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Comparative study of magnetic fields in sunspots from observations in spectral lines with different Landé factors

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Introduction

The main goal of our study is to explore the problem of extremely strong magnetic fields (> 5 kG) in solar atmosphere including possible existence these fields in the latent, spectrally 'unvisible' form.

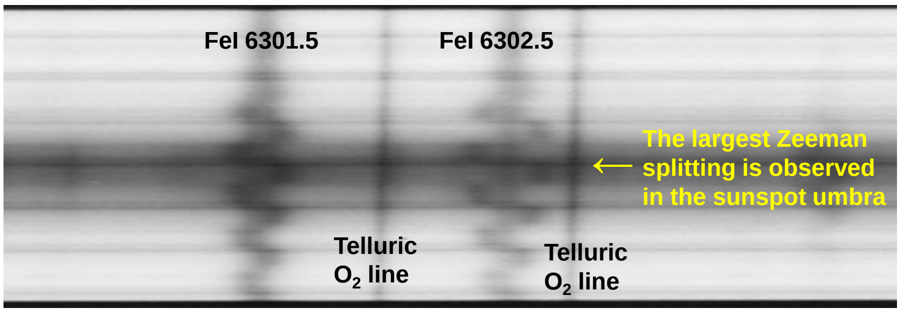
Concerning the explicit, unconcealed, presence of strong magnetic fields in the spots, it is well known that <u>the strongest fields exist</u> at great sunspots, exactly, <u>in sunspot umbra.</u>

According to observations, the field strength is here, as rule, 2100–2900 G and sometime 3500–4000 G (Solanki, 2003; Lozitska, 2010).

Baranovsky and Petrova (1957), and Steshenko (1968) measured field values in sunspot of 4900 G and 5350 G, respectively.

The record field of 6100 G in a sunspot umbra was reported by Livingston et al (2006).

The Zeeman effect in spectrum of a sunspot



This spectrum was obtained with quarter-wave plate and Skomorovsky's polarized mosaic giving I+V and I-V spectra for close places on the Sun. One can see well-visible splitting of solar FeI lines and absence of such splitting in telluric lines . Such spectral manifestations corresponds to magnetic field strength about 3000 G in the sunspot umbra. Unfortunately, such spectra are useless for conclusions about possible existence of extremely strong (~10^4 G) tangled fields (e.g. mixed-polarity fields).

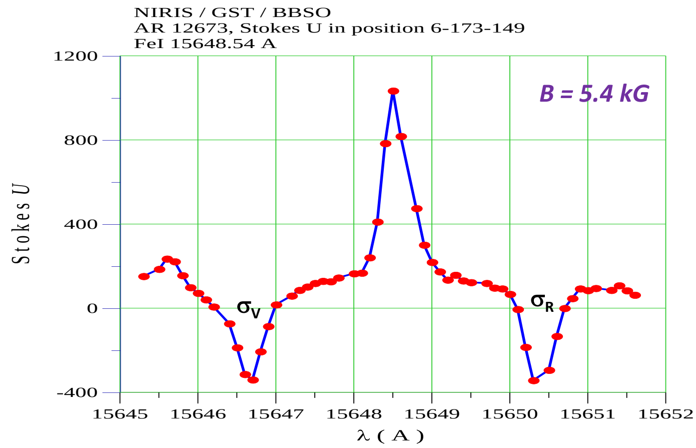
Some recent publications on this topic:

- Wang Y., Yurchyshyn V., Lin C. et al. Strong transverse photosphere magnetic fields and twist in light bridge …// Res. Notes of the American Astron. Society, 2018, 2, No. 1 (magnetic field of 5.57 kG was measured in sunspot penumbra light bridges using FeI 15648.5 line)

- Takenori J. Okamoto, and Takashi Sakurai, Super-strong magnetic fields in sunspots, arXiv:1712.08700v1[astro-ph.SR] 23 Dec 2017 (magnetic field of 6.25 kG was measured in a sunspot using FeI 6302.5 line)

