OSCIILLATIONS ACCOMPANYING A HE I 10830 Å NEGATIVE FLARE IN A SOLAR FACULA II. RESPONSE OF THE TRANSITION REGION AND CORONA

NIKOLAI KOBANOV¹ AND ANDREI CHELPANOVA¹

¹Institute of Solar-Terrestrial Physics of Siberian Branch of Russian Academy of Sciences, Irkutsk, Russia

ABSTRACT

We studied oscillations related to flare SOL2012-09-21T02:19 in the transition region and chromosphere based on Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) and Solar Dynamics Observatory (SDO) data, as well as data from the ground-based Horizontal Solar Telescope. We found that 2-minute oscillations triggered by the flare first appeared in the RHESSI channels then subsequently showed up in the SDO 171 Å and 304 Å channels and after that in the chromospheric HeI 10830 Å line. The delay of the chromospheric signal compared to the RHESSI signal is 7 minutes, which indicates that the wave perturbation propagated from the corona to the chromosphere. We used the sharp increase in 3- and 5-minute oscillations during the flare in the lower atmosphere to trace the propagation of the oscillation trains to the transition region and corona. The results show that the 171 Å channel signals lagged behind the photospheric and chromospheric signals by 200 s on average. We suggest that we observed slow magnetoacoustic waves both in the case of 2-minute oscillations propagating downwards from the corona and in the case of 3- and 5-minute oscillations leaking to the corona from beneath.

Corresponding author: A.A. Chelpanov
chelpanov@iszf.irk.ru
1. INTRODUCTION

In the recent decades, quasi-periodic pulsations (QPPs) in solar flares became the subject for many studies of different ranges in the electromagnetic spectrum (Aschwanden 1987; Grechnev, White, and Kundu 2003; Kislyakov et al. 2006; Sych et al. 2009; Nakariakov and Melnikov 2009; Kupriyanova et al. 2010; Nakariakov et al. 2016; Inglis et al. 2016; Kupriyanova et al. 2019). Pugh et al. (2017); Dominique et al. (2018) showed the difficulties in revealing QPPs and proposed algorithms to improve their identification in flare time series. McLaughlin et al. (2018) discussed the problems of QPP modelling.

In the preceding article (Chelpanov and Kobanov 2018), hereafter Article I, we analysed the influence of the small-scale flare on the oscillations in the lower atmosphere of a facula. We showed that small flare SOL2012-09-21T02:19 that we identified as a negative flare due to a sharp increase in the HeI 10830 Å line absorption caused a deep modulation of the oscillation regime from the photosphere to the upper chromosphere. This impact was registered in the magnetic field strength, Doppler velocity, intensity, and line profile half-widths. This influence notably differed (up to the modulation sign) in different parts of the facula region.

The question of how the flare influenced the oscillation characteristics in the upper solar atmosphere was left out of the subject matter in Article I.

The aim of this article is to study the transition region and coronal oscillations related to the flare as well as to try to detect wave disturbances propagating both from the corona to the chromosphere and in the reverse direction. Note that our measurement capabilities drastically decreased compared to the lower atmospheric layers. In the transition region and corona, we can detect the oscillation and wave processes mostly based on the intensity variations in the Atmospheric Imaging Assembly (AIA) signals.

2. INSTRUMENT AND METHODS

To study flare SOL2012-09-21T02:19, we used the data from the Horizontal Solar Telescope (HST, Kobanov 2001; Kobanov, Chelpanov, and Kolobov 2013) at the Sayan Solar Observatory, the Solar Dynamics Observatory (SDO, Pesnell, Thompson, and Chamberlin 2012), and the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI, Lin et al. 2002).

