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# MIXED-POLARITY MAGNETIC FIELDS IN THE AREA OF A SEISMIC SOURCE ASSOCIATED WITH A LARGE PROTON SOLAR FLARE

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We found observational evidence of a close contact of strong magnetic fields with opposite magnetic polarities in the area of a seismic source connected with the large proton solar flare of October 28, 2003 of X17.2/4B class. The observations were carried out with the Echelle spectrograph of the Astronomical Observatory of Taras Shevchenko National University of Kyiv. Our analysis is based on the observations of $I \pm V$ profiles of nine spectral FeI lines with different Lande factors and height of formation in the atmosphere. Probably, the magnetic field structure in the flare contained at least two components, namely, the moderate background field of S polarity and spatially unresolved fluxtubes with strong magnetic fields ($\sim 10^3$ G). At the level of the middle photosphere ($h \simeq 300$ km), the magnetic field polarity in fluxtubes was likely N, that is, opposite to the polarity of the background field. This is indicated by the fact that the photospheric lines with the Lande factors in the range $q_{\text{eff}} = 1.0 \div 1.5$ showed smaller measured magnetic fields $B_{\text{eff}}$ than the lines with $q_{\text{eff}} = 2.0 \div 3.0$. In contrast, in the upper photosphere and in the temperature minimum zone, the magnetic polarity in the strong component was S, which follows from the splitting of emission peaks in the Fe I 5269.5 and Fe I 5397.1 lines. This picture was observed on an area of approximately 2.5 Mm$^2$, which corresponds to the spatial resolution of our observations. The semi-empirical model, constructed on the basis of the observations of Fe I 5123.7 and 5434.5 lines, has a unique peculiarity, namely, a very thin layer (40–50 km) in the upper photosphere where the magnetic field reaches 90 kG and has N polarity. Perhaps, such a very heterogeneous magnetic field structure on the photospheric level (sign-changing with height) caused the necessary conditions for the appearance of a seismic source in the solar flare.

**Key words**: Sun, solar activity, solar flares, super-flare of 28 October 2003 of X17.2/4B class, seismic source, solar magnetic fields, mixed-polarity and extremely strong fields, semi-empirical model.

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## I. INTRODUCTION

The solar flare on October 28, 2003 occurred during a sharp rise in solar activity in late October-early November 2003, when several large flares of X class appeared on the Sun. This flare was of X17.2 / 4B class and was studied by many authors, in particular, in articles [1–9], etc. It occurred in active region NOAA 0486, which later, 4 November 2003, produced a solar flare of X28+ class, the most powerful during last 43 years [10]. According to GOES measurements, the flare on October 28, 2003 ranked third in terms of the maximum X-ray flux at $\lambda = 1 - 8$ Å. In this flare, a unique Balmer decrement was recorded in lines H$\alpha$ and H$\beta$, in which the intensity ratio of these lines was equal to $I(\mathrm{H}\beta) I(\mathrm{H}\alpha) = 1.68$, which is unprecedented for all observed solar flares [7]. Also, in this flare, there were three seismic sources that occurred in three different locations in the active region NOAA 0486 [1,4]. The energies of the non-thermal electrons in the flash phase are estimated in the range from $2 \times 10^{32}$ to $6 \times 10^{33}$ erg [8], which corresponds to the upper energy limit for solar flares.

Such extreme manifestations require an explanation from the point of view of modern ideas about the occurrence of solar flares and their energy release. Today, there is no doubt that the energy source of the flares is magnetic fields on the Sun. The flash arises as a result of the magnetic reconnection of magnetic field lines in areas with complex magnetic topology, which includes a close contact of opposite magnetic polarities [11]. It is expected that this reconnection with a powerful energy release occurs mainly in the solar corona and the chromosphere. The role of the photosphere is probably secondary here. Nevertheless, today there is not enough data on whether there are conditions for the magnetic reconnection also at the photosphere level.