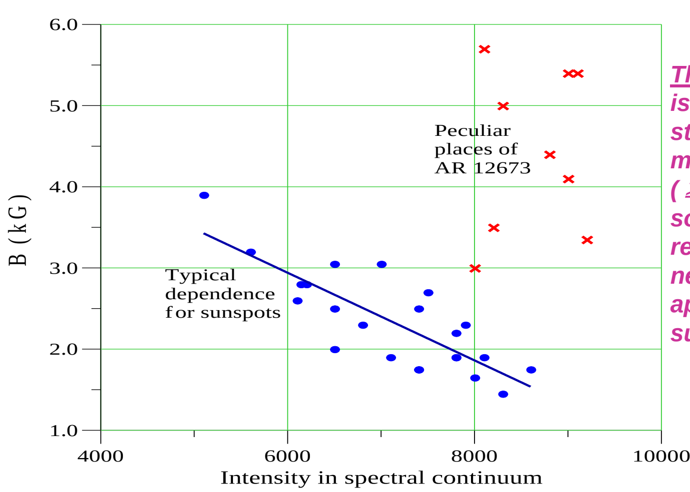
- Lozitsky V. G. Yurchyshyn V.B., Ahn K., Wang H., Lozitska N.I. Problem of super-strong magnetic fields on the Sun: Brief chronology and new observational data // Odessa Astronomical Publications. – 2018. – Vol. 30. - P. 152-158. - 5.7 kG from FeI 15648.5 line

Full Zeeman splitting in Stokes U profile of FeI 15648.5 line observed with the Goode Solar Telescope of Big Bear Solar Observatory in light bridge of AR 12673



In FeI 15648.5 line, it s possilbe to measure magnetic field module for B ≥ 1.5 kG. Unfortunately, due to the use of the Fabry-Perot filter, upper accessible magnetic field limit is about 7-8 kG.

Two types of magnetic structures in AR 12673 according to direct measurements in FeI 15648.5



The good news is that the strongest magnetic fields (≥ 5 kG) in the solar active regions may not necessarily appear in the sunspot umbra.

Lozitsky, Yurchyshyn, Wang et al (2018)

Two important methodological notes

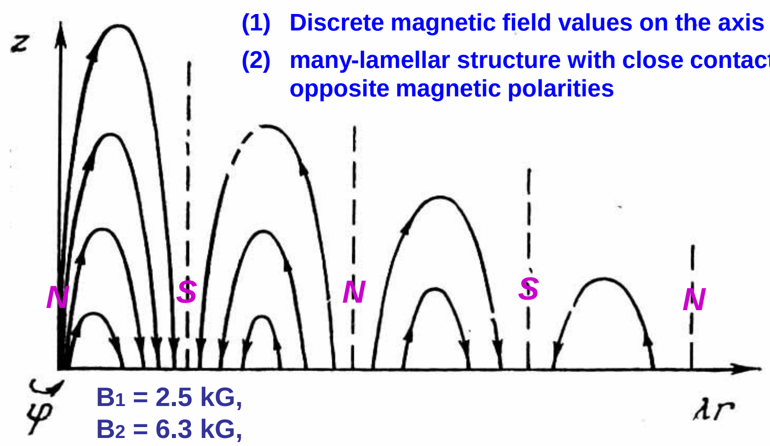
(a) Spectral lines with very small Landé factors must be used to search and measure especially strong magnetic fields,

(b) particularly strong magnetic fields, perhaps, can be of mixed magnetic polarity. In this case, it is useful to use the Stokes parameter *I* (integrated intensity). Indeed, some theoretical models predict precisely the multilayer mixed-polarity structure of formations with extremely strong fields. For example, the model by Solov'ev and Lozitsky (1986).

Transversal magnetic field distribution in linear force-free model by Solov'ev & Lozitsky (1986)

Two exotic peculiarities:

1. **Discrete magnetic field values on the axis**
2. **many-lamellar structure with close contact of opposite magnetic polarities**



B_1 = 2.5 kG,
B_2 = 6.3 kG,
B_3 = 8.3 kG,
B_4 = 10.0 kG, B_5 = 11.5 kG, B_6 = 12.8 kG…

How can you detect strong entangled magnetic fields in sunspots?