The spectral observations of the SiI 10827 Å and HeI 10830 Å lines were carried out with the HST. The telescope is built at the height of 2000 m above sea level. It is equipped with a 900-mm main mirror. The focal length of the mirror is 20 m. A photoelectric guiding system stably positions an observed object with an accuracy of under 1″. The 6-meter spectrograph allows to measure line-of-sight (LOS) velocity, intensities, line-widths, and magnetic fields at a wide variety of spectral lines in the visible and infrared ranges (Kobanov, Chelpanov, and Kolobov 2013). The spectrograph is equipped with two mirror systems, which allows to record the spectral line characteristics in two different parts of the spectrum. The slit of the spectrograph comprises 65″ on the solar surface. The spectral resolution is 10 mÅ per pixel on average. The time cadence of the series is 1.5 seconds.

The description of the telescope equipment and measurement methods can be found in articles Kobanov (1990, 2001).

The Atmospheric Imaging Assembly (AIA, Lemen et al. 2012) on board SDO continuously provides full-disk images in EUV channels with a 12-second cadence and UV channels with a 24-second cadence. The pixel size of the AIA images corresponds to 0.6″. We also used the X-ray flux recorded by the RHESSI.

The HST LOS velocity signals were restored using the lambdameter technique (Rayrole 1967; Kobanov, Chelpanov, and Pulyaev 2018). The accuracy of the LOS velocity signal is 20 m s⁻¹. The line intensities were normalized to the adjacent continuum intensities in order to compensate for the atmospheric weather condition changes. We applied the Fast Fourier Transform Interactive Data Language (IDL) algorithm to analyse the oscillation spectra of the signals. In order to avoid edge artifacts, we used the bell-shaped window function to 0.1 series length at each end of the signals. The signals were filtered in the given frequency ranges using the Morlet wavelet of the sixth order. To corroborate the presence of the 2-minute variations in the signals, we used the Empirical Mode Decomposition (EMD) technique (Kolotkov, Anfinogentov, and Nakariakov 2016).

3. RESULTS

We analysed oscillations in the transition region and corona directly above the negative flare location. To do this, we use the SDO/AIA 304 Å, 171 Å channels along with the RHESSI 3–6 keV and 6–12 keV channels—the two channels, whose intensity increased during the flare. The AIA channel signals were averaged over a 3″ by 3″ area in order to minimize possible projection effects.

3.1. Propagation of the Flare-Related QPPs from the Corona to the Chromosphere

QPPs with a period close to two minutes were registered simultaneously in the 3–6 keV and 6–12 keV
Oscillations Accompanying a Negative Flare II

RHESSI channels, which supports the solar origin of these pulsations (Figure 1). The two-minute period also increases during the flare in the wavelet-filtered series and in the EMD mode, whose period is close to 2 minutes.

Note that oscillations with the 3- and 5-minute periods are more typical of the underlying photosphere and chromosphere, and the 2-minute period is observed rarely, if at all, in faculae. In such circumstances, the presence of the oscillations with a 2-minute period in the lower layers can confidently indicate that the oscillations triggered by the flare propagate from the corona to the chromosphere.

The AIA 171 Å and 304 Å channel signals, as well as the He I 10830 Å spectral data support the fact that 2-minute oscillations propagate downwards from the corona to the lower layers. Figure 2 clearly shows that the signals of the lower levels lag behind those of the upper ones. The centers of the wave trains gradually shift from 02:15 in the RHESSI signal to 02:22 in the He I 10830 Å line signal. The wave train in the 171 Å channel follows 180±20 s after the wave train in the RHESSI data, and 180±25 s after that it appears in the 304 Å channel. The center of the main wave train in the He I 10830 Å line lags 60±15 s behind that of the 304 Å channel.

The signals that we measure at different levels are averaged over 3″ by 3″ areas, whose centers are aligned perpendicular to the solar surface. In order to examine whether the signal diverted from the vertical propagation at the 304 Å level, we measured the signals in four similar areas displaced in different direction by 3.6″ from the original location. The amplitude of the signals in these areas was 4–5 times lower. In our opinion, this indicates that we measured the signals in the main propagation channel of the studied waves. Thus, at the transition region—chromosphere—photosphere height range this channel is close to vertical.

