitude range of 0–130 km are equal to zero and do not exceed 0.4 km s^{-1} at the altitude of $h =$ 500 km. That is, according to the named sunspot models, the turbulent velocity should be very low throughout the entire thickness of the photosphere and grow very slowly, not exceeding 0.4 km s^{-1}. In contrast to this, in the investigated spot there are complex non-monotonic changes in this velocity, which exceed the indicated value by a factor of 2–3.

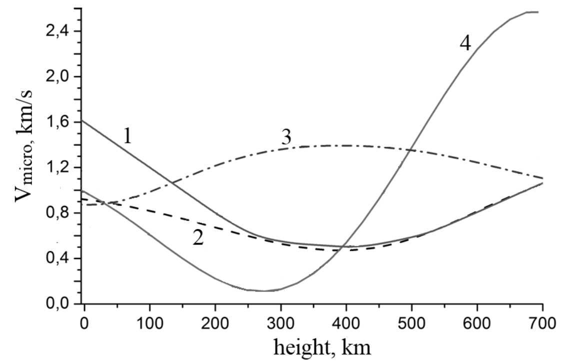

Fig. 16. Comparison of reproduced altitude dependences of micro-turbulent velocity for different objects: 1 — quiet photosphere according to MACKKL model [27], 2 — photosphere outside the sunspot under study ($S = 350$), 3 — sunspot penumbra ($S = 1330$), 4 — sunspot umbra ($S = 1050$)

Obviously, these atypical features of turbulent velocities could hardly have arisen without the influence of the magnetic field. If so, then the magnetic field itself, as can be seen from Fig. 14, should be local in height and extend to an altitude of the order of the thickness of the solar photosphere (~ 500 km).

IX. DISCUSSION

The Fe I 5434.5 Å line as a tool for studying superstrong magnetic fields is a poorly studied line in the solar spectrum. Let us recall some studies in this area.

Stenflo *et al.* [34] found that in non-sunspot regions near the solar disk center this line gives a zero polarization signal in the Stokes V, which corresponds to $g_{\text{eff}} = 0$. However, later, a weak polarization was observed in this line studying the spectrum of a bright solar flares [35, 36]. It was found that $I \pm V$ profiles of this line had narrow splitted emission peaks in the line core. If we interpret as this splitting the Zeeman effect, then the corresponding magnetic field is about 50 kG. A similar effect was found in another line, Fe I 5123.7 Å. It is important to note that both lines have empirically determined Landé factors, −0.014 and −0.013, respectively. It is notable that the cases of maximum splitting of the emission peaks in these lines had a polarization sign (i. e., the sign of the Stokes V), which corresponded precisely to the negative Landé factor. Obviously, this is a strong argument in favor of the Zeeman effect and the reality of super-strong magnetic fields in the flare. At the moment, similar effects have already been found in five solar flares [35–38].

Further study of the FeI 5434.5 Å line in a flare showed that the bisectors of the $I \pm V$ profiles have characteristic features (local extrema of splitting) not only in the core of the line, but also in its wings, at a distance of 130–180 Å from the line center [38]. Because the value of the probable instrumental effects was found to be about 3–5 times lower than the named one, it was concluded that this is some solar effect, not instrumental in nature. In the case of the Zeeman effect, the corresponding magnetic field strength should be 0.7–0.9 MG. In addition, as it was mentioned above, signatures of magnetic fields with a strength of about 90 kG were also found recently in a limb solar flare [18].

As to the possible influence of the Paschen–Back effect, it is important to note that empirical determinations of the Landé factors were made under laboratory conditions precisely at fields in this range of $10^4 - 10^5$ G. Obviously, this automatically excludes any influence of the Pashen–Back effect. In addition, theoretical estimates show that this effect occurs in the Fe I 5434.5 line in magnetic fields above 3 MG [36].

