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ANOMALOUS WIDENING OF 5434.5 LINE IN SUNSPOTS: SUPER-STRONG MAGNETIC FIELDS?

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ABSTRACT. We present results of spectral observations of two sunspots in six metal lines near Fe I 5434.5 Å, which have effective Lande factors $g_{\rm eff}$ from –0.014 to 2.14. The observations were made on July 8 and August 25, 2015, with the ATsU-5 telescope of GAO NAS of Ukraine using a circular polarization analyzer and spectra registration with the SBIG ST-8300 CCD camera. The following line parameters are compared: observed splitting of $I \pm V$ profiles, the width and depth of the Stokes I profiles. Significant differences of the measured magnetic field strengths $B_{\rm eff}$ were found in separate places of the spots and by lines with different $g_{\rm eff}$ values. The Fe I 5434.5 Å line ($g_{\rm eff}$ = –0.014) shows measurable splitting in some locations of the sunspots, which corresponds to the magnetic field $B_{\rm obs} \approx 20$ kG. Comparison of the widths and depths of the line profiles revealed several special places in the sunspots, where the Fe I 5434.5 Å line was expanded additionally by ≈ 15–35%, whereas other lines with larger Lande factors did not have such a feature. One of the reasons for this expansion could be a sharp and local increase of turbulent velocities, but no active processes such as solar flares or significant Doppler flows were observed at these locations. A semi-empirical model constructed for the first sunspot by FeI 5434.5 line using inverse code with Tikhonov`s stabilizers shows an anomalous feature – the maximum of microturbulent velocities in the upper photosphere and the temperature minimum zone instead of the usual small increase of microturbulence at these heights. This may be the effect of very strong magnetic fields of mixed polarity or unresolved turbulent structures. As to first case, the estimated value of the magnetic field in such locations of sunspots is ~10^5 G, which requires additional careful verification.

Keywords: Sun, solar activity, sunspots, magnetic fields, spectral lines, the Zeeman effect, semi-empirical model, turbulent velocities, superstrong magnetic fields.

АНОТАЦІЯ. Представлені результати спектральних спостережень двох сонячних плям у шести лініях металів поблизу лінії Fe I 5434.5 Å, які мають ефективні фактори Ланде $g_{\rm eff}$ від –0.014 до 2.14. Спостереження були виконані 8 липня і 25 серпня 2015 р. на телескопі АЦУ-5 Головної астрономічної обсерваторії НАН України з використанням аналізатора кругової поляризації і з реєстрацією спектру з допомогою камери SBIG ST-8300 CCD camera. Були співставлені такі параметри ліній: спостережене розщеплення профілів $I \pm V$, ширини і глибини профілів Стокса I. Виявлені суттєві розбіжності виміряних магнітних полів $B_{\rm eff}$ у окремих ділянках сонячних плям а також по лініях з різними величинами $g_{\rm eff}$. Лінія Fe I 5434.5 Å ($g_{\rm eff}$ = –0.014) виявляє достовірне розщеплення у деяких місцях плям, яке відповідає магнітному полю $B_{\rm obs} \approx 20$ кГс. Співставлення ширин і глибин профілів ліній показало, що у деяких місцях лінія Fe I 5434.5 Å додатково розширена на ≈ 15–35%, тоді як інші лінії з більшими факторами Ланде не мають такої особливості. Однією з причин такого розширення могло бути різке й локальне зростання турбулентних швидкостей, однак ніяких активних процесів типу сонячних спалахів або значних допплерівських потоків не було помічено у цих місцях. Напівемпірична модель першої плями, побудована за даними в лінії FeI 5434.5 інверсним методом з використанням стабілізаторів Тихонова для забезпечення стійкості розв'язків рівнянь переносу випромінювання, має цікаву особливість – максимум мікротурбулентних швидкостей у верхній фотосфері і зоні температурного мінімуму замість слабкого зростання мікротурбуленції на цих висотах. Це може бути внаслідок дуже сильних магнітних полів змішаної полярності або ж внаслідок присутності просторово нероздільних турбулентних структур. Щодо першого випадку, то наближена оцінка магнітного поля у цих місцях плям дорівнює ~10^5 G, що потребує додаткової ретельної перевірки.

