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MAGNETIC FIELD WEAKENING IN DEEP LAYERS OF A SUNSPOT

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ABSTRACT. The preliminary results of spectral-polarization observations of a large sunspot on August 17, 2024, observed on the Echelle spectrograph of the horizontal solar telescope of the Astronomical Observatory of Taras Shevchenko National University of Kyiv are presented. Direct measurements of the magnetic field in this spot were performed by splitting the bisectors of the profiles of ten spectral lines, mainly the Fe I lines, as well as three lines of Fe II, Cr II, and Sc II ions. The magnetic field, measured by splitting the sigma components of the Fe I 5250.2 line, reached 3400 G, however, the field magnitude by other lines with smaller Landé factors was significantly smaller, apparently reflecting the longitudinal component B_{LOS} of the magnetic field, rather than its intensity modulus. The shape of the bisectors of the $I \pm V$ profiles generally corresponds to a homogeneous field only for the Fe I lines, while for the ion lines these bisectors have a rather peculiar appearance, with a minimum splitting at approximately half the depth of the profiles and a maximum in the core of such lines or in their wings. If the magnetic field averaged over the entire profile is determined based on the average splitting of the bisectors at different depths of each spectral line, the following main effects are revealed: (a) the ion lines show 300–1200 G weaker magnetic fields than the neutral atom lines, (b) the measured B_{LOS} value increases with the Landé factor for the neutral atom lines, but for ions, the corresponding dependence is obviously the opposite, (c) for the neutral atom lines the B_{LOS} value decreases with increasing excitation potential *EP* of the lower term of the line. Effect (b) for the neutral atoms can be explained by the significant inclination of the field lines to the line of sight, while effects (a) and (c) indicate that the magnetic field strength in the spot decreased with depth. However, it remains unclear what role thermodynamic effects and the subtelescopic structure of the magnetic field might play here.

Keywords: Sun, solar activity, sunspots, magnetic fields, spectral lines, the Zeeman effect, altitudinal inhomogeneity of the magnetic field.

АНОТАЦІЯ. Представлені попередні результати спектрально-поляризаційних спостережень великої сонячної плями 17 серпня 2024 р., яка спостерігалась на ешельному спектрографі горизонтального сонячного телескопа Астрономічної обсерваторії Київського національного університету імені Тараса Шевченка. Прямі вимірювання магнітного поля у цій плямі були виконані по розщепленню бісекторів профілів 10 спектральних ліній, в основному ліній Fe I, а також трьох ліній іонів Fe II, Cr II та Sc II. Магнітне поле, виміряне по розщепленню сігма-компонент лінії Fe I 5250.2, досягало 3400 Гс, однак величина поля по інших лініях з меншими факторами Ланде була значно меншою, відображаючи, очевидно, поздовжню компоненту магнітного поля B_{LOS}, а не його модуль напруженості. Форма бісекторів профілів $I \pm V$ в основному відповідає однорідному полю лише для ліній Fe I, тоді як для ліній іонів ці бісектори мають досить своєрідний вигляд, з мінімальним розщепленням приблизно на половинній глибині лінії, а максимальним – в ядрі таких ліній або в їх крилах. Якщо визначати усереднене по всьому профілю магнітне поле, виходячи з середнього розщеплення бісекторів на різних глибинах кожної спектральної лінії, то виявляються такі основні ефекти: (а) лінії іонів показують на 300-1200 Гс слабші магнітні поля, ніж лінії нейтральних атомів, (б) виміряна величина B_{LOS} зростає з фактором Ланде для ліній нейтральних атомів, але для іонів, очевидно, відповідна залежність є протилежною, (в) для ліній нейтральних атомів величина B_{LOS} зменшується при збільшенні потенціалу збудження нижнього терма *EP*. Ефект (б) стосовно ліній нейтральних атомів можна пояснити значним нахилом силових ліній до променя зору, тоді як ефекти (а) і (в), вказують на те, що напруженість магнітного поля у плямі зменшувалась з глибиною. Однак наразі залишається неясним, якою тут може бути роль термодинамічних ефектів а також субтелескопічної структури магнітного поля.

