Unique spectral manifestations around the D3 line observed in the region close to the seismic source of a large solar flare

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Unique spectral manifestations around the D3 line observed in the region close to the seismic source of a large solar flare

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ABSTRACT
The main goal of our research is to search for super-strong magnetic fields in active processes on the Sun. Our method is based on Stokes *V* spectro-polarimetry in a wide spectral range from –14 Å to +29 Å relative to the D3 He I line. The object of the study is the area of a seismic source in the large solar flare on October 28, 2003 of the X17.2/4B class. The novelty of our study: we found characteristic spectral manifestations – secondary Stokes *V* peaks – far from D3 line, at distances of several angstroms. These secondary peaks have the following features: (a) their amplitudes reach 4% – almost an order of magnitude more than previously detected in other flares, (b) in the general picture, the sign of the circular polarization changes when passing through the D3 center, and (c) narrower spectral peculiarities were found at distances of +4.0, +6.3, and +8.5 Å, where the polarization sign also changes sharply. This unusual feature likely results from significant factors in the area of the seismic source, including substantial descending plasma velocities which exceed 400 km s^{-1} and, perhaps, super-strong magnetic fields.

Key words: magnetic fields, Sun: activity, Sun: flares, Sun: magnetic fields.

1. INTRODUCTION

The solar flare on October 28, 2003 of the X17.2 / 4B class was one of the most powerful – it ranks third in the list of such flares according to the criterion of peak X-ray power recorded by the GOES detectors since 1976. Three seismic sources have been detected in this flare according to Kosovichev (2006) and Zharkova & Zharkov (2007). Notably, seismic sources are among the least studied phenomena accompanying the energy release of solar flares. Possible sources of energy include magnetic fields and beams of electrons and protons. Given this, it is important to obtain new observational data on magnetic fields and plasma velocities in the region of seismic sources of flares.

This flare was studied by many authors, for example, Kiener et al. (2006), Mandrini et al. (2006), Maurya & Ambastha (2008), and others. Lozitsky et al. (2018) found that this flare had a unique Balmer decrement, with the record ratio $I(H\beta) / I(H\alpha) = 1.68$ of $H\beta$ and $H\alpha$ intensities, a ratio unprecedented in observed flares. According to a semi-empirical chromosphere model, three discrete layers with a high density (up to $n_H = 10^{18}$ cm^{-3}) were found in this flare.

The flare on October 28, 2003 is also interesting from the perspective of the possible existence of particularly strong magnetic fields in it. Currently, there are very different estimates of local magnetic fields in solar flares – from 10^2 to 10^5 G (see, e.g., Harvey, 2012; Kleint, 2017; Libbrecht et al., 2019; Yakovkin and Lozitsky, 2022; 2023).

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The main goal of our study is to search for characteristic polarization effects in a large interval of –14 Å to +29 Å around the D3 line, which may indicate extremely strong magnetic fields. Such polarization effects were previously reported in far wings of the D3 line by Yakovkin and Lozitsky (2023) for the 2004 July 12 active prominence and the 2014 June 10 limb flare of X1.5 class, where a spectral interval of ±15 Å around the D3 line was studied.

2. OBSERVATIONS AND DATA PROCESSING

Observations of the flare were carried out with the Echelle spectrograph of the horizontal solar telescope of the Astronomical Observatory of Taras Shevchenko National University of Kyiv (HST AO KNU). Observers were Natalia Lozitska and Vsevolod Lozitsky. Some details of this instrument and features of observations were described in paper by Lozitsky et al. (2018) and Yakovkin and Lozitsky (2023). The main advantage of observations with this 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.

In this study, we investigate aforementioned flare at 11:15 UT, which has not been studied yet using Zeeman spectrograms obtained with HST AO KNU. Our results correspond to the S2/S3 seismic source region according to Kosovichev (2006) and Zharkova & Zharkov (2007). This source was in the area of sunspot penumbra of *S* magnetic polarity (Fig. 1).