Ключові слова: Сонце, сонячна активність, сонячні плями, магнітні поля, спектральні лінії, ефект Зеємана, напівемірична модель, турбулентні швидкості, надсильні магнітні поля.

1. Introduction

Magnetic fields in sunspots are measured, as a rule, using spectral lines with the largest Lande factors. This provides the highest accuracy of measurements and the ability to determine such an important characteristic as the modulus of the magnetic field strength, in addition, regardless of instrumental polarization, the inclination of the field vector to the line of sight and the scattered light. Although in this case, there are some methodological problems that are encountered when comparing data from different observatories (Lozitska et al., 2015). As for the most mass magnetographic measurements to date, they usually give a longitudinal component of the magnetic field and, moreover, are not corrected for changing the profile of the spectral line due to non-magnetic changes in the transition from the photosphere to the sunspot. As a result, the most reliable measurements of magnetic fields in sunspots today are traditional spectral measurements or modern Stokes diagnostics using realistic models of the solar atmosphere. However, in the latter case, lines with large Lande factors are also commonly used. This automatically limits the range of magnetic field strengths available for measurements. Regarding direct data for cases corresponding to the filling factor f close to unity (i.e., $f \approx 1$), the strongest magnetic fields in the spots were found to be within 5.5–6.1 kG (Livingston et al., 2006; Lozitsky et al., 2018). However, sunspots with such superstrong fields are rare; for the most part, the typical magnetic field strength in developed sunspots (with shadow and penumbra) is in the range of 2–3 kG.

Subtle effects were found in line profiles which indicate that the magnetic field strength in spatially unresolved elements of sunspots can be 7–8 kG (Van Noort et al., 2013; Lozitsky, 2016). The filling factor for such elements can reach values f = 0.2–0.3, and the Doppler shifts correspond to plasma lifting with speeds of 2–3 km / sec. However, in the article by Van Noort et al. (2013) the conclusion is different: the substance in the subtelescopic elements goes down with speeds of about 20 km / sec. A possible reason for the difference between these findings is that in the papers by Lozitsky (2016) the umbra of large spots was studied, whereas in the article by Van Noort (2013) – penumbra of sunspots.

It should be noted that the particularly strong magnetic fields in the range of 7–8 kG are, in fact, close to the upper limit of detectable (measurable) fields when to use the spectral lines like FeI 5250.2 or FeI 6302.5 with large Lande factors. The mentioned authors analyzed the spectral lines of Fe I 6301.5 and 6302.5 with effective Lande factors 1.67 and 2.50, respectively, which in case of high magnetic strengths are split so strongly that their Zeeman σ components begin to overlap mutually, complicating the diagnosis of fine photometric effects in the adjacent spectral continuum. This is especially true in the sunspot umbra where the numerous and variable molecular blends can occur. That is why it is better to use spectral lines with small Lande factors ($g_{\rm eff} \le 1$) to measure even stronger magnetic fields.

It is important to note that modern methods of measuring magnetic fields in sunspots are mainly oriented on observations of fields of regular polarity, which give characteristic manifestations in the Stokes parameters Q, U and V. However, for spatially unresolved magnetic fields of mixed polarity, the corresponding observed manifestations in these parameters may be close to zero, i.e. not detectable. At the same time, strong mixed-polarity fields can be detected by the Stokes I profile, that is, by the integral intensity, on the basis of observations of significant expansion of this profile. However, in practice, this parameter is almost never analyzed when interpreting observations.