According to observations, a very close (spatially unresolved) contact of the magnetic fields of opposite polarity is really possible at the photospheric level. So, for places of an active region outside of sunspots and flares, it was found that magnetically sensitive lines with large Lande factors are expanding much more than it can be expected for sub-kilogauss magnetic fields [12]. This additional expansion is probably caused by magnetic fields of mixed polarity with the strength of up to 1 kG. A similar expansion was also found in solar flares [13]. On the basis of

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the comparison of the half-widths of the Stokes $I$ profiles of FeI 5247.1 and 5250.2 lines it was concluded that the intensity of the background magnetic field was ± 1.05 kG. In the same place, indications of the existence of spatially unresolved magnetic fields with discrete values of 1.3–1.5, 3.9–4.0 and 7.4–7.8 kG were found.

In papers [6,14], it is shown that the characteristic features of the Stokes $V$ profiles of some FeI lines in solar flares (namely, the weaker secondary peaks of the opposite sign, located at great distances from the centers of the lines) indicate a rather strong magnetic field of the kG range, having opposite magnetic polarity. In the first paper, the above-named solar flare on October 28, 2003 was studied, but for the time of 11:13 UT. Evidence was found of a subtelescopic contact of three components of the magnetic field: a background field with the strength of 300 G and S polarity, a small scale field with the strength of 1300–3100 G and the same polarity and another strong component of 8–10 kG and the opposite (N) polarity. Thus, the above results indicate that in areas of solar flares the necessary conditions for a magnetic line reconnection may also exist at the photospheric level.

In this paper, we study the flare on October 28, 2003 at the time of 11:14 UT, when the enter slit of our instrument was projected on the location of one of the seismic sources in this flare. In addition, unlike the previous study of this outbreak, we use more spectral lines with different Lande factors, formation altitude and temperature sensitivity.

## II. OBSERVATIONS AND SELECTED SPECTRAL LINES

The flare of October 28, 2003, occured in the active region NOAA 0486 which on that date was not very far from the disc center, cosine of its heliocentric angle $\mu$ was 0.91. The peak of the H$\alpha$ flare emission was observed in the time interval $11^{\mathrm{h}}00^{\mathrm{m}} - 11^{\mathrm{h}}10^{\mathrm{m}}$ UT [5,9]. Some other parameters of the flare were described above in the Introduction.

The flare was observed with the Echelle spectrograph of the horizontal solar telescope of the Astronomical Observatory of Taras Shevchenko National University of Kyiv [15]. This instrument can record the solar spectrum simultaneously from 3800 to 6600 Å with the spectral resolution of 30 mÅ in the green region and space resolution 1–2 Mm. As it was mentioned above, the spectrum for $11^{\mathrm{h}}14^{\mathrm{m}}$ is studied in the present paper. This spectrum was obtained with a circular polarization analyzer giving simultaneously two spectra $I + V$ and $I - V$ in two different bands for each order of diffraction where $I$ and $V$ are corresponding Stokes $V$ parameters. The spectrogram of the flare was obtained on the ORWO WP3 photo-emulsion and scanned using the MΦ-4 microdensitometer.

Nine spectral lines were selected for analysis (Table). In this Table, wavelength $\lambda$, the equivalent width of a line in the spectra of the quiet Sun, $W$, and the excitation potential of the low term, $EP$, are given according to Moore *et al.* [16]. Effective Lande factors $q_{\mathrm{eff}}$ for the majority of the lines correspond to the laboratory determined values [17] excluding lines Nos. 2, 4 and 6, for which this parameter corresponds to the theoretical case for the $LS$ coupling.

Lines Nos. 1 and 9, according to laboratory measurements, have very small and negative Lande factors. They can be a test for the presence of particularly strong magnetic fields of the range of $10^4$ G in the upper photosphere [18, 19]. Lines Nos. 2–6 are formed in the middle photosphere and have essentially different Lande factors in the range 1.0–3.0. They can be used to diagnose spatially unresolved magnetic fields of the range of $10^3$ G on the basis of the "line ratio" method [20, 21]. The kernels of lines Nos. 7 and 8 are formed in the zone of the upper photosphere and the temperature minimum and can be used to measure the magnetic field near the main energy source of the solar flare.