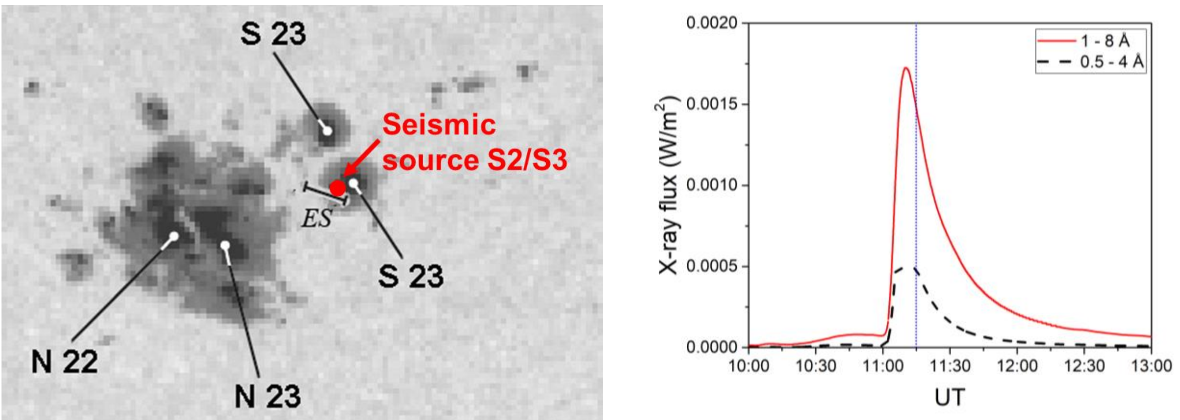

Figure 1. General appearance of the active region NOAA 0486 in spectral continuum from SOHO, and GOES X-ray flux.

In this Figure, position of the entrance slit of the spectrograph of AO KNU is marked with the *ES* interval, and the location of the seismic source is marked with a red circle. The results of visual measurements of the magnetic field in spots are also given (in hundreds of gauss) and their magnetic polarities performed in the Fe I 5250.2 line. The panel on the right shows the changes in the X-ray flux according to the GOES 12 data from NOAA/NWS Space Weather Prediction Center. The moment 11:15 is marked with a blue vertical line. This moment is close to the X-ray maximum, with 1 – 8 Å flux being at 85% of its maximum, and the 0.5 – 4 Å flux still at its maximum value.

In order to obtain quantitative information on intensity distribution in spectra of the flare, the spectrogram for 11:15 UT was scanned using an Epson Perfection V 550 scanner. The method of processing of such scanograms for obtaining scientific information was described in detail in the paper by Yakovkin and Lozitsky (2023).

3. RESULTS AND SHORT DISCUSSION

The observational data obtained are presented in Figs. 2 – 4. Fig. 2 presents Stokes the *I* profiles at different locations along the spectrograph entrance slit, with a slight data averaging within a spectral interval of about 100 mÅ. In this Figure, the numbers of photometric sections correspond to the distances in mega-meters (Mm) from the left boundary of the entrance slit in Fig. 1. The profiles are artificially shifted vertically for a clearer presentation. The photometric section No.18 (marked as S18) is the closest to the location of the seismic source. In this section, the emission in the D3 line was quite significant, reaching a value of 4.6 in the units of the spectral continuum intensity. However, the emission in photometric section S15 was even stronger, with the D3 emission reaching the level of 5.3 units. Compared to these strong effects in D3 line, the emission in D2 and D1 lines was much weaker and reached only up to 1.7 units. The corresponding emission peaks can be seen in Fig. 2 at Δλ = +14.37 Å and +20.33 Å, respectively.