Ключові слова: Сонце, сонячна активність, сонячні плями, магнітні поля, спектральні лінії, ефект Зеємана, висотна неоднорідність магнітного поля.

1. Introduction

Magnetic fields in sunspots are generally measured using spectral lines with the largest Lande factors. It was by these lines that it was found that the typical magnetic field strength in developed sunspots is 2000-3000 G and reaches 5000-6000 G on very rare occasions (see, e.g., Livingston et al., 2006; Solanki, 2003). A significant advantage of such spectral lines is that they are suitable for direct measurements of an important characteristic of the magnetic field – the modulus (absolute value) of the intensity vector. This possibility can be realized due to the fact that at magnetic fields of $B \geq 2.5$-3 kG, the Zeeman splitting $\Delta\lambda_H$ is complete in some narrow lines of neutral iron Fe I, which have a half-width $\Delta\lambda_{1/2}$ of about 0.1 Å and large Lande factors ($g_{eff} = 2.5$-3). In this case, the Zeeman π- and σ-components are completely separated in spectra. In solar magnetometry, this splitting mode is called the strong-field mode (SFM). In terms of physical content, the specified SFM differs from the same-name mode in atomic physics, where the latter is realized when the Zeeman splitting in magnitude significantly exceeds the multiplet splitting of the fine structure of atomic terms. In this case, the Paschen-Back effect occurs, when in spectral lines with complex (non-triplet) splitting, the anomalous splitting pattern (with several Zeeman subcomponents) gradually disappears, and this pattern in appearance approaches a simple Zeeman triplet, which has only three splitting components – one central π-component and two side σ-components (Frisch, 2010).

In the vast majority of spectral lines, the Landé factor is close to unity, i.e. close to the value that should theoretically be for a classical Lorentz triplet. In this case, at magnetic fields of several kilogauss, incomplete Zeeman splitting occurs by which it is possible to measure (with a circular polarization analyzer) not the modulus of the magnetic field strength B, but only its longitudinal component $B_\parallel \equiv B_{LOS}$ (Unno, 1956). This splitting mode in solar magnetometry is called as the weak-field mode (WFM), which formally corresponds to the condition $\Delta\lambda_H \ll \Delta\lambda_{1/2S}$. More precisely, this condition corresponds to a truly weak field only when this field is homogeneous (single-component), and the corresponding filling factor f is close to unity, i.e. $f \approx 1$. If the magnetic field is inhomogeneous and contains, for example, two components, one of which corresponds to $f \ll 1$, then the observed case $\Delta\lambda_H \ll \Delta\lambda_{1/2}$ may mask the situation when a strong Zeeman splitting actually occurs in the component with a small filling factor, i.e. when $\Delta\lambda_H \approx \Delta\lambda_{1/2}$ (Stenflo, 1973, 2011).

It is worth noting the fundamental difference between the values of the longitudinal component of the magnetic field B_{LOS} measured from spectral-polarization and magnetographic measurements. In the first case, this component is measured directly by the shift of the spectral lines, without any reference to the atmospheric model or standard line profile. In the second case, it is not the Zeeman splitting that is measured directly, but the amplitude of the circular polarization measured at the steepest parts of the profile (Babcock, 1953; Scherrer et al., 1995). This amplitude is compared with a similar polarization signal from the "average" profile corresponding to locations on the Sun outside the active regions. The ratio of these amplitudes is multiplied by a certain calibration factor, which gives the correct value of the magnetic field for the "average" line profile. However, in active regions, especially in solar flares and spots, this "average" profile can differ significantly from the real one, and the corresponding magnetic field magnitude can differ from its true magnitude. This is the main reason why it was not possible to carry out a satisfactory empirical calibration of the solar magnetograph, using direct measurements by visual and photographic methods for comparison (Severny, 1967). The corresponding empirical calibration curve turned out to be very scattered and indicated the possibility of quite large measurement errors, up to 200-300%.

Another type of instrument measures solar magnetic fields more realistically - the lambda meter (Semel, 1980; 1981). It does not use any assumptions about the standard line profile. As a result, weakening of the line profile, for example, does not affect the measured magnetic field magnitude. The only parameter used to calibrate the measurements is the Lande line factor – as in the spectral-polarization measurements analyzed below.