| No. | Element and number of multiplet | Wavelength $\lambda$ (Å) | Equivalent width $W$ (mÅ) | Excitation potential $EP$ (eV) | Effective Lande factor $q_{\mathrm{eff}}$ |
|---|---|---|---|---|---|
| 1 | FeI — 16 | 5123.723 | 101 | 1.01 | −0.013 |
| 2 | FeI — 843 | 5242.500 | 80 | 3.63 | 1.0 |
| 3 | FeI — 1 | 5247.058 | 59 | 0.09 | 1.998 |
| 4 | CrI — 18 | 5247.574 | 76 | 0.96 | 2.5 |
| 5 | FeI — 1 | 5250.216 | 62 | 0.12 | 2.999 |
| 6 | FeI — 66 | 5250.654 | 104 | 2.20 | 1.5 |
| 7 | FeI — 15 | 5269.54 | 478 | 0.86 | 1.208 |
| 8 | FeI — 15 | 5397.14 | 239 | 0.91 | 1.426 |
| 9 | FeI — 15 | 5434.527 | 184 | 1.01 | −0.014 |

Table. List of spectral lines under study

The region of penumbra of a sunspot in the active region NOAA 0486 was investigated, where, according to [1, 4], one of the seismic sources of the flare existed. According to the autors, the heliographic coordinates of this source are practically the same and correspond to $L = 291.00$ and $\varphi = -16.64$. In one work, this source is denoted as S2, in the another as S3, so we will call it S2/S3 below. As it turned out as a result of the photometry of the spectrogram, the brightest hydrogen emission was precisely here. The ratio of the maximum emission in the nucleus of the $H\beta$, $I_{\max}(H\beta)$, to the intensity of the closest spectral continuum, $I_c$, was as follows: $I_{\max}(H\beta)/I_c \simeq 2.2$. The intensity $I_c$ in the spectral continuum has been reduced here about 2 times.

## III. PROFILES OF LINES AND MAGNETIC FIELDS

The observed $I \pm V$ profiles of lines Nos. 1–6 have Fraunhofer profiles, without emission peaks in their nuclei. This indicates that in the middle photosphere, where these lines are mostly formed, the perturbations of the medium were relatively weak. In contrast, three stronger lines No. 7–9, which belong to the 15th iron multiplet, have strong emission peaks in their cores (Fig. 1).

The difficulty in interpreting such data is that they reflect simultaneously the surface and high-altitude heterogeneity of the magnetic field, as well as thermodynamic effects. In the quiet atmosphere, the core of a Fraunhofer line is formed higher than its wings [22]. Therefore, if the magnetic field is heterogeneous on the surface of the Sun, from the comparison of the splitting of the nucleus and the wings of the line one could estimate the high-altitude magnetic field gradient. To do this, it is convenient to consider the splitting of bisectors in the profiles of the lines, which reflects the value of Zeeman splitting at different distances from the center of the line or at different depths of its profile. In a purely longitudinal and homogeneous magnetic field, when its value is the same at different altitudes, the bisectors of profiles $I+V$ and $I-V$ must be parallel with each other. In fact, observed bisectors of the lines in solar flares may have local splitting maxima, which presumably reflect the surface heterogeneity of the magnetic field [23]. Therefore, as an approximation, the following characteristics of the magnetic field will be used below. By splitting the "centers of gravity" of the Fraunhofer profiles, the value of the effective magnetic field $B_{\text{eff}}$ can be found. In the physical sense, it is close to that which is measured with the solar magnetograph. This is a magnetic field, averaged over the area of the entrance aperture and the height of the formation of the line. If, however, only the emission peaks are extracted in the spectrum, considering for these distances ±100 mÅ from the line centers in Fig. 1, then in this way one can estimate the magnetic field magnitude exactly where these emission peaks are formed, that is, in the upper photosphere.

It turned out that the splitting of emissive peaks corresponds to 1.1 kG for Fe I 5269.5 line, and 1.3 kG for Fe I 5397.1 line with measurement errors of about ±0.1 kG. The polarity of the corresponding magnetic field is S, i.e. the same as at the photospheric level according to the visual measurements in this sunspot by the FeI 5250.2 line. It is also important to note that the splitting of the Fraunhofer wings of these lines also corresponds to the S polarity, and this relates mainly to the middle level of the photosphere.