In addition, earlier in the analysis of this flare, Chelpanov and Kobanov (2018) showed that the velocity of the perturbation propagation was 70 km s⁻¹ in the image plane at the 171 Å level.

3.2. Penetration of the Photospheric 5-minute and Chromospheric 3-minute Oscillations to the Corona

As Article I showed, the amplitudes of 3- and 5-minute chromospheric oscillations drastically increased during the flare. The signals look as increased amplitude oscil-
lation trains, which appeared simultaneously with the flare. Such a train structure of the signals serves as a useful means to study propagating oscillations in the solar atmosphere. Note that in the absence of flare perturbations, intrinsic oscillations of these periods, though with lower amplitudes, may occur continuously in both active and quiet regions. In this case, however, estimates of the phase relations in the propagating signals show more ambiguity. While the direct phase lag measurements can be straightforwardly carried out at the lower levels, this poses difficulties in the transition region and corona (Krishna Prasad, Jess, and Khomenko 2015; Zhao et al. 2016). Krishna Prasad, Jess, and Khomenko (2015) demonstrated a signal amplitude modulation, which helped them trace the propagation of p-modes from the photosphere to the corona in a form of slow magnetoacoustic waves.

Figure 3b shows 5-minute oscillations in the LOS velocity signals of the Si \textsc{i} 10827 Å (temperature minimum) and He \textsc{i} 10830 Å (upper chromosphere) lines. The chromospheric oscillation train follows the photospheric one 60 s later on average. As seen in Figure 3b, the phase difference notably decreases by the end of the oscillation train. This might be due to the change in the oscillation regime from the running acoustic waves to standing waves in the upper photosphere. Figure 2b in Article I supports this explanation: the phase shift between the intensity and LOS velocity oscillations of the Si \textsc{i} 10827 Å line changes from 180° to 90° by the end of the flare. The oscillation train of the AIA 304 Å channel (Figure 3a) almost coincides with that of the He \textsc{i} line in panel b. In turn, 5-minute oscillations in the 171 Å channel lag behind those in the 304 Å by approximately 100 s. These time relations indicate that 5-minute oscillations propagated from the facular photosphere through the chromosphere and transition region to the lower corona.

The 3-minute oscillation trains in the 304 Å and 171 Å channels lag behind the chromospheric oscillations in the He \textsc{i} line by 120±20 and 200±28 s, respectively (Figure 4). As in the case of 5-minute oscillations, this clearly indicates that 3-minute oscillations propagate from the chromosphere to the corona.

In this article, we chose not to measure the propagation speeds of the observed wave disturbances in the corona for the following reasons: first, the height scale of the SDO/AIA channels is difficult to define in flaring regions; second, the real propagation trajectory of different oscillation modes differ and may notably diverge from the vertical direction. We, however, do it for the height interval between the temperature minimum (Si \textsc{i} 10827 Å) and upper chromosphere (He \textsc{i} 10830 Å). According to Bard and Carlsson (2008); Leenaarts, Carlsson, and Rouppe van der Voort (2012), the difference in the formation heights of these two lines may reach 800–900 km. Thus, based on the direct measurement of the signal phase delay, we can determine its propagation speed (Kobanov et al. 2013). The time lag between the signals is 60 s on average, which yields the propagation speed of the 5-minute oscillations to be 13–15 km s\(^{-1}\).

4. DISCUSSION
Oscillations Accompanying a Negative Flare II

QPPs with a 2-minute period are observed rarely compared to those with sub-minute periods. Kuznetsov et al. (2016) concluded that such QPPs are closely related to eruptive events.