According to measurements with a lambda meter, the magnetic field in a sunspot was found to be almost the same by 12 spectral lines with Lande factors in the range of 0.93 – 3.00; the corresponding discrepancy was within 10% (Semel, 1981). This was considered in the mentioned work as a positive result of testing the use of such a measurement technique, which gives only the longitudinal component $B_\parallel$. In addition, this result, in the author's opinion, indicates that in a sunspot the spatially unresolved structure is less pronounced than in a solar plage. For a solar plage, the discrepancy of the magnetic field values was found by different lines turned out to be almost an order of magnitude larger and depended mainly on the equivalent line width. In particular, strong lines like Fe I 5233 showed 3-6 times greater intensities than weaker lines like FeI 5250.2.

These results for sunspots differ somewhat from similar data obtained by Venglinsky and Lozitsky (2012). Mentioned authors studied two large sunspots, which were observed on March 25, 1991 and July 22, 2004 at the HST of the AO KNU. The magnetic field was measured by the Zeeman splitting of many (≈ 150) spectral lines of various chemical elements - mainly Fe I, as well as Fe II. It turned out that the results by the Fe I and Fe II lines differ significantly. It is especially interesting that although in the sunspot umbra the magnetic field by the Fe I lines was stronger than the field by the Fe II lines, in the sunspot penumbra and in the surrounding photosphere an inverse relationship was found. Moreover, in the middle of the studied spots a significant "dip" in the magnitude of the magnetic field by the Fe II lines was recorded; no such result has been found in the scientific literature. Perhaps, it indicates the spatial heterogeneity of the field and the influence of thermodynamic effects on the measurement results. It is also possible that different sunspots differ greatly in their magnetic and thermodynamic properties, and therefore new research in this area has significant scientific value.

The purpose of our research was to verify the above-mentioned patterns on new observational material obtained in Kyiv during the war, in 2024.

2. Observations and data processing

Observational material for our study was obtained with the Echelle spectrograph of the horizontal solar telescope (HST) of the Astronomical Observatory of Taras Shevchenko National University of Kyiv (Lozitsky, 2016). The main value of observations with named spectrograph is that a wide spectrum interval, from 3800 to 6600 Å, can be recorded simultaneously where many thousands of spectral lines can be observed. Another advantage of our observations is that $I + V$ and $I - V$ spectra were obtained simultaneously, on separate adjacent bands of the spectrograms. This was made thanks to the fact that the circular polarization analyzer consisted of a λ/4 plate in front of the entrance slit of the spectrograph and a beam splitting prism (analogous to the Wollaston prism) behind the entrance slit. Therefore, $I + V$ and $I - V$ spectra relate to the same moment of time and to the same locations on the Sun.

The sunspot under study was observed 17 August 2024 in active region NOAA 3784 and had diameter of penumbra about 40 Mm. Observers were Vsevolod Lozitsky and Ulyana Pavlichenko. This sunspot was located from the disk center at a distance $\rho/R \approx 0.54$. According to visual magnetic field measurements made in Fe I 5250.2 Å line, peak magnetic field intensity in this sunspot was 3700 G, polarity was N. Echelle Zeeman-spectrogram of the sunspot was obtained at 6:24 UT using the ORWO WP3 photo-plates; exposure was 30 sec.

The spectrogram of the sunspot was scanned using an Epson Perfection V 550 scanner, which allows to obtain two-dimensional scans of images recorded on transparent films or on photo-plates. Methodological details of processing such scanograms for the scientific analysis are described by Yakovkin and Lozitsky (2022).

3. Selected spectral lines

Table 1 lists the selected spectral lines which were used. In this Table, λ is the wavelength in angstroms (Å), *EP* is the excitation potential of the lower term in electron-volts (eV), by (Moore et al., 1966), g_{eff} is the effective Landé factor. These factors for lines Nos. 1, 2, 6, 7, 9, and 10 correspond to those empirically determined in laboratory conditions (Zemanek and Stefanov, 1976). For the other lines, theoretical factors for the case of a *LS* coupling are given. This choice of spectral lines is useful for diagnosing the magnetic field in the vertical and horizontal directions. In particular, ion lines are generally formed deeper than neutral atom lines, while lines with smaller Lande factors are more suitable for diagnosing particularly strong magnetic fields (Lozitsky, 2015). The pair of lines 5247.1-5250.2 is suitable for study the spatially unresolved magnetic field by the line ratio method (Stenflo, 1973).