1. If very strong ($\geq 10^3$ G) tangled or mixed-polarity magnetic fields exist in sunspots , they should give latent (hidden) spectral manifestations in Stokes Q, U and V, but well-visible manifestations in Stokes I, namely, they can product essential Zeeman broadening of Stokes I.

2. In case of observations in one spectral line only, such broadening can not be separated from effects of thermodymamical conditions and turbulent velocities.

3. In order to separate magnetic and non-magnetic effects, several spectral lines are needed with different Lande factors. Lines with larger Lande factors should demonstrate larger broadening than lines with small such factors.

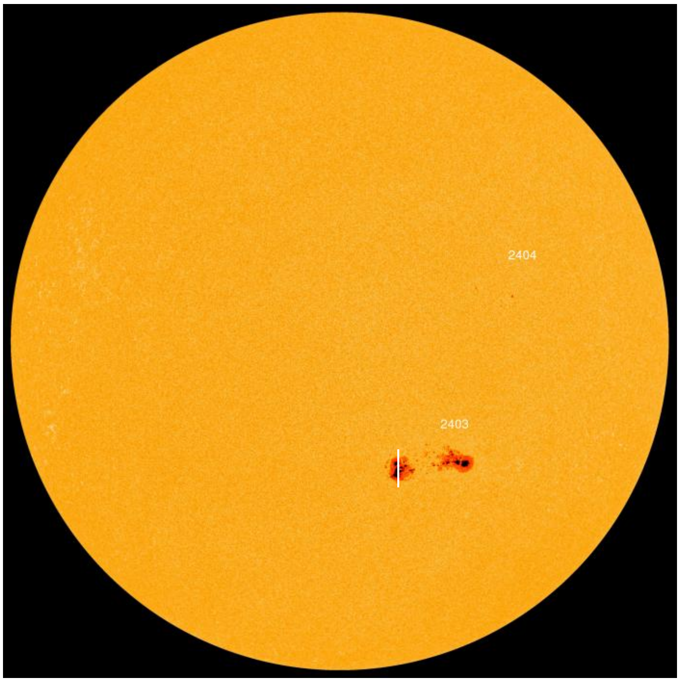
OBSERVATIONS WITH ATsU-5 GAO

Observations were carried out on horizontal solar telescope ATsU-5 of Main Astronomical Observatory of National Academy of Sciences of Ukraine in June-August 2015.

A significant advantage of ATsU-5 is that its spectral resolution is very large, about 400,000, while on the GST of BBSO it is about 125,000, the same is roughly on Hinode, on the GST AO KNU it is about 200,000. In addition, on the ATsU-5 about 6-8 spectral lines can be observed simultaneously, whereas in the Hinode - only 2 lines, and on GST BBSO - one line only (due to the use the Fabry-Perot filter having a very small dispersion region).

Spectra recordings were performed using the SBIG ST-8300 CCD camera. For observations of I+V and I–V spectra, the polarization mosaic made by V.I. Skomorovsky and quarter-wave plate were used.

Measured spectra were corrected for flatfield, parasitic interference, and curvature of spectral lines.