In this study, we use both of the mentioned methodological factors: spectral lines with very small Lande factors and data on the line profiles in the integral intensity. The purpose of our work is to obtain new data for the problem of the upper limit of the magnetic field in the sunspots using the spectral data obtained with a circular polarization analyzer.

2. Observations

Observational material for our study was obtained with the horizontal solar telescope ATsU-5 of Main Astronomical Observatory of National Academy of Science of Ukraine. The telescope is well tested and has a half-width of the instrumental profile ≈ 20 mÅ for λ = 6328 Å (Osipov, 2015). During observations, the spectra of sunspots and surrounding areas were recorded using an SBIG ST-8300 CCD camera in the wavelength range about ± 4 Å around FeI 5434.5 Å line. To obtain the spectra $I + V$ and $I - V$, a polarization mosaic by Skomorovsky (1974) and a quarter-wave plate were used.

In this paper, we analyze the observations of two sunspots which were observed on July 8 and August 25, 2015. The second sunspot was in the tail part of the active region of NOAA 2403, which was located from the center of the disk at a distance ρ/R = 0.415, μ = 0.91. The diameter of the penumbra of this spot was about 45 Mm; the spot was irregular in shape, especially its umbra (Fig. 1).

The exposure of the spectrum of this spot was made at the following time interval: $07^h36^m – 07^h46^m$ UT. During the exposure, the entrance slit of the spectrograph crossed the spot in the north-south direction on the disk, as it is shown in Fig. 1.

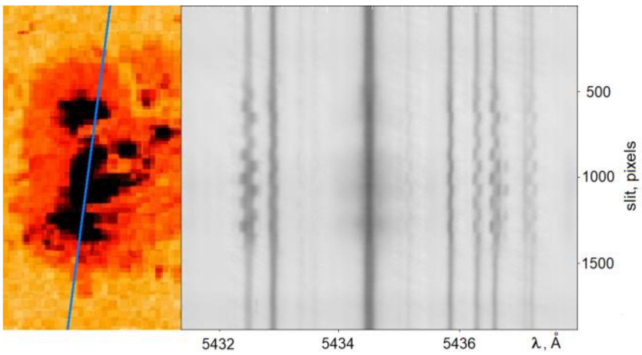

Figure 1: The images of the sunspot of 25 August, 2015 in white light according to the SOHO data (left), and its spectrum according to observations on the ATsU-5, which is analyzed in this paper (right). The strongest spectral line in the middle part of this spectrum is Fe I 5434.5 Å line ($g_{\rm eff}$ = –0.014).

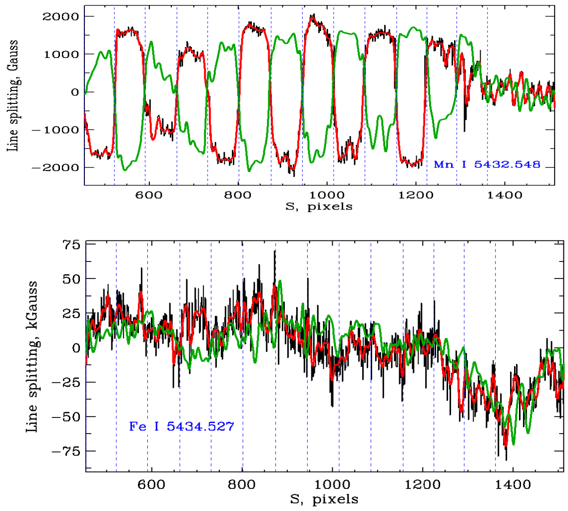

Figure 2: Shift of 'center of gravity' of spectral lines with Lande factors $g_{\rm eff}$ = 2.143 and $g_{\rm eff}$ = –0.014 for sunspot of 28 Aug 2015. Red and green lines represent calibrated positions of 'center of gravity' of *I* + *V* and *I* – *V* profiles along direction of entrance slit of spectrograph.