Liu et al. (2011) in their analysis of the AIA 171 Å intensity variations in a C3-class flare revealed waves with the dominant period of 181 s propagating along the coronal loop funnel. The measured phase velocity of these waves reached 2000 km s\(^{-1}\). The authors identified them as the fast magnetoacoustic waves. Earlier, Terekhov et al. (2002) found a period of 143.2 s in a 8–20 keV light curve of a flare. Before that, an idea that Alfvén waves transport the flare energy from the corona to the lower solar atmosphere was proposed by Emslie and Sturrock (1982) and later developed by Fletcher and Hudson (2008). In this theory, the preference was given to torsional Alfvén waves. This is hardly applicable in our case, since torsional Alfvén waves are not accompanied by intensity oscillations in the He\(\text{I} 10830\) Å chromospheric line shown in Figure 2d.

Yuan et al. (2013) observed ‘quasi-periodic propagating fast magneto-acoustic wave trains (QPF)’ 100 Mm away from the C2-class flare site. QPF period was under 1 min, and the propagation speed was 700–800 km s\(^{-1}\).

Ning (2014) found a 2-minute period in a B8.1-class flare. The wave perturbation propagated along the flare loop at a speed of 130 km s\(^{-1}\), which is close to the local sound speed. Nisticò, Pascoe, and Nakariakov (2014) observed wave trains caused by a powerful flare. The measured period was close to 1 min, and the propagation velocity exceeded 1000 km s\(^{-1}\).

Zhang et al. (2015) showed that fast and slow magnetoacoustic waves can propagate by the same trajectories. They measured the period and velocity of the fast waves to be 2 min and 900 km s\(^{-1}\), and those of the slow waves to be 3 min and 100 km s\(^{-1}\). The authors, however, note that, as opposed to the fast wave trains, the slow waves most likely result from the chromosphere leakage rather than from the flare disturbance.

Brosius and Inglis (2018) found periods around 2 minutes in the LOS velocity and intensity variations in a flare ribbon during chromospheric evaporation. Milligan et al. (2017) observed two main periods of 120 and 180 minutes in an X-class flare, and these 2-minute oscillations were registered both in the hard X-ray and the chromospheric EUV radiation. The authors state that this is due to the chromospheric response to accelerated particles. The delays between the X-ray oscillations and the oscillations in different AIA channels were not estimated in this article.

The 2-minute oscillations that we observed were most likely generated by the small flare. Their spatial and temporal concurrence indirectly supports this suggestion.

Having analysed the characteristics of these oscillations we believe that they can be related to slow magnetoacoustic waves.

The problem of the oscillation propagation from the chromosphere to the corona and in the reverse direction has existed for a long time. In the last decades, with the advent of the space telescope data it has prompted more interest. Nevertheless, due to the complexity of the problem, the conclusions of the early studies contain notable discrepancies. For example, De Moortel et al. (2002) found that oscillations with a period of 321±71 s are observed above faculae in the Transition Region and Coronal Explorer (TRACE) 171 Å channel intensity. They suggested that this results from photospheric oscillations propagating through the transition region to the corona. With this, the authors found no evidence for the downward propagation. In the analysis of similar TRACE 171 Å data, De Pontieu, Erdélyi, and de Wijn (2003) concluded that 5-minute oscillations in the upper transition region do not result from a direct leakage of the p-mode from the photosphere through the chromosphere. The authors believe that these oscillations are connected non-linearly.

Centeno, Collados, and Trujillo Bueno (2006); Khomenko et al. (2008) provided observational evidence that 5-minute oscillations propagate from the photosphere to the chromosphere in the vertical magnetic tubes of faculae. The authors state that the cut-off frequency may significantly decrease due to radiative losses. However, de Wijn, McIntosh, and De Pontieu (2009) based on the high-resolution Hinode data, found that 3-minute oscillations propagate upwards in vertical magnetic tubes of faculae, while propagating 5-minute oscillations were observed only at facular peripheries in inclined magnetic fields. Chelpanov, Kobanov, and Kolobov (2015) showed that in the AIA 304 Å channel intensity, the main oscillation power is distributed in the 3–6 mHz range above facular magnetic knots and in the 1.5–3 mHz above facular peripheries. They found oscillations at a frequency of 5 mHz in the magnetic field strength signals in magnetic knots.