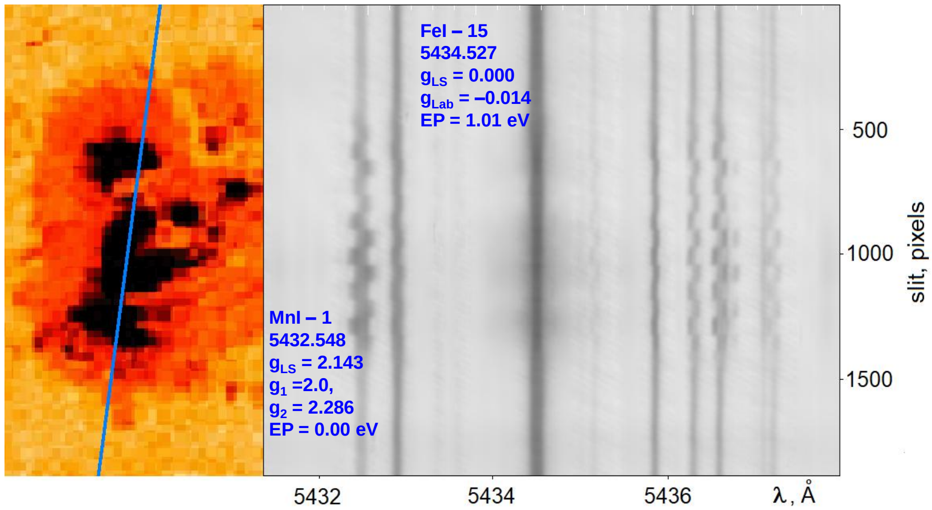


Sunspot
observed by
S. Osipov
with ATsU -5
25.08.2015
07^h36^m-07^h46^m UT

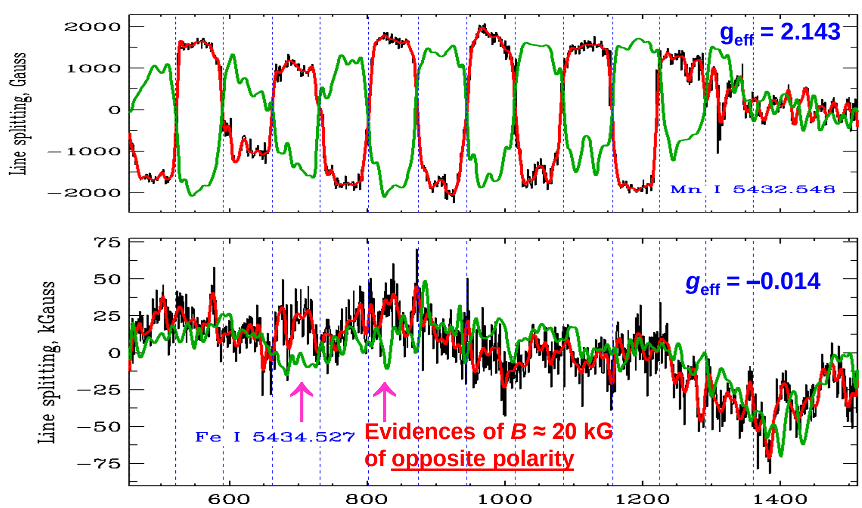
Selected magnetosensitive lines which were used for magnetic field diagnostics in the sunspot

No.	Element, multiplet	λ, Å	EP, eB	g_{eff}
1	MnI – 1	5432.548	0.00	2.143
2	FeI – 1143	5432.950	4.43	0.666
3	FeI – 15	5434.527	1.01	– 0.014
4	NiI – 70	5435.871	1.98	0.500
5	FeI – 1161	5436.299	4.37	1.440
6	FeI – 113	5436.594	2.27	1.816

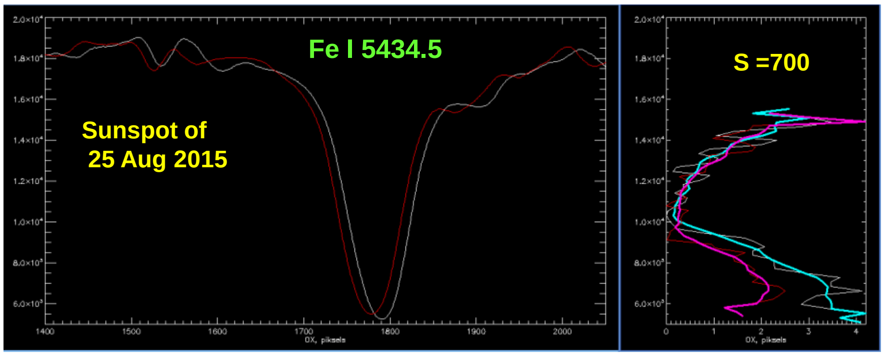
The image of the spot of 25.08.2015 in white light according to the SOHO data (left), as well as of the spectrum according to the observations on the ATsU-5, which is analyzed in this report (right). The strongest spectral line approx. in the middle of this part of the spectrum is Fe I 5434.5 Å line (g_{eff} = –0.014).