A new point in our study of sunspots was that we tried to find indications of superstrong fields in the Stokes I profiles, i. e. in unpolarized light. This is a very difficult task, as it requires careful consideration and differentiation between magnetic and non-magnetic factors. The prospect of such an approach is that the successful solution of this problem opens up the possibility to diagnose even magnetic fields of mixed polarity, which do not have characteristic manifestations in the polarization profiles $\{Q, U, V\}$. However, this task rests on a rigid selection of spectral lines according to the criterion first formulated by Stenflo [39]: the lines must belong to one multiplet, have the same oscillator power and temperature sensitivity, and the height of formation in the solar atmosphere. In the presented study, line Fe I 5397.1 Å was proposed for the Fe I 5434.5 line as the closest to that specified for these parameters. Nevertheless, the obtained observational data show that these two lines, so close in their profiles and their visible changes upon transition from the photosphere to the spot (Fig. 12), however, behave differently in terms of diagnostic parameters FWHM, FW025 and FW075 (Fig. 13—14). In particular, for line Fe I 5397.1 Å , the strongest maxima of the all three above parameters are observed in the same place, which corresponds to the abscissa 72–73. At the same time, for line Fe I 5434.5 Å the first two parameters have the strongest maxima at abscissa ≈ 66, and parameter FW075 — at abscissa ≈ 53. There are also other strong maxima in the FeI 5434.5 line on $S_{\max} \approx 80$ and ≈ 109 (Fig. 14). As noted above, this discrepancy can hardly be explained by purely nonmagnetic changes in the line profiles.

It can be expected that the main factors influencing the profiles of the studied lines in spots are such physical conditions as pressure, temperature, turbulent velocities, and magnetic fields, with magnetic fields most strongly affecting the line profiles with large Landé factors. If the magnetic fields have a strength on the level of several kilogauss, they should not significantly affect lines of the 5434.5 type with a Landé factor of about 0.01 in absolute value. A distorting effect of low spatial resolution is also possible, but it is highly doubtful that averaging of observational data on such a scale could cause the above additional peaks at $S_{\max} \approx 80$ and ≈ 109.

That is why we are inclined to tentatively conclude that the revealed difference (Fig. 14) may indirectly reflect the existence of the above especially strong magnetic fields. This assumption should be tested in the future based on new observations and simulation data for realistic atmospheric models.

X. CONCLUSION

For two sunspots, we presented observed changes in their profiles during the transition from the photosphere to the sunspot umbra in order to find characteristic signs of the existence of particularly strong magnetic fields. For one of the sunspots, namely July 8, 2015, a splitting of the $I \pm V$ profiles of the Fe I 5434.5 line was found in one of the spots of the sunspot shadow, corresponding to a magnetic field of ≈ 25 kG. The polarity of this superstrong magnetic field is opposite to that of the background "kilogaussian" field. A similar case of opposite polarity was found earlier in another sunspot [12]. Perhaps these observations confirm the theoretical model by Soloviev and Lozitsky [26], in which very strong magnetic fields up to $\sim 10^4$ G are surrounded by areas of a magnetic field of opposite polarity. In order to expand the search to the case of magnetic fields of mixed polarity, which do not give polarization in the line profiles, we analyzed the Stokes I profiles for lines with different Landé factors. In this regard, of particular interest are the data on the two lines of the 15^{th} multiplet of iron with wavelengths 5397.1 and 5434.5 Å , which have almost the same depths of formation and temperature sensitivity, but very different Landé factors. For the sunspot on September 5, 2021, when comparing the observed widths of these lines at different places on the Sun along the direction of the entrance slit, we unexpectedly found discrepancies in the localization of the expansion maxima along these lines, especially in the FW075 parameter, i. e. the line width at a depth of 75% of the maximum. It is unlikely that this was a purely non-magnetic effect, given the almost identical depth of formation of these lines and their temperature sensitivity. Also, the influence of spectral blends is expected to be less significant in the

Fe I 5434.5 line, which has an anomalous behavior. If we assume that the noted effect is magnetic, then the corresponding magnetic field strength is $\sim 10^5$ G. This estimate is not a result of direct measurements, but only the probable value of the magnetic field in the case of the magnetic nature of the indicated effect, which still needs to be carefully verified on the basis of additional studies in the future.

A semi-empirical model of the sunspots of July 8, 2015 was constructed by the FeI 5434.5 line using the so-called Tikhonov stabilizers, which modify the objective function, to ensure the smoothness and stability of the solutions of the inverse problem. This model has an anomalous feature: an atypical altitude profile of turbulent velocities, with high velocities (up to 2.4 km/sec) in the upper photosphere. We can not exclude that this "turbulent" expansion is actually an expansion by the very strong mixed-polarity magnetic field. If so, the corresponding magnetic fields should be also superstrong, sufficient to expand the profile of the spectral line with a very small Landé factor, about 0.01.