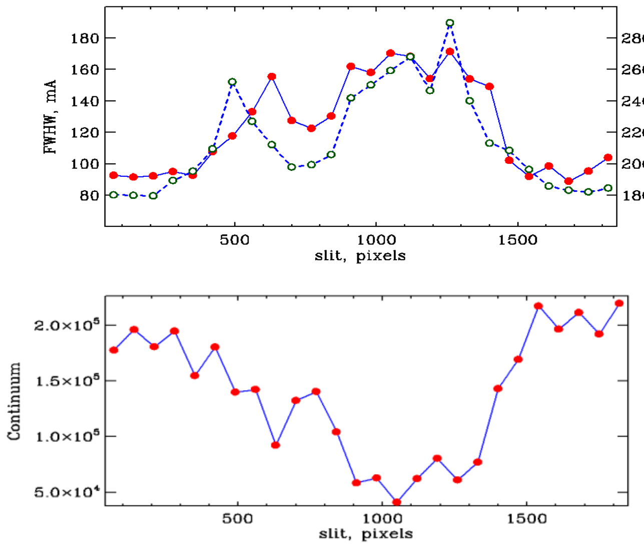

Figure 3: Comparison of the half-widths of lines with $g_{\rm eff}$ = 2.143 and -0.014, versus the intensity in the spectral continuum (lower graph). It can be seen that line with $g_{\rm eff}$ = –0.014 (stroke line) has a sharp jumps at position slits ≈ 500 and 1260.

First sunspot was observed on July 8, 2015, in active region NOAA 2381. Beginning of exposure of this sunspot was at $7^h\,12^m$ UT.

3. Effective magnetic fields

The effective (averaged) magnetic fields $B_{\rm eff}$ were measured by the displacement of the centers of gravity of the profiles *I* + *V* relative to *I* − *V*. For a uniform magnetic field and incomplete splitting of the Zeeman π and σ components, this should give a value close to the longitudinal component of the magnetic field.

Figure 2 shows, for illustration, distribution of spectral positions of two lines with very different Lande factors, $g_{\rm eff}$ = 2.143 (upper graph) and $g_{\rm eff}$ = –0.014 (lower graph). These positions are presented along direction of entrance slit of spectrograph for two orientations of quarter-wave plate, +45° and –45° relatively optical axis of polarization mosaic. Along the horizontal axis on Figures, 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.

One can see the following well-visible effects in line with large Lande factor: (a) periodical deviations of line position when to transit from given band of mosaic to the next, and (b) discrete change of the sign of deviation to the opposite one for different orientations of quarter-wave plate. Namely such effects demonstrate the magnetic nature of these manifestations. On this Figure, equivalent width of the mosaic strip is 3.3 Mm on the Sun.

In order to determine the magnitude of the measured magnetic field according to these graphs, it is necessary to take for each specific strip of the mosaic half the difference of the position of the line with different orientation of the quarter-wave plate. For example, in Fig. 2 in the abscissa interval *S* = 800-870 the line positions correspond to values of +1800 G and – 2000 G. Subtracting the second value from the first and taking half of it, we have an average field in this strip, equal to 1900 G.

A similar examination of the observational data for line with very small Lande factor (–0.014) shows that in some places of the sunspot it also has similar evidence of Zeeman splitting. For example, this is seen in the abscissa intervals *S* = 670–720 and 820–830, where, at different positions of the plate λ / 4, the "center of gravity" of the line deviates in opposite directions relative to the direction of spectral dispersion. If to interpret it as a manifestation of the Zeeman effect, then the corresponding magnetic field should be at the level of ≈ 20 kG. Another conclusion follows from Fig. 2: the corresponding places in the sunspot with particularly strong fields are quite local, with a typical scale, probably 1–3 Mm.

4. Stokes *I*

Comparison of the half-widths of the Stokes *I* profiles for the same lines as in Fig. 2 is shown in Fig. 3. One can see that line with large Lande factor (solid line on upper graph on the Figure) has the largest broadening exactly in such places where the intensity in spectral continuum is minimal.