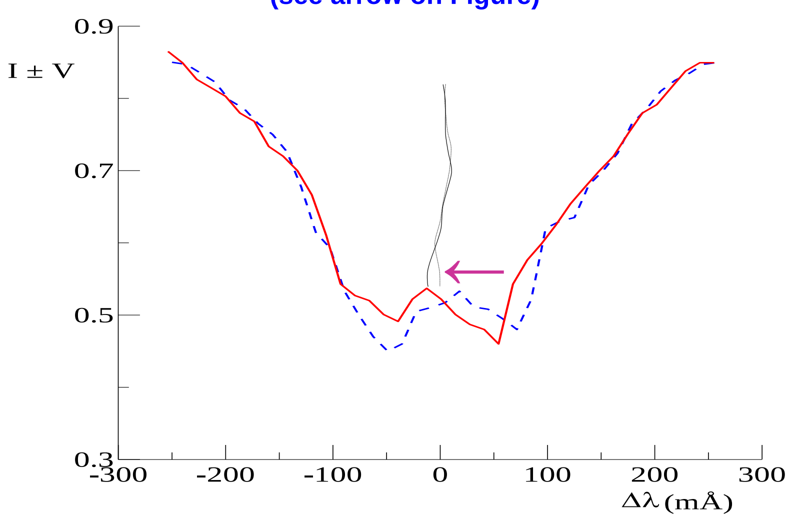
Shift of 'center of gravity' of spectral lines with Lande factors g_{eff} = 2.143 and g_{eff} = –0.014 for sunspot of 28 Aug 2015. Red and green lines presents calibrated positions of 'center of gravity' of *I* + *V* and *I* – *V* profiles along direction of entrance slit of Echelle spectrograph



An additional argument in favor of the reality of the superstrong magnetic field of *B* ≈ 20 kG.
The bisectors of *I* ± *V* profiles of FeI 5434.5 line have maximum splitting in the line core. A similar situation was observed in solar flares (Lozitsky, 1993, 1998, etc.).

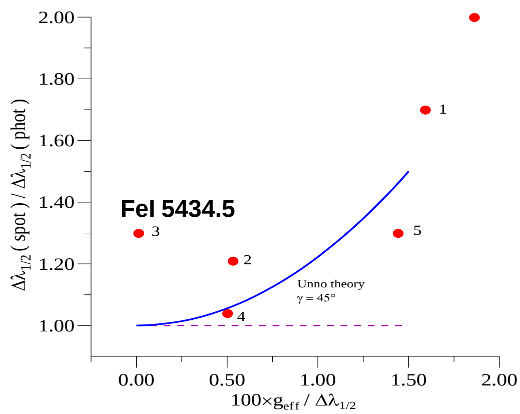


Observed Stokes *I* ± *V* profiles of FeI 5434.5 line in solar flare of 16 June 1989. One can see that maximum of bisector splitting and splitting of emissive peaks is observed in the line core (see arrow on Figure)