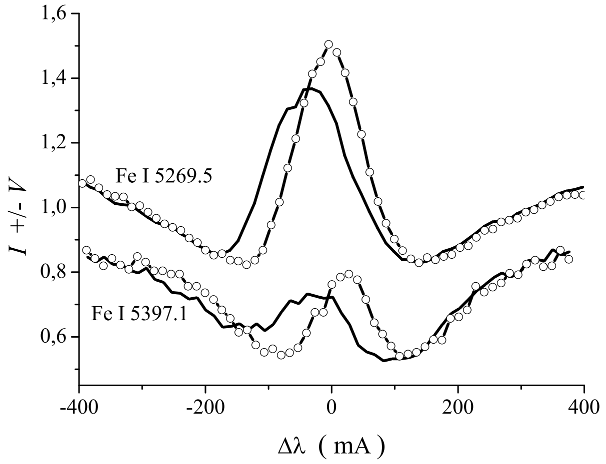

Fig. 1. Observed $I \pm V$ profiles of the Fe I 5269.5 and Fe I 5397.1 lines in solar flare of 2003 October 28 for time 11:14 UT. Position of second line is original, while first line was artificially displaced along vertical axis on 0.4 above for better comparison.

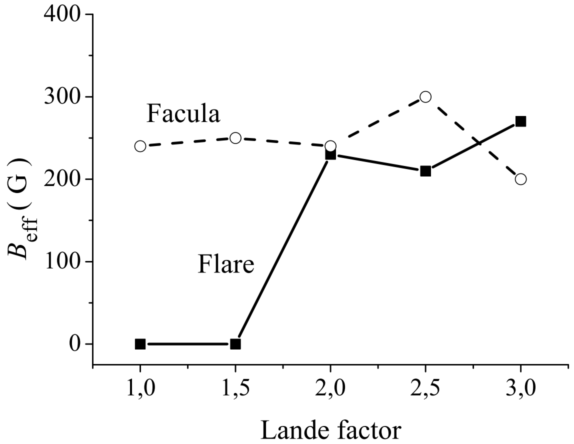

Fig. 2. Comparison of effective magnetic fields $B_{\text{eff}}$ in the solar flare on October 28, 2003 and in the faculae on August 7, 2013, measured using lines with different Lande factors.

From these data, we can conclude that the polarity of the magnetic field in the flare region remained unchanged (S) in the transition from the middle photosphere to the upper photosphere and perhaps the temperature minimum zone. Another conclusion follows from the comparison of the magnitude of the splitting of emission peaks and Fraunhofer wings. From Figure 1 it can be seen that Fraunhofer wings are splitted 2–5 times less than emission peaks, that is, the corresponding splitting equals to fields of 200–500 G. This can be explained by the fact that in the flare there was a two-component magnetic field structure (strong small-scale field + weaker background field). The emission peaks of the lines formed mainly in small-scale (spatially unresolved) flux tubes, while the Fraunhofer sections of the profiles formed both in the flux tubes and in the background field. As a result, this gave a weaker splitting of the Fraunhofer wings of the lines in comparison with the emission peaks.

The two-component magnetic field structure follows also from the comparison of the measurements of the effective magnetic field $B_{\rm eff}$ by lines No. 2–6, which outside the spots are formed in the average photosphere at the altitude of about 300 km [22], but have significantly different Lande factors (Fig. 2). In this comparison, the $B_{\rm eff}$ magnetic field was measured by the splitting of the 'centers of gravity' of $I \pm V$ profiles. The Figure shows an interesting effect: a significant reduction of $B_{\rm eff}$ in the transition from lines with large Lande factors to lines with lower Lande factors. If the magnetic field was one-component and the actual magnetic field in the investigated site did not exceed 300 G, the $B_{\rm eff}$ value for all lines would be the same. However, in reality this is not the case. Such an effect may not be instrumental, because similar measurements in the same lines carried out in the solar facula on August 7, 2013 gave a completely different dependence, namely $B_{\rm eff} \simeq$ const along lines from $q_{\rm eff}$ in the range 1.0–2.0 (error bars are ±60 G for the line with $q_{\rm eff} = 1.5$, and ±30 G for the line with $q_{\rm eff} = 3.0$). This facula was in the tail part of the active region NOAA 1809, which on the day of observation was located not far from the Sun's disc center.

