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Spectral manifestations of strong and especially strong magnetic fields in the active prominence on July 24, 1999

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We present the results of the study of the magnetic field in the active prominence on July 24, 1999 for the moment 07:00 UT, using the observational material obtained on the Echelle spectrograph of the horizontal solar telescope of the Astronomical Observatory of Taras Shevchenko Kyiv National University. Our analysis is based on the study of $I \pm V$ profiles of the Hα line, which were related to heights in the range of 11-20 Mm. It was found that the bisectors of the $I \pm V$ profiles are non-parallel to each other in majority of places of this prominence. This indicates the inhomogeneity of the magnetic field: with a uniform magnetic field, the named bisectors should be parallel. Moreover, the maximum splitting of bisectors is observed not only in the core of the line (which was found earlier by other authors), but also in its far wings, at distances of 1.5-2.5 Å from the line center. The specified maximum of splitting corresponds to magnetic field of about 3000 G, but this value should be considered only as a lower estimate of the true local magnetic fields. In particular, the second maximum of bisector splitting may indicate that the actual value of Zeeman splitting in small-scale structures with a small filling factor reaches the above value of 1.5-2.5 Å which corresponds to the field strength of almost 100 kG. From our study it follows that evidences on such extremely magnetic fields may not actually be a rare phenomenon, but a rather common one, which, however, can be recorded only under certain favorable observational conditions.
Key words: Sun, solar activity, prominences, magnetic fields, spectro-polarimetry, super-strong fields.

INTRODUCTION

Solar flares and active prominences are the most rapidly changing manifestations of solar activity. Active prominences can be classified as the final stage of the limb solar flares, and therefore the actual boundary between them can be purely conditional, that is, there are cases when an active prominence can be called a limb flare.

Magnetic fields in solar flares and active prominences are significantly less-studied than in sunspots due to the following circumstances:

(a) solar flares and active prominences appear suddenly and exist for a relatively short time (from several minutes to several hours), and therefore it is not always possible to obtain representative observational material about them. Sunspots are much more convenient for observations, they exist for quite a long time - from several days to several weeks [19];

(b) in sunspots, it is possible to measure the modulus of the magnetic field intensity |*B*| using narrow spectral lines (~ 0.1 Å) with large Lande factors (g = 2.5-3). In solar flares and prominences, it is necessary to analyze the spectral manifestations of the Zeeman effect, as a rule, by broad spectral emissions (~ 0.5 – 1 Å) of lines with lower Lande factor (about 1.0), when not the intensity modulus |*B*| is measured, but in the best case, the longitudinal component of the magnetic field B_{LOS} [22].

The magnitude of the magnetic field in solar flares and active prominences, measured by different authors and by different methods, was obtained in a very wide range, from 10^2 to 10^5 G [1,2, 4-10, 14-18, 23-27]. That is, in some cases, the measured magnetic field in solar flares exceeds the magnetic field in sunspots, where it is found in the range of 2-8 kG (see, e.g., [3, 11, 12, 19]). It is especially interesting that very strong magnetic fields in flares are registered at the levels of the chromosphere and even the lower corona, i.e., where theoretically one can expect (with untwisted power tubes) magnetic fields with a magnitude of only a few tens of gauss. Obviously, there are certain specific mechanisms for maintaining significantly enhanced magnetic fields in a very rarefied atmosphere with low gas and dynamic pressure. It is possible that these mechanisms are related to certain topological features of the corresponding structures, which may be of the force-free type. Solving this problem requires not only further theoretical researches, but also careful analysis of new observational data.

The task of the present work is to test the conclusion that there were no particularly strong magnetic fields in the July 24, 1999, active prominence. This conclusion was made in a recently published paper [25] for this prominence at moment 6:49 UT. However, the spectrum of this prominence was recorded also 11 min later, at 7:00 UT. We investigate this last spectrum using the same technique and using the same spectral line, H-alpha. The corresponding results are briefly presented in our paper.