We suggest that, given such large time lags between the signals and the other characteristics, we observed slow magnetoacoustic waves (Zimovets and Struminsky 2009; Nakariakov and Zimovets 2011). This refers to both 2-minute oscillations propagating downwards from the corona and 5- with 3-minute oscillations leaking from the photosphere and chromosphere to the lower corona (the 171 Å channel).

5. CONCLUSION
In the analysis of flare SOL2012-09-21T02:19, we found QPPs with a 2-minute period in the 3–6 and 6–12 keV RHESSI channels. Similar variations were found in the SDO/AIA EUV channels and in the spectral data of the ground-based telescope in the He i 10830 Å line. These variations have a form of an oscillation train with increased amplitudes that lasted for 3–4 periods. The centers of the oscillation trains gradually shifted from increased amplitudes that lasted for 3–4 periods. The authors suggest that such a delay unambiguously indicates the propagation of the flare-triggered wave disturbance with a period of 2 minutes from the corona to the chromosphere.

We measured the 3- and 5-minute oscillation delays in their propagation from the photosphere and chromosphere to the transition region and corona. The 5-minute oscillation signal of the He i 10830 Å line lags 60 s on average behind the Si i 10827 Å line signal, while the AIA 304 Å and 171 Å signals lag 100 s and 200 s, respectively. Three-minute oscillations in the 304 Å and 171 Å channels lag 120 s and 200 s behind the chromospheric signals.

We suggest that the combination of the oscillation characteristics applies to the slow magnetoacoustic wave mode in a greater degree than to other modes.

The results show that the oscillation train structure of the signals resulting from an abrupt increase of the oscillation amplitudes in the lower atmosphere caused by a small-scale flare (Chelpanov and Kobanov 2018) may serve as a useful means in studies of the wave propagation processes in the transition region and corona.

The research was partially supported by Project No.II.16.3.2 of ISTP SB RAS. Spectral data were recorded at the Angara Multiaccess Center facilities at ISTP SB RAS. We acknowledge the NASA/SDO and RHESSI science teams for providing the coronal observation data. We are grateful to the anonymous referee for the useful remarks and suggestions.

REFERENCES

Aschwanden, M.J.: 1987, Theory of radio pulsations in coronal loops. SoPh 111, 113 – 136. DOI. ADS.

Bard, S., Carlsson, M.: 2008, Constructing Computationally Tractable Models of Si I for the 1082.7 nm Transition. ApJ 682, 1376 – 1385. DOI. ADS.

Brosius, J.W., Inglis, A.R.: 2018, Localized Quasi-periodic Fluctuations in C II, Si IV, and Fe XXI Emission during Chromospheric Evaporation in a Flare Ribbon Observed by IRIS on 2017 September 9. ApJ 867, 85. DOI. ADS.

Centeno, R., Collados, M., Trujillo Bueno, J.: 2006, Oscillations and Wave Propagation in Different Solar Magnetic Features. In: Casini, R., Lites, B.W. (eds.) Solar Polarization 4, Astronomical Society of the Pacific Conference Series 358, 465. ADS.

Chelpanov, A.A., Kobanov, N.I.: 2018, Oscillations Accompanying a He i 10830 Å Negative Flare in a Solar Facula. SoPh 293, 157. DOI. ADS.

Chelpanov, A.A., Kobanov, N.I., Kolobov, D.Y.: 2015, Characteristics of oscillations in magnetic knots of solar faculae. Astronomy Reports 59, 968 – 973. DOI. ADS.

De Moortel, I., Ireland, J., Hood, A.W., Walsh, R.W.: 2002, The detection of 3 and 5 min period oscillations in coronal loops. A&A 387, L13 – L16. DOI. ADS.