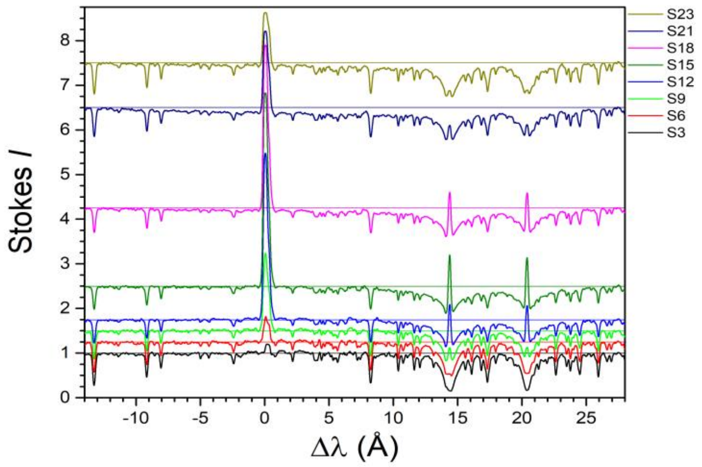

Figure 2. Stokes *I* profiles in different photometrical sections of the studied flare. The section No.18 is located the closest to the seismic source.

From the investigation of the *I* ± *V* profiles of D3 line we found that the centroid splitting of spectral peaks in locations of strong emission corresponds to B_{LOS} =1–1.5 kG. The corresponding Stokes *V* profiles, generally, have a characteristic anti-symmetric shape and are confined in the interval about ± 1 Å. (Fig. 3). However, it is notable that in addition to these primary peaks of the Stokes *V*, a few secondary peaks far beyond the specified interval are also observed. The secondary Stokes *V* peaks have the form of relatively narrow spikes, significantly red-shifted by 4–9 Å relative to the primary emission in the D3 line. As can be seen from Fig. 3, the location of these secondary peaks in the spectrum practically remains constant within the sections separated by a fairly large distance, up to 3–9 Mm. Given this circumstance, it makes sense to average the data over several photometric sections to build a general picture of the observed effects.

For more reliable detection of these secondary peaks, the observational data were averaged over intervals of 384 mÅ to further reduce the noise effects of the graininess of the WP3 ORWO photo-emulsion. The resulting Stokes *V* profiles reach the level of 4–5%, which clearly exceeds the measurement errors of around 1% (Fig. 4). The blue curve represents the distribution of the Stokes *V*, and the red curve represents changes in the d*I*/dλ parameter, indicating the expected changes in the spectrum in the weak-field approximation. Here, beyond the primary peaks in the

D3 line (that is, beyond approximately ± 1 Å), a complex pattern of secondary peaks is observed, which has following main features:

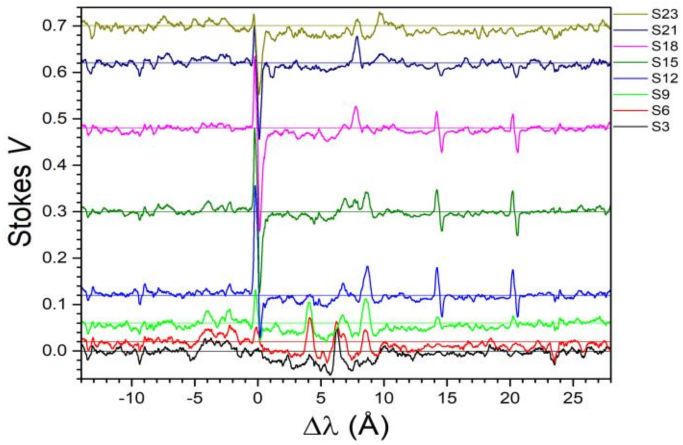

Figure 3. Stokes *V* profiles in different photometrical sections of the flare under study.