OBSERVATIONS

The observational material for our study was obtained with the horizontal solar telescope of the Astronomical Observatory of the Taras Shevchenko National University of Kyiv (HST AO KNU). The telescope is equipped with an Echelle spectrograph, a photo-guide, and a spectro-helioscope. Some other peculiarities of this telescope are presented in paper [12].

The main value of observations with the Echelle 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 such observations is that $I + V$ and $I - V$ spectra can be 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.

For spectral order where Hα line is placed (m = 32), spectral resolution (i.e. FWHM) is about 50 mÅ. Spatial resolution of our observations is 1.5-2 Mm. The method of recording spectra is photographic, on WP3 ORWO plates of large size - 18×24 or 24×24 cm. The spectrum of the investigated prominence was recorded with an exposure of 60 seconds. Signal-to-noise ratio for these astro-plates is about 100 in case of normal exposure. In case of prominence under study, exposures were 60 sec. Thanks to such large plates, it is possible to register simultaneously the spectrum of almost the entire visual area with sufficiently high dispersion, 0.4-0.8 Å/mm. If typical CCD matrices to use, it would be possible to simultaneously register only a small part (≈ 1%) of the spectrum that is recorded on photographic plates.

DATA PROCESSING

The spectrograms were scanned using an Epson Perfection V 550 scanner, which allows for obtaining two-dimensional scans of images recorded on transparent films or on photo plates. In order to convert the density into intensity, it is necessary to take into account the characteristic curve of the photographic material as well as the curve of the scanner itself. Both curves are nonlinear and require preliminary determination by special methods. In order to do this, we used a step attenuator, for which transmittances are precisely known. When converting photometrical densities into intensities, the scattered light in the spectrograph was taken into account by subtracting the intensities corresponding to the intervals between images of different orders of the spectrum of the Echelle spectrograph.

During the pre-processing of observational data, spectrum recordings of $I + V$ and $I - V$ profiles in intensities were mutually linked by wavelengths using narrow telluric lines; the accuracy of this binding is about 1-2 mÅ. This ensures the accuracy of measuring the magnetic field along the Hα line at the level of approximately 100 G.

For comfortable data processing, Ivan Yakovkin has developed a convenient computer program 'Profile_manipulator_v0.4', that allows you to quickly process large arrays of observational data. In particular, the program allows you to smooth the observational data with an arbitrary width of the smoothing interval, to average the data over many photometric sections, to find not only parameters I and V but also $dI/d\lambda$ and to estimate the measurement errors of the corresponding quantities.

Scanning made it possible to obtain local values of intensities with a step of about 4 mÅ. We used such very fine spectral discretization in order to reliably eliminate very narrow artifacts associated with small dust particles in the spectrogram. The narrowest artifacts are much narrower than the FWHM of the instrumental profile and are best detected and eliminated precisely at fine discretization. If we had used spectral sampling with a step of 50 mÅ, some artifacts could have gone unnoticed and would have introduced significant distortions to the observational data.

GENERAL APPEARANCE OF THE Hα LINE IN THE SPECTRUM

The image of the Hα line in the spectrum at 7:00 is shown in Fig. 1 together with its image at 6:49 UT according to the paper by Yakovkin and Lozitsky [25]. The wavelength in the spectrum increases from left to right, and the height in the atmosphere increases from bottom to top. Each pair of images refers to the same location on the Sun and moment in time, but to the *I* + *V* and *I* - *V* spectra. The total height of each spectrum in the Figure corresponds to 30 Mm.

From the comparison of these images, it can be seen that at the first moment the emission in the line was wider and it was not stratified in height. In contrast, at the second moment the emission was much narrower and stratified, in particular, it had a noticeably bright and compact core with relatively narrow profiles. This compact nucleus had a small "red" shift in the spectrum of about 0.2 Å, which corresponds to a radial velocity of 9 km/sec. The Figure also shows that above the compact core of the emission, a much wider emission was observed, which had a "blue" asymmetry and a generally blue wavelength shift. As for altitudes in the atmosphere, the compact core corresponded to an altitude range of 11-13 Mm, while the broad asymmetric emission started at an altitude of about 15 Mm.