But the most interesting thing here is that in the flare, the spectral lines with $q_{\rm eff}$ in the range 1.0–1.5 show lower values of $B_{\rm eff}$ than the lines with $q_{\rm eff} = 2.0 \div 3.0$. Previously, on the basis of magnetographic and photographic measurements outside the flares, another, inverse dependence was observed, when lines with $q_{\rm eff} = 1.0 \div 1.5$ showed larger measured magnetic fields than lines with $q_{\rm eff} = 2.0 \div 3.0$. [24, 25]. This dependence can be explained by the fact that the structure of the magnetic field is two-component, and the magnetic polarity in spatially unresolved flux tubes with kG fields is the same as the polarity of the background field.

As for solar flares, the dependencies of "$B_{\rm eff} - q_{\rm eff}$", similar to those presented in Fig. 2, were obtained earlier also in papers [13, 26]. Within the framework of a two-component model, such dependencies allow for double interpretation.

First, this can be in the case when masked emission manifestations of the Zeeman effect happen in the flux tubes with a strong magnetic field ($\sim 10^3$ G), similar to the one shown above in Fig. 1 for lines No. 7 and 8. In this case, the emission in the fluxtubes should produce Stokes $V$ of the opposite sign, that should reduce the observed Zeeman splitting and $B_{\rm eff}$ value. Secondly, this can be the case when the flux tubes have in fact pure Fraunhofer profiles, but the magnetic polarity here is opposite to the polarity of the background field. Also in this case, Stokes $V$ from the fluxtubes and background field should have different signs that should reduce the observed $B_{\rm eff}$ value. A detailed consideration of this issue shows that second case is more probable. Indeed, as shown by the visual review of the spectra of the most powerful flares observed with our instrument during last four solar cycles, lines No. 2–6 never have clear emission peaks at flares. Therefore, the emission manifestations of the Zeeman effect in their nuclei are unlikely.

According to this interpretation, magnetic polarities in spatially unresolved fluxtubes and ambient field are different at the level of the middle photosphere. That is magnetic polarity in fluxtubes is N, whereas in ambient field it is S. Comparing this picture with the data by lines Nos. 7 and 8 (Fig. 1), we can conclude that the magnetic polarities in spatially unresolved fluxtubes were different at the levels of the middle and upper photosphere. That is, the magnetic sign inversion existed in a relatively narrow range ($\simeq 200 - 300$ km) of the solar photosphere in the area of the seismic source of the flare. To the author's best knowlege of literary sources, this is the case for the first time.

## IV. A SEMI-EMPIRICAL MODEL

For build a semi-empirical model of the photospheric layers of the flare, we used observations of 'non-split' Fe I 5123.7 and 5434.5 lines and a computer program which is an independent implementation of the algorithms in the PANDORA code published by Avrett & Loeser [27]. This program was created by E. A. Baranovsky (with the help by place E. Malanushenko) and it allows to determining the magnetic field and thermodynamical conditions on the both photospheric and chromospheric levels using non-LTE approximation. The PANDORA code, in its application, is similar to the SIR code [28] and the inverse code by Stodilka [29], which uses Tikhonov's stabilizers to solve the inverse radiation transfer problem.

The semi-empirical model was built by trial and error. A large number of theoretical line profiles were calculated for various distributions with the height of the magnetic field and thermodynamic parameters and such altitude distributions were selected as the most likely that gave the best agreement of the simulations and observations.

Figure 3 illustrates the best result of the modeling for the Fe I 5434.5 line versus observations in the frame of a one-component model. As for the observations, it can be seen from the Figure that the splitted emission peak in the line is localized in the range of approximately $-100 \leq \Delta\lambda \leq +70\,$mÅ, i.e. it has a noticeable "violet" displacement, corresponding to the plasma lifting with the velocity of about 1.8 km/s. The observed emission peaks in the line core are asymmetric, however, if the bisectors of these peaks are carried out (they are shown in the figure with almost vertical intervals), they turn out to be almost parallel, and their splitting corresponds to about 20 mÅ.