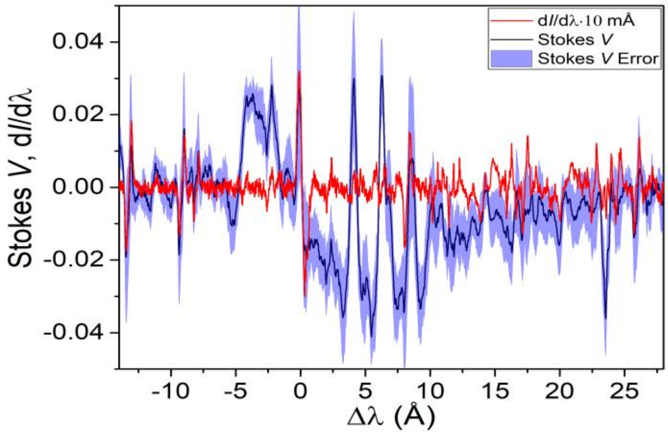

Figure 4. Stokes *V* and d*I*/dλ parameters in the studied flare for averaging interval 6 Mm starting from the photometrical section No.3.

(a) the distribution of the parameter *V* changes its sign when passing through the center of the D3 line (Δλ = 0). There is a definite similarity to the effect reported by Yakovkin and Lozitsky (2023) for a different, less powerful solar flare. However, significant differences include (i) a much larger amplitude of secondary peaks, which reaches 4% for the flare we studied, while in the referenced article this amplitude was only 0.5%, (ii) a significantly larger width of these secondary peaks – about 3 – 8 Å in the studied flare, compared to 1.5 – 2.4 Å for the limb flare studied in Yakovkin and Lozitsky (2023), (iii) the positive "blue" peak has a much smaller area (≈ 2.5 times) than the negative "red" peak;

(b) against the background of a broad secondary peak in the distance range Δλ = +1 to +10 Å, several narrower secondary peaks (with FWHM ≈ 0.6 Å) are also observed at different distances from D3, in particular at +4.0, +6.3, and +8.5 Å.

Such complex pattern probably reflects at least two effects: Zeeman and Doppler ones. If we assume that feature (a) directly reflects the full magnetic splitting (strong field regime), this would imply a huge Zeeman splitting, about 5 Å. Such splitting, according to calculations using the HAZEL code (Asensio Ramos et al., 2008), corresponds to a magnetic field of 10^5 G range. However, presented in Figs. 3 and 4 profiles of Stokes *V*, unlike those obtained by Yakovkin and

Lozitsky (2022, 2023), have the above-mentioned essential point (iii): the unequal area of positive and negative peaks to the right and to the left of the line center. If the emission in the line is optically thin, this should not be the case with the Zeeman and Paschen-Back effects. Therefore, in this study, we do not insist on the presence of such particularly strong magnetic fields. On the other hand, it is impossible to explain the change of the sign of the Stokes *V* when passing through the center of the line solely by the Doppler effect, since it does not provide polarization in the spectral line on its own.

As for the Doppler effect, it can be indicated by the feature (b). It seems that the narrow peaks at +4.0, +6.3, and +8.5 Å represent spectral features strongly shifted relative to the center of the D3 line, which can be either peaks of the same sign of circular polarization, or pairs of peaks with an alternating sign, typical of the Zeeman and Paschen-Back effects. Both these cases indicate significant plasma descent velocities in the range of 200 – 435 km s^{-1}. However, the maximum velocities of the plasma can be even higher if the secondary negative peak at $\Delta\lambda$ = +23.5 Å is related to the D3 line. Then the corresponding speed could be even $\approx$ 1200 km s^{-1}. Clearly, this topic requires additional investigation.

4. CONCLUSION

Our observational data highlight the perspective of studying broad spectral intervals (several angstroms or more) around selected magneto-sensitive lines to obtain new, crucial information about active processes on the Sun. Regarding the extremely powerful solar flare of October 28, 2003, classified as X17.2/4B, we identified an unusual shape of the Stokes *V* profiles of the D3 He I line in the region close to the seismic source. This unusual shape likely results from significant factors in the area of the seismic source, including substantial descending plasma velocities which exceed 400 km s^{-1} and, perhaps, super-strong magnetic fields.

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DATA AVAILABILITY

The original contribution presented in the study are included in the article.

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