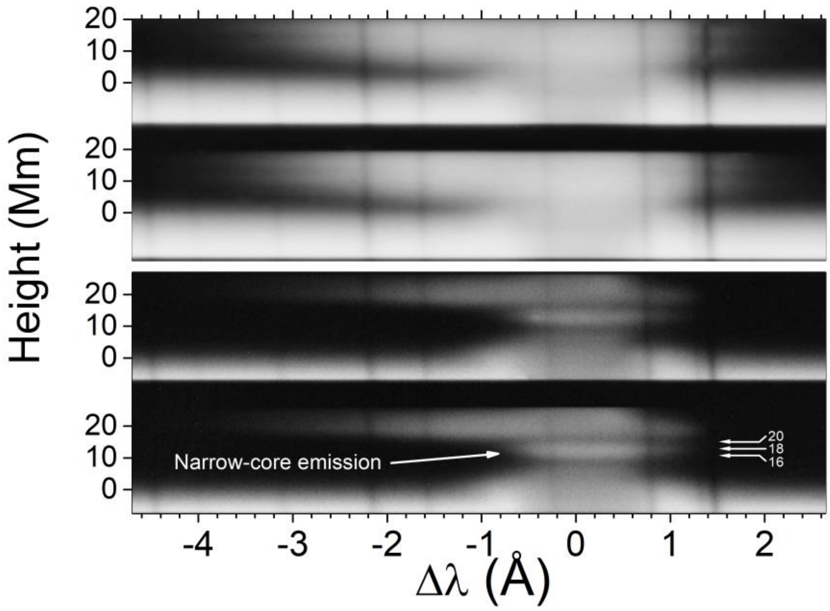

Figure 1. General view of the Hα line in the spectrum of the active prominence on July 07, 1999, for two moments: 6:49 (top two images) and 7:00 UT (bottom two images). Numbers 16, 18 and 20 show the locations of the corresponding photometric sections.

In general, thus, the Hα line at both moments of time has a significantly disturbed appearance, with a noticeable expansion in comparison with the Fraunhofer profiles, in which the width of this line is close to 1 Å. The following question is of interest: in what place of the prominence - in compact core with narrow profiles or in places of broad emission - can the signs of magnetic field inhomogeneity be more obvious? The answer to this question was obtained during a detailed study of *I* ± *V* profiles.

OBSERVED $I \pm V$ PROFILES AND THEIR BISECTORS

In order to search for subtle effects in the spectrum, we found the averaged smoothed values of the intensities by averaging the data in 100 steps, i.e. 400 mÅ, which is approximately 4 times less than the observed emission width of the Hα line even in compact emissive core (Figs. 2 and 3). The effect of such smoothing is presented in Fig. 2, where line profiles before and after smoothing are compared. The location of the smoothed profiles in the Figure is original, while the unsmoothed profiles are artificially shifted along the y-axis by +0.3 for a better comparison of these data. Corresponding bisectors are also shown for smoothed profiles.

From Fig. 2 shows that the specified smoothing significantly clarifies the local differences between $I + V$ and $I - V$ profiles. If all our local measurements were statistically independent, then combining the data for 100 points in the spectrum would increase the signal-to-noise ratio by about 10 times. In fact, since the width of the instrument profile of the spectrograph is 50 mÅ, which corresponds to approximately 12 points on a registragram, only those intensity values that are more than the FWHM of the instrument profile can be considered statistically independent. In this case, the real signal-to-noise ratio increased approximately by the root of 7.7, that is, by 2.8 times.