De Pontieu, B., Erdélyi, R., de Wijn, A.G.: 2003, Intensity Oscillations in the Upper Transition Region above Active Region Plage. ApJL 595, L63 – L66. DOI. ADS.
Kislyakov, A.G., Zaitsev, V.V., Stepanov, A.V., Urpo, S.: 2006, On the Possible Connection between Photospheric 5-Min Oscillation and Solar Flare Microwave Emission. *SoPh* **233**, 89 – 106. DOI. ADS.

Kobanov, N., Chelpanov, A., Kolobov, D.Y.: 2013, Negative flare in the He I 10830 Å line in facula. *Journal of Atmospheric and Solar-Terrestrial Physics* **173**, 50–56. DOI. ADS.

Kobanov, N.I.: 1990, On spatial characteristics of

Kobanov, N., Chelpanov, A., Pulyaev, V.: 2018, Negative

Kislyakov, A.G., Zaitsev, V.V., Stepanov, A.V., Katz, N.L., Kushner, G.D., Levay, M., Lindgren, R.W., Mathur, D.P., McFeaters, E.L., Mitchell, S., Rehse, R.A., Schrijver, C.J., Springer, L.A., Stern, R.A., Tarbell, T.D., Wuels, J.-P., Wolfson, C.J., Yanari, C., Bookbinder, J.A., Cheimets, P.N., Caldwell, D., Deluca, E.E., Gates, R., Golub, L., Park, S., Podgorski, W.A., Bush, R.I., Scherrer, P.H., Guinin, M.A., Smith, P., Auker, G., Jerram, P., Pool, P., Soufi, M., Windt, D.L., Beardsley, S., Clapp, M., Lang, J., Waltham, N.: 2012, The Atmospheric Imaging Assembly (AIA) on the Solar Dynamics Observatory (SDO). *SoPh* **275**, 17 – 40. DOI. ADS.

Lin, R.P., Dennis, B.R., Hurford, G.J., Smith, D.M., Zehnder, A., Harvey, P.R., Curtis, D.W., Pankow, D., Turin, P., Bester, M., Csillaghy, A., Lewis, M., Madden, N., van Beek, H.F., Appleby, M., Raudorf, T., McTiernan, J., Ramaty, R., Schmah, E., Schwartz, R., Krucker, S., Abiad, R., Quinn, T., Berg, P., Hashii, M., Sterling, R., Jackson, R., Pratt, R., Campbell, R.D., Malone, D., Landis, D., Barrington-Leigh, C.P., Slassi-Sennou, S., Cork, C., Clark, D., Amato, D., Orwig, L., Boyle, R., Banks, L.S., Shirey, K., Tolbert, A.K., Zarro, D., Snow, F., Thomsen, K., Henneck, R., McHedlishvili, A., Ming, P., Vivian, M., Jordan, J., Wanner, R., Crubb, J., Preble, J., Matranga, M., Benz, A., Hudson, H., Canfield, R.C., Holman, G.D., Cranell, C., Kosugi, T., Emslie, A.G., Vilmer, N., Brown, J.C., Johns-Krull, C., Aschwanden, M., Metcalf, T., Conway, A.: 2002, The Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI). *SoPh* **210**, 3 – 32. DOI. ADS.

Liu, W., Title, A.M., Zhao, J., Ofman, L., Schrijver, C.J., Aschwanden, M.J., De Pontieu, B., Tarbell, T.D.: 2011, Direct Imaging of Quasi-periodic Fast Propagating Waves of ~2000 km s\(^{-1}\) in the Low Solar Corona by the Solar Dynamics Observatory Atmospheric Imaging Assembly. *ApJL* **736**, L13. DOI. ADS.