In this work, we used spatially averaged profiles to study a sunspot's magnetic field. Such observations hide the extremely complex fine thermodynamic structure of a sunspot. Obviously, to obtain a more realistic empirical model of a sunspot and its subsequent use to obtain data on the magnetic fields in the sunspot core and its penumbra, observations with a high spatial resolution are necessary. Along with this, it is necessary to carry out three-dimensional modeling of the spectral line profiles considered in this article, using multidimensional models of spots obtained as a result of numerical MHD simulation.

On the whole, therefore, we cannot make an unambiguous conclusion about the existence of these superstrong magnetic fields in sunspots, but we draw attention to interesting and mysterious effects in the line profiles, which may indicate these superstrong fields and require additional verification.

ACKNOWLEDGEMENTS

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ПОРІВНЯЛЬНЕ ДОСЛІДЖЕННЯ СПЕКТРАЛЬНИХ ЛІНІЙ З РІЗНИМИ ФАКТОРАМИ ЛАНДЕ, СПОСТЕРЕЖЕНИХ У СОНЯЧНИХ ПЛЯМАХ

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Проаналізовано спектри двох сонячних плям 8 липня 2015 року та 5 вересня 2021 року, які спостерігали на сонячному телескопі АЦУ-5 Головної астрономічної обсерваторії НАН України. Основною метою дослідження був пошук ознак надсильних магнітних полів ($> 10^3$ Гс) у сонячних плямах з огляду на те, що такі магнітні поля можуть мати змішану магнітну полярність. ПЗЗ-камера SBIG ST-8300 була використана для запису спектрального інтервалу близько 8 Åпоблизу лінії Fe I 5434.5 Å, де є шість ліній металів з ефективними факторами Ланде $g_{\rm eff}$ від -0.014 до 2.14. Також була вивчена лінія FeI 5397.1 з $g_{\rm eff} = 1.426$ у спектрі другої сонячної плями. У першій плямі виявлено розщеплення профілів $I \pm V$ лінії Fe I 5434.5, яке відповідає магнітному полю напруженістю ≈ 25 кГс, що має протилежну магнітну полярність відносно "кілоґауссового" магнітного поля (≈ 2 кГ), визначеного за лініями з великими факторами Ланде. Детальне порівняння спектральних ширин профілів Стокса I двох ліній 15-го мультиплету заліза, FeI 5434.5 і 5397.1 Å, показало, що їх додаткове розширення (локальні максимуми розщеплення) іноді спостерігають у різних місцях на Сонці.Ураховуючи, що ці лінії мають майже однакову температурну чутливість і висоту утворення в атмосфері, малоймовірно, що це немагнітний ефект через зміни термодинамічних умов і поля швидкостей. Що стосується можливого впливу спектральних бленд, то парадокс полягає в тому, що саме "чистіша" лінія Fe I 5434.5 демонструє найбільш незрозумілі піки розщеплення. Це посилює припущення, що спостережувані піки розщеплення мають магнітну природу. Але тоді, якщо припустити, що додаткове розширення лінії Fe I 5434.5 пов'язане з магнітним полем, його значення має бути на рівні $\sim 10^5$ Гс. Напівемпірична модель для першої сонячної плями була побудована з використанням так званих стабілізаторів Тихонова, які модифікують цільову функцію, щоб забезпечити плавність і стійкість розв'язків оберненої задачі. Ця модель має аномальну особливість, а саме: максимум мікротурбулентних швидкостей у ділянці температурного мінімуму, тобто там, де в моделі спокійної фотосфери наявний мінімум цих швидкостей. Можливо, ця особливість також указує на дуже сильні магнітні поля в цій сонячній плямі. У підсумку ми не можемо зробити остаточний висновок про наявність указаних вище надсильних магнітних полів у сонячних плямах, але звертаємо увагу на цікаві та загадкові ефекти в профілях ліній, які потребують додаткових досліджень.

Ключові слова: Сонце, сонячна активність, сонячні плями, магнітні поля, ефект Зеємана, надсильні магнітні поля.