It can be seen that the calculated line profiles are in satisfactory agreement with those observed, in particular, in terms of the intensity of emission peaks and their splitting. True, the Fraunhofer wings of the line are narrower in the model than those observed. For example, at the intensity level of 0.8, the observed profile is approximately 40% wider than the one according to the model. This may mean that the temperature in the lower layers of the model is somewhat overestimated compared to the real one.

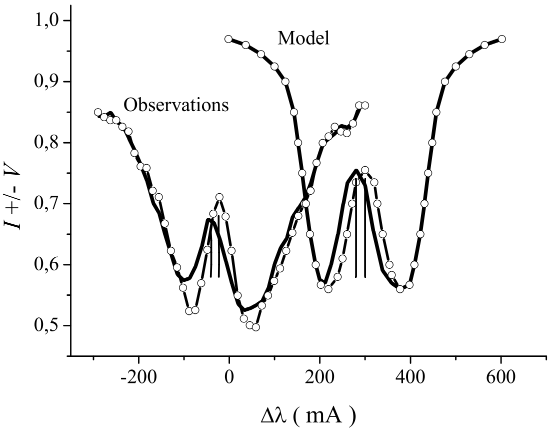

Fig. 3. Comparison of the observed and theoretical $I \pm V$ profiles of Fe I 5434.5 line in the flare under study. For a better comparison of these profiles, the theoretical profiles were artificially shifted by +300 mÅ.

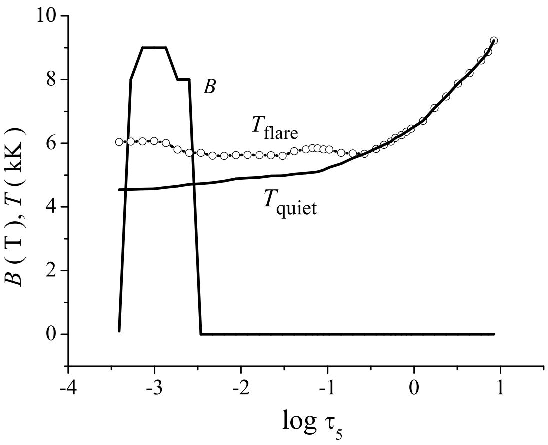

Fig. 4. The distribution of the magnetic field $B$ and the temperature $T$ with an optical thickness of $\tau_5$ in the flare. For a better comparison of these data, the magnetic field is presented in tesla (T), and the temperature — in kilo-quelvines (kK). $T_{\rm flare}$ and $T_{\rm quiet}$ are temperatures in the flare and quiet atmosphere [30].

In the semi-empirical model, the magnetic field has a remarkable feature, namely, a very narrow and high peak of the magnetic field in the range of $-3.3 \le \log\tau_5 \le -2.5$ (Fig. 4) where $\tau_5$ is the optical thickness in the continuum at the wavelength of 5000Å. The geometrical thickness of this layer corresponds to 40–50 km. Here, the magnetic field reaches $9T = 90\,$kG, which is about 2 times more than according to the direct measurements of bisector splitting. For $\log\tau_5 \ge -2.5$, the magnetic field is close to zero, which reflects the fact that there is no observed splitting in line Fe I 5123.7, which is formed, in general, lower than line Fe I 5434.5. Notice, the magnetic polarity of this superstrong field is N, i.e. opposite to that by lines Nos. 7 and 8.

As for the temperature in the flare, $T_{\rm flare}$, it is increased essentially (by about 500–1500 K) for all values of $\log\tau_5 \le -0.5$, although the maximum difference between $T_{\rm flare}$ and $T_{\rm quiet}$ is observed precisely in the range of the maximum magnetic field.