Table 1. Some characteristics of selected spectral lines

No.	Element, multiplet number, wavelength (Å)	*EP*, eV	g_{eff}
1	Fe I-383 5232.952	2.94	1.261
2	Fe II-49 5234.630	3.22	0.869
3	Cr II-43 5237.325	4.07	1.33
4	Sc II-26 5239.893	1.45	1.00
5	Fe I-843 5242.495	3.63	1.00
6	Fe I-1089 5243.783	4.26	1.509
7	Fe I-1 5247.058	0.09	1.998
8	Cr I-18 5247.574	0.96	2.50
9	Fe I-1 5250.216	0.12	2.999
10	Fe I-66 5250.654	2.20	1.502

4. Results and their discussion

Line profiles and their bisectors. Since the equivalent length of the entrance slit of the spectrograph was approximately 27 Mm on the Sun, it was possible to study individual adjacent photometric sections with a width of 1 Mm each. In this way, we could compare the photometric profiles in individual areas on the Sun along the direction of the entrance slit, along which we introduce a horizontal coordinate L with a discreteness also of 1 Mm. In this preliminary study, we present results only for L = 18 Mm, which corresponds to the middle part of the sunspot umbra.

For example, in Fig. 1 we present the profiles of line No. 5 from the list in Table 1, which has a rather small Landé factor (1.0) and exhibits a relatively weak splitting in the core of the spot. This splitting can be regarded as a weak field regime (WFA), in which, at a uniform field, only the longitudinal component B_{LOS} of the intensity vector can be determined.

It can be seen from the figure that the bisectors of the $I + V$ and $I - V$ profiles are almost parallel to each other, and have a sharp deviation to the right in the wings of the line. Such parallelism of the bisectors is theoretically quite expected for the regime of weak splitting in a homogeneous field. As for the named sharp deviation of the bisectors to the right, this effect is repeated in all lines

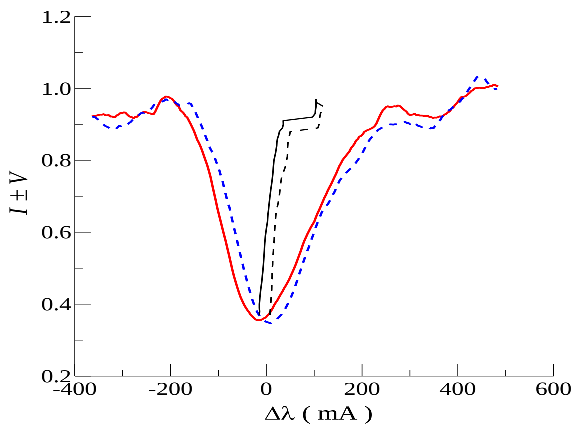

Figure 1: Stokes $I \pm V$ profiles and bisectors of Fe I 5242.495 line in sunspot umbra for L = 18 Mm.

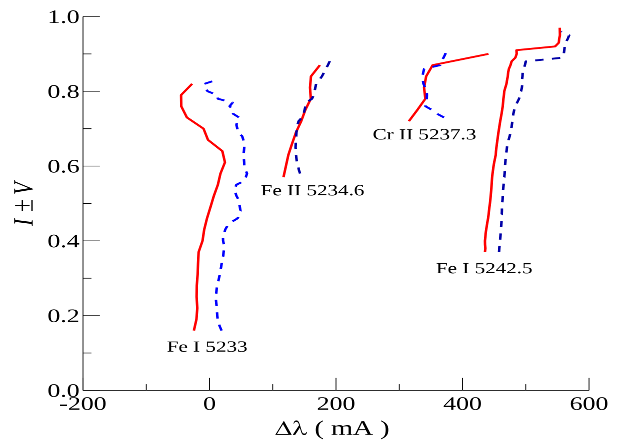

Figure 2: Comparison of the bisectors for some spectral lines. The position of the bisectors for the Fe I 5233 is original, while ones for the other lines are artificially shifted in the horizontal direction for better comparison of the data.