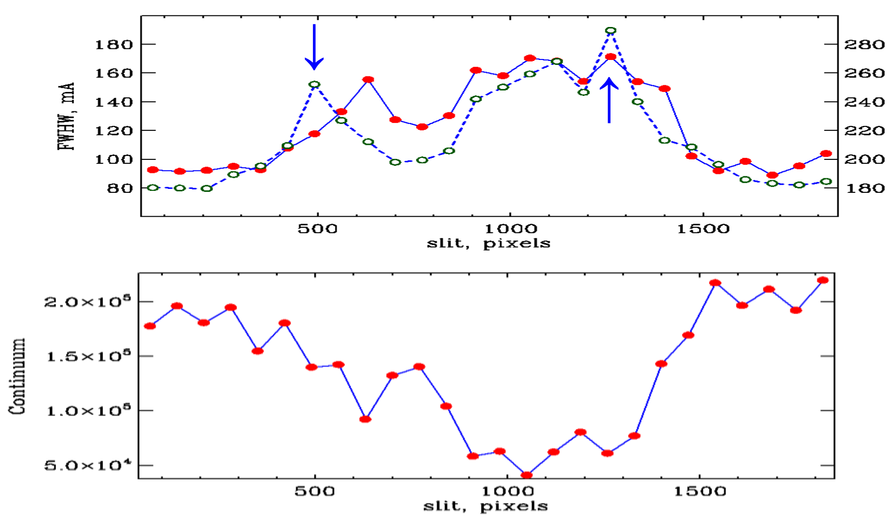


Lozitsky V.G. Journal of Physical Studies, 2009,Vol. 13, No. 2

Comparison of the relative expansion of the Stokes profile *I* for 6 spectral lines with different Lande factors observed by S.M. Osipov on ATsU-5 in a sunspot on August 25, 2015, depending on the normalized magnetic sensitivity of these lines. The numbers indicate the line numbers; the blue curve is a theory for a uniform magnetic field. One can see that the line №3 deviates significantly from the theoretical dependence. This means that the effects of the presence of particularly strong tangled magnetic fields are not excluded.



Comparison of the half-widths of lines No. 1 and No. 3 (g_{eff} = 2.143 and -0.014, respectively) with the intensity in the spectral continuum (lower graph). It can be seen that line No. 3 has a sharp half-width jumps at the boundary of the umbra and penumbra of the sunspot



In principle, there are two possible alternatives to expain sharp jump of FWHW for line with $g_{eff} = -0.014$:

(a) it is a purely non-magnetic line extension, probably by turbulent velocities , or

(b) an expansion by much stronger magnetic fields. In principle, some combination of these effects (a) + (b) is possible.

With respect to turbulent velocities, this assumption seems doubtful, since no active processes were observed at this places ($S \approx 500$ and 1250), such as a solar flare or high beam velocities. Therefore, let us try to estimate what magnetic field is necessary for this line to increase its width to the observed value.

For the FeI 5434. 527 Å line, the calibration formula for linking the parameters $\Delta\lambda_H$ and B is as follows:

$$\Delta\lambda_H = 1.93\times10^{-7} B .$$

Given this formula, it is easy to get an expression to estimate the required magnetic field:

$$B = 0.5[(\Delta\lambda_{1/2,junp})^2 - [(\Delta\lambda_{1/2,spot})^2]^{1/2} / 1.93\times10^{-7} ,$$

where $\Delta\lambda_{1/2,jump} \approx 0.290$ Å is observed half-width of No.3 line in jump, and $\Delta\lambda_{1/2,spot} \approx 0.260$ Å is the same parameter outside of FWHW jump.

Substituting these values, we obtain $B \approx 3.3\times10^5$ G.

Conclusions

We analyzed the Zeeman effect in six metal lines near Fe I 5434.5 Å, which have effective Lande g_{eff} factors from –0.014 to 2.14.

In two sunspots of 8 July and 25 Aug 2015, the specific spectral manifestations in FeI 5434.5 line were found which corresponds to magnetic field B_{obs} ≈ 20 kG of opposite magnetic polarity. Namely this case the theoretical model by Solov'ev (2020) predicts.

Comparison of the widths and depths of the line profiles revealed a special places in the sunspots, where the Fe I 5434.5 Å line was expanded additionaly by ≈ 15%, 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 this location. Another reason for this expansion may be the presence of extremely strong and spatially unresolved magnetic fields of mixed magnetic polarity.

Regarding the assumptions of the occurrence of such superstrong fields in spots, then Prof. Solov'ev A.A. has recently proposed an amazing MHD model in which the magnetic field strength can be increased by 2-3 orders of magnitude not by the twisting of the lines of force, but by the elasticity of the curved lines of force.

It seems to me that this configuration is extremely surprising, it can only be 'created with hands'.

But let us listen what Prof. Solov'ev himself will say about this in following report…

Дякую !