

## COMPARING THE MAIN OSCILLATION CHARACTERISTICS IN THE SOLAR CHROMOSPHERE AND MAGNETOSPHERE BASED ON STUDIES MADE AT ISTP SB RAS

**A.A. Chelpanov**

*Institute of Solar-Terrestrial Physics SB RAS,  
Irkutsk, Russia, chelpanov@iszf.irk.ru*

**M.A. Chelpanov**

*Institute of Solar-Terrestrial Physics SB RAS,  
Irkutsk, Russia, max\_chel@iszf.irk.ru*

**N.I. Kobanov**

*Institute of Solar-Terrestrial Physics SB RAS,  
Irkutsk, Russia, kobanov@iszf.irk.ru*

**R.T. Sotnikova**

*Irkutsk State University,  
Irkutsk, Russia, rsotnikova@bk.ru*

**Abstract.** The aim of this paper is to structure and extend the knowledge of solar chromospheric sources of oscillations in the solar wind and their relationships with pulsations registered in the magnetosphere. We compare the oscillation spectra that we observe using instruments of the Institute of Solar-Terrestrial Physics in different chromospheric structures with those observed in the solar wind and magnetosphere. We explore the possibility that the observed periodic variations of the chromospheric line widths can be interpreted as torsional Alfvén wave manifestation — this mode can propagate long distances without dissipating in the interplanetary

space; it can penetrate into Earth's magnetosphere directly or due to processes occurring at the plasmopause. We emphasize the similarities in the oscillation characteristics observed in different media, the similarities in the parameters of the media themselves and the processes developing in them. We believe that similar approaches can be applied to studying these media.

**Keywords:** solar faculae, sunspots, MHD waves, magnetosphere.

### INTRODUCTION

Magnetohydrodynamic (MHD) waves are thought to be one of the mechanisms of energy transport in the heliosphere. They occur in all its regions, from the photosphere to Earth's atmosphere.

In all layers of the solar atmosphere there is a rich variety of periods and MHD modes. A large amount of observational data has been accumulated for objects of various types. In this work, we generally use the waves that are observed in the upper chromosphere because they are more likely to influence processes in the solar wind (SW) in contrast, for example, to photospheric oscillations, which are known to be trapped sometimes in a limited range of heights without penetrating into the upper atmosphere.

Oscillations in the upper atmosphere and magnetosphere have also been studied for a long time. One of the key mechanisms leading to the generation of ultralow-frequency (ULF) waves in Earth's magnetosphere is the mechanism of direct penetration of waves from SW through the magnetopause, which was first proposed by Guglielmi, Troitskaya [1973], [Mazur, 2010; Greenstadt et al., 1983]. In [Kessel, 2008; Takahashi, Ukhorskiy, 2007, 2008], SW pressure fluctuations are considered as the main source of long-period pulsations in the magnetosphere.

We examine properties of the oscillations observed in the chromosphere and SW to find a link between them. This work is based on the observation results from previous research carried out at the Institute of Solar-Terrestrial Physics of Siberian Branch of Russian Academy of Sciences (ISTP SB RAS) on geomagnetic oscillations associated with MHD oscillations in the

upper solar chromosphere.

We focus on the studies conducted for a number of structures of the solar atmosphere in different spectral lines formed in a wide range of heights.

We study the oscillation characteristics of line-of-sight velocity, intensity, and profile width. Methods of measurements are described in [Kobanov, 1985, 2001]. In this work, we analyze the possible effects of torsional Alfvén waves, characterized by the rotation of magnetic tube segments. Alfvén waves can propagate over long distances with minimal dissipation, traveling from the chromosphere through the corona in SW and reaching Earth. On the other hand, Cranmer and van Ballegoijen [2005] have shown that the transition region can reflect a large number of Alfvén waves in a wide range of periods. In interplanetary space, the reflection is essential only for periods of the order of tens of hours or more. In our previous studies, we observed periodic variations in the width of chromospheric lines, which can be interpreted as manifestations of torsional Alfvén waves in different structures of the solar atmosphere. The next step is to trace the dynamics of these waves in SW and Earth's magnetosphere after they have been generated in the solar chromosphere.

Below we provide a brief description of the characteristics of periodic oscillations in the Sun and Earth's magnetosphere, which were found in our observational data.

### OSCILLATIONS ON THE SUN

Oscillations in the solar chromosphere manifest themselves in a wide range of periods. Characteristics of the oscillations are known to be determined by the mag-

netic field strength and topology in solar structures: sunspots, faculae, coronal holes. ISTP SB RAS has extensive experience of research into oscillations in these objects, which we have used for this paper. We pay special attention to observational signatures of Alfvén waves in objects of interest. Observing Alfvén waves on the Sun is a difficult task because they are incompressible waves and hence cannot produce intensity variations. As a result, Alfvén waves cannot be recorded in emission variations [Nakariakov, Verwichte, 2005]. They have been recorded so far on the basis of indirect signatures or directly in spicules at the limb with the use of high-resolution data. One of their signatures is periodic variations in spectral line profile width. De Pontieu et al. [2015] have shown that these variations do not depend on the spatial resolution of the instrument in use.

It should be noted that until an alternative convincing explanation for the abnormally high amplitudes of the chromospheric spectral line profile width variations is found, the version of torsional Alfvén waves in the solar chromosphere has the right to exist.