According to the scanning results, the profiles of the Hα line in the area of the compact nucleus turned out to be quite symmetrical, and their half-width was 1.2-1.3 Å here (Figs. 2 and 3). It was also found that the bisectors of profiles $I \pm V$ have a reliable splitting, and this splitting increases when moving to the tops of the profiles. A similar effect was found earlier in paper by other authors, e.g., [4, 10, 17]. To calibrate this splitting in the values of the magnetic field strength, the following formula was used [25]:

$$\Delta\lambda_H = 2.01\times 10^{-5} B, \quad (1)$$

where $\Delta\lambda_H$ is expressed in Å, and B – in gauss (G).

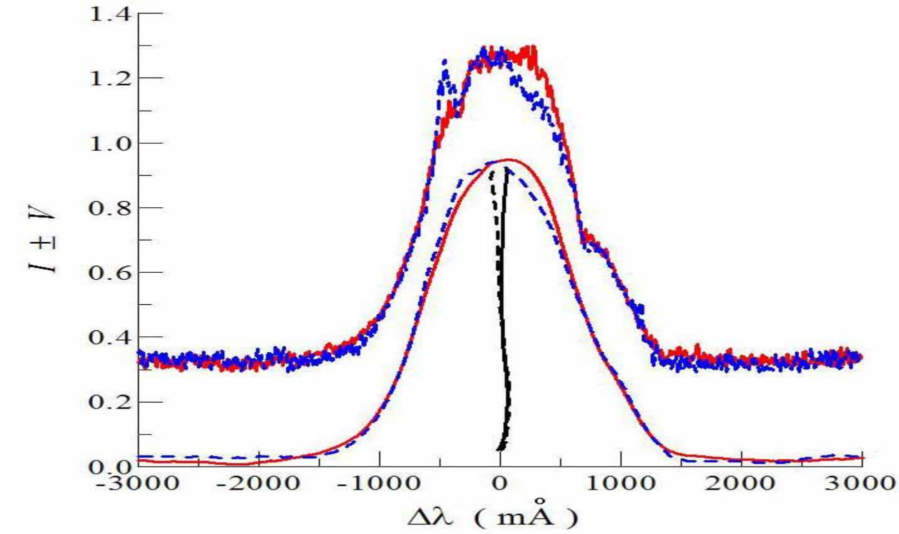

Figure 2. Unsmoothed and smoothed $I \pm V$ profiles of the Hα line in photometric section #18, corresponding to the narrow and bright emission core in Fig. 1. Above the level of the photosphere, this corresponds to a height of about 13 Mm (see text).

From the comparison of the profiles in Figs. 2 and 3, it can be seen that the splitting of the bisectors is observed in both cases, and the magnitude of this splitting is greater in the core of the line than in the wings, reaching 50.4 mÅ and 123.3 mÅ for heights of 11 and 13 Mm, respectively. If we assume that the magnetic field is purely longitudinal, then the Zeeman splitting $\Delta\lambda_H$ should be 2 times smaller, that is, 25.2 and 61.64 mÅ, respectively. Substituting these values into formula (1), we get magnetic field strength of 1250 and 3070 G with measurement errors of ± 100 G. If we assume that the magnetic field is not purely longitudinal, i.e. has a non-zero deviation of the lines of force from the line of sight, then the magnitude of the magnetic field should be even greater.

Thus, the magnetic field in the investigated prominence was sharply heterogeneous, and its value increased with height: in the height interval of 2 Mm, the magnetic field intensity increased sharply by 1820 G. Hence, the height gradient of the magnetic field is approximately equal to 0.9 G/ km, that is, it had typical value for places of solar flares.