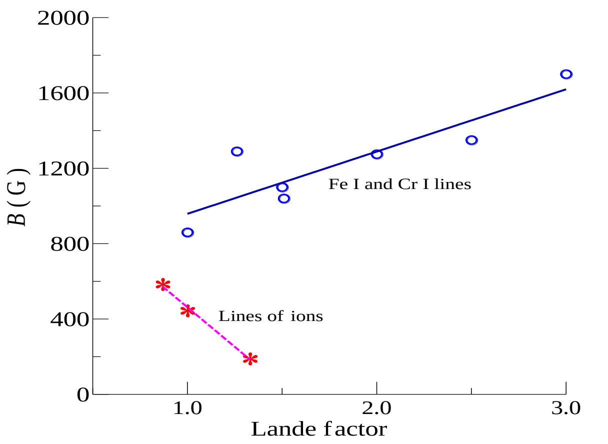

Figure 3: Comparison of measured magnetic fields with Landé factors of lines. Typical measurement errors are ± 100 G.

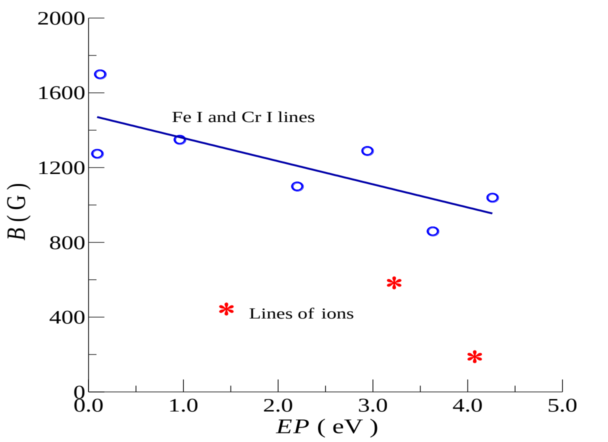

Figure 4: Measured magnetic fields *B* vs. excitation potential *EP* of the lower term.

of neutral atoms and is associated with a weak component located in the red wing at a distance of about 350 mÅ from the center of the lines. This indicates that the velocity field in the studied spot was inhomogeneous: in addition to the main component with a large filling factor, there was another component with a smaller factor, which had a positive velocity (plasma descent) of 20 km/sec.

A more interesting case is presented in Fig. 2, where the bisectors for the four lines are compared. It can be seen that the strong line Fe I 5233 has almost parallel bisectors too, while the ion lines have a rather peculiar shape, similar to the letter "X". To the best of our knowledge, such a case of bisector crossing is reported here for the first time. The mentioned bisector crossing cannot be explained within uniform magnetic field models, and likely reflects the different the magnetic field sign at the locations where the core and the wings are formed, similar to the magnetic field sign reversal along the line of sight reported in a different sunspot by Franz & Schlichenmaier (2013).

It can also be noticed that Fe I 5233 line has in its wings a local deviation of the bisectors to the left, i.e. in the opposite direction relative to Fe I 5242 line. This means that areas of relatively slow plasma rise are detected at the level of formation of this line.

Averaged magnetic fields. Since the bisectors behave very differently in different parts of the line profiles, we determined the average splitting of the bisectors for the entire profile of each line to estimate the corresponding magnitude of the averaged magnetic field. These data are presented in Figs. 3 and 4 in comparison with the Landé factor of the lines and the excitation potential of the lower term.

The dependence "*B* vs. *g*" for lines of neutral atoms presented in Fig. 3 is quite expected theoretically. After all, when using a circular polarization analyzer, the value of the Zeeman splitting gives B_{LOS} only in the case when this splitting is significantly less than the half-width of the spectral line (Unno, 1956). If the Zeeman splitting $\Delta\lambda_H$ increases so much that it is comparable to the half-width $\Delta\lambda_{1/2}$ of the line, then from the measurements we obtain a value intermediate between the longitudinal component and the modulus of the magnetic field strength. So, then, one would expect that the larger the Lande factor, the larger the measured magnetic field should be if the angle between the line of sight and the field line is significantly different from 0 or 180 degrees. However, what is incomprehensible from this point of view is the dependence for ions, which has the opposite character (here the measured field is probably anticorrelated with the Landé factor). However, the observational data for ions in this case are not enough to draw more confident conclusions.