## V. SUMMARY AND DISCUSSION

The main conclusion of our study is that a close contact of strong magnetic fields of opposite polarities existed in the area of the seismic source of the powerful proton solar flare on October 28, 2003 of X17.2/4B class. This picture was observed on an area of approximately 2.5 Mm$^2$, which corresponds to the spatial resolution of our observations. Observational evidences was obtained that the structure of the magnetic field contained at least two components, namely, the background field of S polarity and spatially unresolved flux tubes with a strong magnetic field ($\sim 10^3\,$G). At the level of the middle photosphere ($h \simeq 300\,$km), the polarity of the magnetic field in the tubes was N, that is, opposite to the polarity of the background field. This is indicated by the fact that the photospheric lines with the Lande factors in the range $g_{\rm eff} = 1.0 \div 1.5$ showed lower measured $B_{\rm eff}$ magnetic fields than the lines with $g_{\rm eff} = 2.0 \div 3.0$ (Fig. 2). In contrast, in the upper photosphere and in the temperature minimum zone, the polarity of the magnetic field in the strong component was S, which follows from the splitting of emission peaks in the Fe I 5269.5 and Fe I 5397.1 lines (Fig. 1). The semi-empirical model, constructed by the observations of Fe I 5123.7 and 5434.5 lines, has a unique peculiarity, namely a superstrong magnetic field about 90 kG, concentrated in a very thin layer (40–50 km) of the upper photosphere (Fig. 4). Its polarity is N, that is, it is opposite to the polarity of the magnetic field in the kilogauss component at the same level of the atmosphere.

The obtained data indicate that in the region of the seismic source S2/S3 of the studied flare, the polarity of the magnetic field in a strong component sharply changed its sign not only in the horizontal direction but also vertically in a relatively thin layer of the solar photosphere ($\simeq 200 - 300\,$km). This may indicate that the strong component was not concentrated in long magnetic tubes, but in thin layers (sheets) or quasi-spherical structures. This assumption is consistent with the semiempirical model in which an extremely strong field is localized in a narrow height range. Such a structure of a magnetic field, with a close contact of strong magnetic fields of opposite polarities, appears to be potentially capable of a magnetic reconnection of the field lines in the form of a solar flare. Perhaps, it is precisely this change-altitude magnetic structure on the photosphere level (and not in the chromosphere and the corona) that was the reason for the origin of a seismic source in the solar flare.

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## МАГНІТНІ ПОЛЯ ЗМІШАНОЇ ПОЛЯРНОСТІ В ЗОНІ СЕЙСМІЧНОГО ДЖЕРЕЛА, ПОВ'ЯЗАНОГО З ВЕЛИКИМ ПРОТОННИМ СОНЯЧНИМ СПАЛАХОМ

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Ми виявили спостережні свідчення того, що в зоні сейсмічного джерела S2/S3 сонячного спалаху балу X17.2/4B28 жовтня 2003 р. був тісний контакт магнітних полів не лише різної напруженості, але й магнітної полярності. Таку картину спостерігали на площі приблизно 2.5 Мм$^2$, що відповідає просторовому розділенню наших спостережень. Ймовірно, структура магнітного поля у спалаху містила як мінімум дві компоненти, а саме, фонове поле S полярності і просторово нероздільні силові трубки з сильним магнітним полем ($\sim 10^3$ Гс). На рівні середньої фотосфери ($h \simeq 300$ км) полярність магнітного поля в силових трубках була

$N$, тобто протилежна до полярності фонового поля. На це вказує те, що фотосферні лінії з факторами Ланде в діапазоні $q_{\mathrm{eff}} = 1.0 \div 1.5$ показували менші виміряні магнітні поля $B_{\mathrm{eff}}$, ніж лінії з $g_{\mathrm{eff}} = 2.0 \div 3.0$. На противагу цьому, у верхній фотосфері і зоні температурного мінімуму полярність магнітного поля в сильній компоненті була $S$, що випливає з розщеплення емісійних піків в лініях Fe I 5269.5 and Fe I 5397.1. Напівемпірична модель, побудована за лініями Fe I 5123.7 і 5434.5, має надсильне магнітне поле близько 90 кГс полярності N, зосереджене у дуже тонкому шарі (40–50 км) верхньої фотосфері. Можливо, саме така дуже неоднорідна (знакозмінна з висотою) структура магнітного поля на фотосферному рівні (а не в хромосфері і короні) зумовила виникнення сейсмічного джерела у сонячному спалаху.