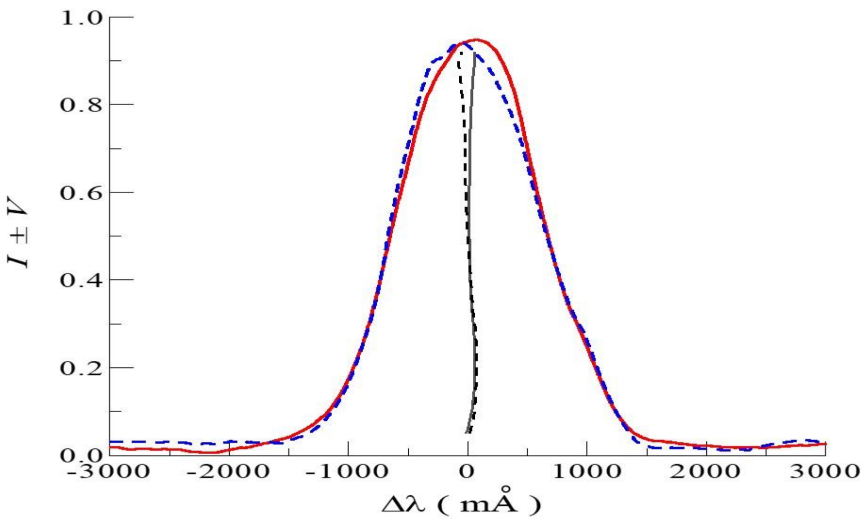

Figure 3. Same as Fig. 2, but for photometric section No. 18, which corresponds to a height of about 13 Mm above the level of the photosphere.

However, the given estimates reflect only the longitudinal component of the magnetic field under the assumption of a filling factor close to unity. In the paper by of Lozitsky et al. [10] it is shown that similar non-parallelism of the bisectors with the largest splitting near the line top can be explained within the framework of a two-component model magnetic field with very strong local magnetic fields in small-scale (spatially unresolved) component. In some cases, it is necessary to assume a non-Gaussian shape of the line profiles, which can be a consequence of the significant optical thickness in the sub-telescopic emission elements of the prominence. According to the calculation for this case, direct measurements of the maximum observed splitting at the intensity level 0.9 (parameter $B_{0.9}$) underestimate the actual local magnetic fields in the prominence by 3–6 times. That is, this means that the splitting of bisectors at the level of 3070 G presented in Fig. 3 may indicate much stronger local magnetic fields, which may even exceed 10 kG.

An even more interesting case was found at a height of 15 Mm, where wider and asymmetric emission in Hα line was observed (Fig. 4). Here there were two bisector splitting maxima - in the core of the line and its far wings. In these places, the maximum splitting of the bisectors corresponds to strengths of 2950 and 3700 G, respectively. Within the framework of the model calculations made in the paper [10], such a case cannot be explained by the two-component structure of the magnetic field: for this, a third component should be added, which gives spectral contributions (i.e., the corresponding Zeeman sigma components) placed on a sufficiently at a great distance from the center of the line, in the range of 1.5-2.5 Å. Substituting these values into formula (1), i.e. assuming that this is exactly what the corresponding Zeeman splitting should be, we obtain field intensities B = (0.75-1.25)$\times 10^5$ G. This value, by an order of magnitude, is in good agreement with the magnetic field strength in a limb flare found by Yakovkin & Lozitsky [25].