However, from Fig. 3 and 4, another more obvious effect is evident: the ion lines give 300-1200 G fields weaker than the neutral atom lines. Calculations of the heights of spectral line formations in the spot showed that this feature reflects the effect of the height of spectral line formations. In particular, if we compare the heights of formations of Nos. 2, 3 and 4 lines (-17.51, 12.59 and 81.01 km, respectively) with the magnetic fields measured by them (290, 320 and 940 G), it is clear that the higher the spectral line is formed, the stronger the magnetic field it shows. We plan to provide more detailed observational data and data on calculations of the heights of line formations in a separate, more detailed article.

We checked whether this result could not be random, that is, only for one point of the sunspot. It turned out that also in other places of the sunspot along the cross-section of its image by the entrance slit of the spectrograph, the magnetic field measured by the lines of ions, in general, is systematically weaker than by the lines of neutral elements. Thus, we cannot explain this difference by the different inclination of the lines of force, and therefore the only possibility remains in the frame one-component field: the magnetic field strength really weakens when deepening into the sunspot.

This, however, seems paradoxical because the pressure, temperature and concentration of the plasma increase with depth (Maltby et al., 1986), and, therefore, the magnitude of the equilibrium magnetic field in the flux tube should also increase. Perhaps, different sunspots can have significantly different magnetic field topology, ranging from homogeneous to significantly inhomogeneous ones (Franz & Schlichenmaier, 2013).

The observed weakening of the magnetic field with depth may indicate that the sunspot is a relatively shallow formation resembling a thin disk, rather than a deep long force tube. In this regard, different authors have come to different conclusions. In particular, based on the study of the torsional oscillations of the spots, it was concluded that the sunspot is a rather deep formation: the length of the corresponding flux tube is several times greater than its thickness (Gopasyuk and Gopasyuk, 2005). However, some theoretical studies, as well as helioseismological data, indicate that the spots, on the contrary, are relatively shallow formations (Kosovichev, 2012). It is possible, however, that in this case not only the height of the line formation plays a role, but also their different temperature sensitivity to changes in thermodynamic conditions at different depths in the spot, as well as the subtelescopic structure of the field, which contains both very strong magnetic fields and opposite magnetic polarities. It seems possible to find the correct answer to this question using the modeling profiles for the case of a significantly inhomogeneous solar atmosphere, which may contain several discrete components with different intensities, polarities, filling factors, Doppler velocities, and thermodynamic parameters.

Probably, it is worth paying attention not only to the effects of the shape of the "X" bisectors (Fig. 2), but also to the subtle effects in the splitting of the bisectors of the type of local maximum, similar to that found in line FeI 5233. As can be seen from this figure, at the intensity level of 0.7- 0.8 this line has a local maximum of splitting, which should not be at a homogeneous magnetic field. A similar effect is found not only for L = 18 Mm, but also in neighboring photometric sections. A possible reason for this effect is the subtelescopic structure of the magnetic field, in which the actual local magnetic field intensities can be much larger than those obtained directly from direct measurements (Lozitsky, 2015).

5. Conclusions

The main result of our work is that the ion lines in the studied sunspot demonstrate significantly lower magnetic field strengths than the lines of neutral atoms. This is probably due to the significant altitudinal gradient of the magnetic field. If this is the case, then a paradoxical situation arises: the magnetic field strength weakens with depth in the spot, while the gas pressure, as is known, increases (Maltby et al., 1986). Our results confirm the previously obtained data of Venglinsky and Lozitsky (2012) that in the sunspot umbra there can be a sharp "dip" of the strengths measured by the ion lines. Although the results of our study do not agree with the measurements of Semel (1981), it cannot be ruled out that different sunspots have very different patterns of spatial inhomogeneity of the magnetic field. In this respect, sunspots may be no less interesting objects for research than solar flares. However, it should be noted that sunspots are much more convenient objects for observation than solar flares.

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