This is well expected effect if we take into account that strongest magnetic fields, as rule, are localized in sunspot umbra. However, the line with a very small Lande factor (dashed line in the Figure 3) behaves differently: in two places, at *S* ≈ 500 and 1260, it has sharp jumps of the half-width. This is surprising because it does not coincide with the darkest places in the sunspot.

Of course, for more confident conclusions, it is necessary to compare the widths of a larger number of spectral lines. This is shown in Fig. 4 for six lines, which presents the relative increase in the line half-width as a function of the

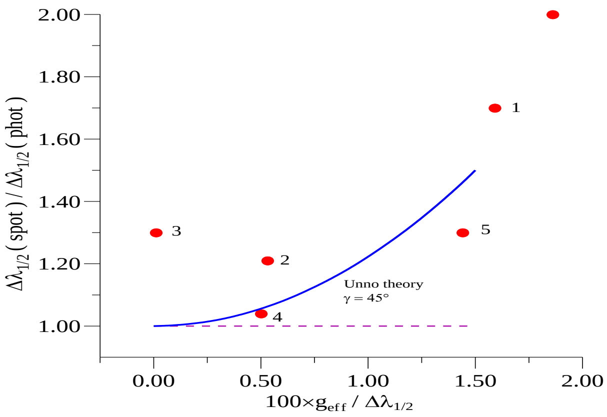

Figure 4: Comparison of the relative increasing of the Stokes profile *I* for six spectral lines with different Lande factors observed by S.M. Osipov on ATsU-5 in the sunspot on August 25, 2015.

magnetic sensitivity normalized to the line half-width. The filled circles with numbers indicate the observations; the blue curve is Unno (1956) theory for a uniform magnetic field. One can see that the line №3 (g_{eff} = –0.014) deviates significantly from the theoretical dependence. This means that this line really "falls out" of the theoretical regularity that is expected for a uniform magnetic field of the "kilo-Gaussian" level.

5. Semi-empirical model

Similar effects were found also in the first sunspot, which was observed on July 8, 2015. For this sunspot, a semi-empirical model was build using Stodilka's (2003) code. This model presents the photospheric layers of the sunspot and was constructed on a base of observations of FeI 5434.5 line by solving the inverse problem for non-equilibrium radiative transfer problem using Tikhonov stabilizers. The main peculiarity of the model is following: it has an anomalous feature – the maximum of microturbulent velocities in the upper photosphere and the temperature minimum zone instead of the usual small increase of microturbulence at these heights (detailed presentation of this model is planned in a separate study). This may be the effect of very strong magnetic fields of mixed polarity or unresolved turbulent structures. In the first case, the estimated value of the magnetic field in such locations of the sunspot is ~10^5 G, which, naturally, requires additional careful verification. Notice, similar magnetic fields were suspected in solar flares (Lozitsky, 2009) on a base of observations also in FeI 5434.5 line.

6. Conclusions

The present study confirms the assumption of Severny (1957) that magnetic fields of several tens of kilogauss can exist in sunspots. Indications of such very strong fields follow from both polarization effects and unpolarized light data. The latest data are especially interesting because they lead to the conclusion about the possible existence of even stronger fields of the ~10^5 G level. In this respect, diagnostics of magnetic fields by the FeI 5434.5 line are especially attractive for future research. The current research narrows the search for such extremely strong fields. Firstly, it is not necessary to have extremely high resolution to detect them. In particular, even a low resolution of 1-3 Mm may be sufficient, since the filling factor, rather than the direct resolution limit, seems to play an important role here. Secondly, data in unpolarized light can be very valuable, but it requires simultaneous analysis of several lines with different Lande factors. Thus, even old observations of sunspots without polarizing optics can contain important information about especially strong magnetic fields in the sunspots.

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