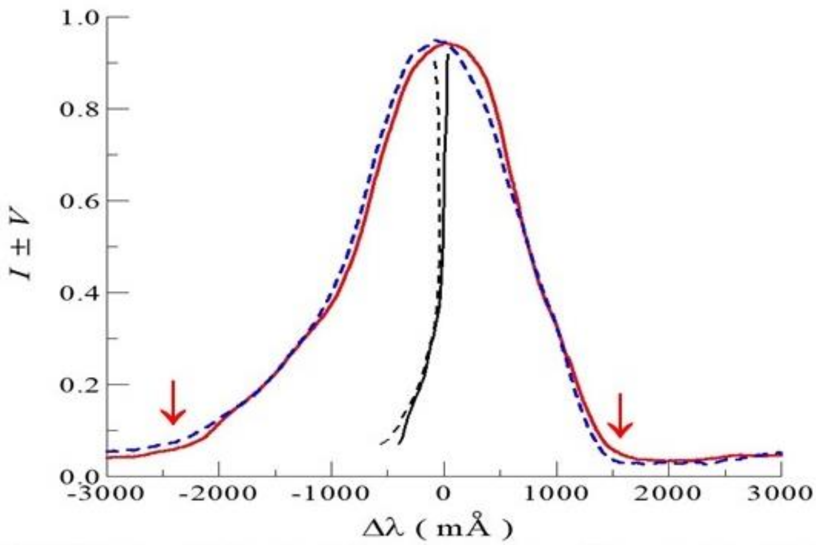

Figure 4. Same as Figures 2 and 3, but for photometric section No. 20, which corresponds to a height of about 15 Mm above the level of the photosphere. The arrows show locations in the far wings of the line that have the opposite sign of circular polarization relative to the line center.

From study of other profiles $I \pm V$ it follows that similar features shown by arrows in Fig. 4, exist with different amplitudes in other photometric sections as well, but not in all of them. In particular, in photometric section No. 22 (that is, at a height of 17 Mm), they are no longer there. This could indicate that such features can be observed in prominences not only at a certain phase of their development, but also in certain places.

DISCUSSION

Cases when the bisectors of the $I \pm V$ profiles have several splitting maxima were noted earlier, moreover, outside the flares and prominences. Probably the first result of this kind was observed in the photosphere of an active region outside the sunspots [13,16]. In these works, in order to reduce the impact of noise due to the graininess of the WP1 ORWO photoemulsion, the data were averaged over a significant area on the Sun - about 35 arc sec, i.e. 25 Mm. The amount of splitting of bisectors from the parameter $\Delta\lambda/g_{eff}\lambda_0^2$ was considered, where $\Delta\lambda$ is the distance from the center of the magnetosensitive line, g_{eff} is its effective Lande factor, λ_0 is its wavelength. When averaging the observational data over many spectral lines (more precisely, on 9 lines of Fe I 5250.2 type with a half-width of about 0.1 Å and on 7 lines of Fe I 5233 type with a half-width of 0.2-0.3 Å), three splitting maxima were detected at the values of the parameter $\Delta\lambda/g_{eff}\,\lambda_0^2$ corresponding to strengths of about 4, 7 and 13 kG. Based on these results, it was first suggested that there is discreteness (a kind of "quantization") of magnetic field strengths in the spatially unresolved structures of magnetic fields of active regions on the Sun. Later, this effect was explained within the framework of the theoretical MHD model of a force-free shielded magnetic element [20] .

When analyzing the observational data of the studied active prominence on July 24, 1999, the observational data was also averaged over a 1 Mm area for each photometric section, but in fact, due to image jitter, the effective linear size of this area was approximately 2 times larger. It is quite likely that small-scale magnetic structures with different magnetic fields and significantly different radial velocities could include on such a large area.

The magnitude of the magnetic field at the level of 10^5 G seems to be much more debatable. The corresponding magnetic pressure is several orders of magnitude greater than the gas and dynamic plasma pressure in the lower solar corona, and therefore such extremely strong magnetic fields cannot theoretically exist in simple untwisted flux tubes [16]. Such extremely strong magnetic fields are likely to exist in some force-free configurations [21], but this issue currently requires further study.

At the end of the discussion, we will indicate the main arguments in favor of the proposed interpretation. Such factors as inhomogeneous structure of prominences including gas pressure, velocity field, and temperature are purely non-magnetic. They do not give polarization in the line profile, therefore, they should not give splitting of bisectors. Significant spatial averaging of the data can only reduce the bisector splitting effect and not generate its significant value. As for the effect of noise growth in the far wings of the line, this issue has been studied in detail in the papers [25, 27]. In addition, it is presented in Fig. 4, the profile difference in the places indicated by arrows is close to 2%. However, when averaging data over 100 points, the level of noise effects should be at least three times smaller, which means that the second maximum of bisector splitting is real. Finally, when constructing the observed profiles, spectral blends - telluric H_2O lines - were carefully taken into account. This was relatively simple, since these blends are very narrow (at least 10 times narrower than the investigated emission of the H-alpha line) and much smaller than it in intensity.