McLaughlin, J.A., Nakariakov, V.M., Dominique, M., Ji

McLaughlin, J.A., Nakariakov, V.M., Dominique, M., Jelinek, P., Takasao, S.: 2018, Modelling Quasi-Periodic Pulsations in Solar and Stellar Flares. *SSRe* **214**, 45. DOI. ADS.

Milligan, R.O., Fleck, B., Ireland, J., Fletcher, L., Dennis, B.R.: 2017, Detection of Three-minute Oscillations in Full-disk Ly\(\alpha\) Emission during a Solar Flare. *ApJL* **848**, L8. DOI. ADS.
Nakariakov, V.M., Melnikov, V.F.: 2009, Quasi-Periodic Pulsations in Solar Flares. *SSRv* **149**, 119–151. DOI. ADS.

Nakariakov, V.M., Zimovets, I.V.: 2011, Slow Magnetoacoustic Waves in Two-ribbon Flares. *ApJL* **730**, L27. DOI. ADS.

Nakariakov, V.M., Pilipenko, V., Heilig, B., Jelínké, P., Karlický, M., Klimushkin, D.Y., Kolotkov, D.Y., Lee, D.-H., Nisticò, G., Van Doorsselaere, T., Verth, G., Zimovets, I.V.: 2016, Magnetohydrodynamic Oscillations in the Solar Corona and Earth’s Magnetosphere: Towards Consolidated Understanding. *SSRv* **200**, 75–203. DOI. ADS.

Ning, Z.: 2014, Imaging Observations of X-Ray Quasi-periodic Oscillations at 3 - 6 keV in the 26 December 2002 Solar Flare. *SoPh* **289**, 1239–1256. DOI. ADS.

Nisticò, G., Pascoe, D.J., Nakariakov, V.M.: 2014, Observation of a high-quality quasi-periodic rapidly propagating wave train using SDO/AIA. *A&A* **569**, A12. DOI. ADS.

Pesnell, W.D., Thompson, B.J., Chamberlin, P.C.: 2012, The Solar Dynamics Observatory (SDO). *SoPh* **275**, 3–15. DOI. ADS.

Pugh, C.E., Nakariakov, V.M., Broomhall, A.-M., Bogomolov, A.V., Myagkova, I.N.: 2017, Properties of quasi-periodic pulsations in solar flares from a single active region. *A&A* **608**, A101. DOI. ADS.

Rayrole, J.: 1967, Contribution à l’étude de la structure du champ magnétique dans les taches solaires. *Annales d’Astrophysique* **30**, 257. ADS.

Sych, R., Nakariakov, V.M., Karlicky, M., Anfinogentov, S.: 2009, Relationship between wave processes in sunspots and quasi-periodic pulsations in active region flares. *A&A* **505**, 791–799. DOI. ADS.

Terekhov, O.V., Shevchenko, A.V., Kuz’mín, A.G., Sazonov, S.Y., Sunyaev, R.A., Lund, N.: 2002, Observation of Quasi-Periodic Pulsations in the Solar Flare SF 900610. *Astronomy Letters* **28**, 397–400. DOI. ADS.

Yuan, D., Shen, Y., Liu, Y., Nakariakov, V.M., Tan, B., Huang, J.: 2013, Distinct propagating fast wave trains associated with flaring energy releases. *A&A* **554**, A144. DOI. ADS.

Zhang, Y., Zhang, J., Wang, J., Nakariakov, V.M.: 2015, Coexisting fast and slow propagating waves of the extreme-UV intensity in solar coronal plasma structures. *A&A* **581**, A78. DOI. ADS.

Zhao, J., Felipe, T., Chen, R., Khomenko, E.: 2016, Tracing p-mode Waves from the Photosphere to the Corona in Active Regions. *ApJL* **830**, L17. DOI. ADS.

Zimovets, I.V., Struminsky, A.B.: 2009, Imaging Observations of Quasi-Periodic Pulsatory Nonthermal Emission in Two-Ribbon Solar Flares. *SoPh* **258**, 69–88. DOI. ADS.