CONCLUSION

The main conclusion of our work is that the investigated active prominence probably had magnetic fields in a wide range of intensities - from 10^3 to 10^5 G. These features were found for the moment 7:00 and for heights in the range of 11-15 Mm above the level of the photosphere, that is, in the lower corona. Comparing this conclusion with the results of paper [25], where the same prominence was studied, but for a different moment, 6:49, it can be assumed that the spectral manifestations of the existence of particularly strong magnetic fields at the level of 10^5 G may be a fairly common phenomenon, which, however, it can be observed only at certain times and in a certain place of active processes on the Sun. The authors think that further research on advanced modeling of the varying thermodynamic and magnetic properties within solar prominences, coupled with high-resolution observational data, is essential for confirming the existence of exceptionally strong magnetic fields or finding possible alternate interpretations.

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REFERENCES

1. Brosius J.W., White S.M. Radio measurements of the height of strong coronal magnetic fields above sunspots at the solar limb // *Astrophys. J.* – 2006. – Vol. 641, L69–L72.

2. Chen B., Shen C., Gary D.E. Reeves K.K. et al. Measurement of magnetic field and relativistic electrons along a solar flare current sheet // *Nature Astronomy***.** – 2020**.** – Vol. 4. – P. 1140-1147**.**

3. Durán C. J.S., Andreas Lagg A., Solanki S.K., Van Noort M. Detection of the strongest magnetic field in a sunspot light bridge // *The Astrophysical Journal*. – 2020. Vol. 895:129 (18pp), // https://doi.org/10.3847/1538-4357/ab83f1

4. Harvey J.W. Chromospheric magnetic field measurements in a flare and an active region filament // *Solar Physics*. - 2012. – Vol. 280, Issue 1. - P.69-81

5. Kleint L. First detection of chromospheric magnetic field changes during an X1-Flare. *Astrophys. J.* – 2017. – Vol. 834, art. id. 26, 10 pp.

6. Koza J., Kuridze D., Heinzel P. et al. Spectral diagnostics of cool flare loops observed by the SST. I. Inversion of the Ca II 8542 Å and Hβ lines // *The Astrophys. J*. – 2019. Vol. 885, article id. 154, 13 pp.

7. Kuckein C., Centeno R., Martínez Pillet V. et al. Magnetic field strength of active region filaments // Astron. And Astrophys. – 2009. – Vol. 501. P. 1113-1121.

8. Kuridze D., Mathioudakis M., Morgan H., Oliver R. et al. Mapping the magnetic field of flare coronal loops // *Astrophys. J*. – 2019. – Vol. 874, art. id. 126, 12 pp.

9. Libbrecht T., de la Cruz Rodriguez J., Danilovic S., Leenaarts J. et al., 2019. Chromospheric condensations and magnetic field in a C3.6-class flare studied via He I D_3 spectro-polarimetry. *Astron. and Astrophys*. – 2019. Vol. 621, id.A35, 21 pp.

10. Lozitsky V., Maslyukh V., Botygina O. Estimates of local magnetic fields in prominences with a large optical thickness in emissive elements // *Bulletin of the Kyiv National University. Astronomy*.– 2015. – Vol. 52. – P. 7 – 11.

11. Lozitsky V., Yurchyshyn V., Ahn K., Wang H. Observations of extremely strong magnetic fields in active region NOAA 12673 using GST magnetic field measurement // *The Astrophysical Journal*. – 2022.- Vol. 928, Iss. 1, id.41, 7 pp. DOI: 10.3847/1538-4357/ac5518
12. Lozitsky V.G. Indications of 8-kilogauss magnetic field existence in the sunspot umbra // *Advances in Space Research*. – 2016. – Vol. 57. – P. 398–407.
13. Lozitsky V.G., 1980. On the calibration of magnetograph measurements taking into account the spatially unresolved inhomogeneties. – 1980. - *Physica Solariterris, Potsdam*. – 1980. - Vol. 14. – P. 88-94.
14. Lozitsky V.G. Superstrong magnetic fields in the solar atmosphere // *Kinematics and Physics of Celestial Bodies*. – 1993. Vol. 9. P. 18-25.
15. Lozitsky V.G. Observational evidences to the 10^5 G magnetic fields in active regions on the Sun // *Journal of Physical Studies*. – 2009. – Vol. 13(2), 2903-1-2903-8.
16. Lozitsky V.G. Small-scale magnetic field diagnostics in solar flares using bisectors of $I \pm V$ profiles // *Advances in Space Research*. – 2015. Vol. 55. - P. 958–967.
17. Lozitsky V.G., Botygina O.A. Comparison of the magnetic fields in active prominences measured from HeI D3 and Hά lines // *Astronomy Letters*. – 2012. – Vol. 38, No. 6. – P. 380–387.
18. Sasikumar Raja K., Venkata Suresh, Singh Jagdev B. Raghavendra Prasad. Solar Coronal Magnetic Fields and Sensitivity Requirements for Spectropolarimetry Channel of VELC Onboard Aditya-L1 // Advances in Space Research. – 2022. Vol. 69. P. 814-822. DOI: 10.1016/j.asr.2021.10.053.
19. Solanki S.K. Sunspots: An overview // *Astronomy and Astrophysics Review*. – 2003. – Vol. 11.- P. 153–286.
20. Solov'ev A. A., Lozitskii, V. G. Force-free model of fine-structure magnetic elements // *Kinematika i Fizika Nebesnykh Tel*. – 1986. - Vol. 2. - P. 80-84.
21. Solov'ev A.A. Force-free magnetic flux ropes: string confinement of super-strong magnetic fields and flare energy release // *Monthly Notices of the Royal Astronomical Society*. - 2022. – Vol. 515, P. 4981-4989.
22. Stenflo J.O. Collapsed, uncollapsed, and hidden magnetic flux on the quiet Sun // *Astronomy & Astrophysics*. – 2011. – Vol. 529, id.A42, 20 pp.
23. Wei Yudian , Chen Bin, Yu Sijie, Wang Haimin, Jing Ju, and Gary Dale E., 2021. Coronal magnetic field measurements along a partially erupting filament in a solar flare // The Astrophys. J. – 2021. Vol. 923:213 (11pp). https://doi.org/10.3847/1538-4357/ac2f99.
24. Xu Z., Lagg A., Solanki S. and Liu Y., 2012. Magnetic fields of an active region filament from full stokes analysis of Si I 1082.7 nm and He I 1083.0 nm // *The Astrophys. J.* – 2012. Vol. 749(2), 138 (11pp).
25. Yakovkin I.I., Lozitsky V.G. Signatures of superstrong magnetic fields in a limb solar flare from observations of the Hα line // *Advances in Space Research.* - 2022. - Vol. 69, Iss. 12. - P. 4408-4418 DOI: https://doi.org/10.1016/j.asr.2022.04.012.

26. Yakovkin I.I., Veronig A.M., Lozitsky V.G. Magnetic field measurements in a limb solar flare by hydrogen, helium and ionized calcium lines // *Advances in Space Research*. – 2021. Vol. 68. P. 1507-1518.
27. Yakovkin I.I., Lozitsky V.G. Search for superstrong magnetic fields in active processes on the Sun using spectro-polarimetry within 15 angstroms around the D3 line *// Monthly Notices of the Royal Astronomical Society*. – 2023, 11p. (published June 20, 2023), DOI: https://doi.org/10.1093/mnras/stad1816