#### Oscillations in coronal holes

Coronal holes are the source of high-speed SW streams, so they become an important object of research into wave propagation and generation in the Sun–Earth system. Coronal holes feature large-scale magnetic fields, which penetrate the solar atmosphere from its lower layers to the corona. These magnetic fields can act as waveguides for MHD waves. From observations of 15 coronal holes, Kobanov and Sklyar [2007] have found pronounced oscillations in three- and five-minute ranges. In the five-minute range, they found signs of propagating waves. Kobanov et al. [2003] observed LOS velocity oscillations with frequencies of 1 mHz and lower along with three- and five-minute oscillations above coronal holes.

Anfinogentov et al. [2010], using the 171 Å coronal line, observed longitudinal and transverse oscillations predominantly with 15–30 min periods in loops located in a coronal hole. These oscillations were caused by eruption at a bright point of the coronal hole.

Zubkova et al. [2014] have shown that the amplitude of chromospheric line profile half-width oscillations observed in 10 coronal holes are too large to be ex-

plained only by temperature variations. Table 1 lists amplitudes of half-width oscillations for observation series recorded in coronal holes. Such oscillations may indicate the presence of torsional Alfvén waves. Frequencies of the half-width oscillations were distributed in the 1.5–6.5 mHz range with the most prominent peaks in the 3.5–5.5 mHz range (Figure 1). Oscillation power in this frequency range increases in structural chromospheric elements within coronal holes. This increase, according to the authors, is due to the concentration of vertical magnetic fields in the vicinity of the chromospheric network. When analyzing characteristics of these oscillations, we should, however, take into account that Alfvén waves propagating in an inhomogeneous MHD medium of the solar atmosphere promote phase mixing, which leads to disruption of monochromaticity and transformation of primary signals [Shestov et al., 2017].

#### Oscillations in faculae

Faculae feature five-minute oscillations in signals of LOS velocities both in the photosphere and in the chromosphere [Kobanov et al., 2013a], although the spatial distribution of the oscillations in faculae is inhomogeneous. In LOS velocity signals, frequencies are higher in regions of intense magnetic field (magnetic hills) and lower closer to the boundaries of faculae [Chelpanov et al., 2015; Chelpanov et al., 2016b]. Kobanov and Pulyaev [2007] have found signs of propagating waves above magnetic hills. Kobanov et al. [2011] have analyzed phase relationships between the five-minute oscillations at different heights and have concluded that the waves propagate both upward and downward, thus returning a part of the wave energy from the chromosphere to the photosphere. We have identified a number of cases where chromospheric line half-width oscillations in faculae were not accompanied by intensity or velocity oscillations [Chelpanov et al., 2016a]. Figure 2 gives examples of half-width oscillation spectra in faculae. Spectral line profile half-width oscillation amplitudes in faculae are presented in Table 2. These examples do not, however, show the relationship between the half-width oscillation amplitude and the center-to-limb position on the solar disk. This can be explained by the

Table 1

Series date and time, UT	Spectral line	Location on the solar disk	Duration, min	Average peak-to-peak amplitude, mÅ
Aug 4, 2005, 06:26	H $\alpha$	32S 4W	43	22.98 (52)
May 29, 2010, 05:31	H $\alpha$	North pole	63	23.21 (45.6)
May 29, 2010, 07:09	H $\alpha$	North pole	63	24.15 (50.5)
Jun 16, 2010, 04:34	H $\alpha$	25°N 35°W	170	27.01 (78)
Jul 06, 2010, 10:21	H $\alpha$	7°N 13°W	83	24.86 (55.6)
Apr 10, 2011, 07:27	H $\alpha$	25°S 15°W	85	20.92 (63.3)
Apr 12, 2011, 01:21	H $\alpha$	56°S 2°E	83	37.26 (88)
Sep 18, 2011, 05:36	H $\alpha$	30°S 52°E	67	33.14 (98.5)
Sep 18, 2011, 07:43	H $\alpha$	30°S 52°E	82	27.87 (50.6)
Sep 19, 2011, 01:57	H $\alpha$	30°S 40°E	65	35.80 (59.25)
Aug 11, 2005, 02:54	Ca II 8542 Å	4°N 47°E	57	46.3 (83.3)
Aug 11, 2005, 04:00	Ca II 8542 Å	60°N 1°E	41	45 (103.5)
Aug 17, 2005, 07:12	Ca II 8542 Å	0°N 37°W	81	70 (115.5)
Sep 29, 2005, 03:29	Ca II 8542 Å	35°S 0°E	52	72.4 (136.9)
May 28, 2010, 06:16	Ca II 8542 Å	North pole	120	44.75 (122.9)

Table 2

Series date and duration, min	Spectral line	Average peak-to-peak amplitude of half-width, mÅ	
		2.5–4.5 mHz	1.0–1.9 mHz
Jul 1, 2003, 42	H $\alpha$ 6563 Å	9–21	23
Sep 12, 2003, 52	H $\alpha$ 6563 Å	20–25	35
Jul 27, 2005, 67	H $\alpha$ 6563 Å	20–50	40
Sep 24, 2005, 84	H $\alpha$ 6563 Å	20–30	–
Sep 21, 2012, 100	HeI 10830 Å	40	–
	H $\alpha$ 6563 Å	35–45	–
May 1, 2013, 47	H $\alpha$ 6563 Å	30–35	40–60
	HeI 10830 Å	40–50	45
Aug 25, 2013, 75	H $\alpha$ 6563 Å	30–35	70
	HeI 10830 Å	45	55
Aug 28, 2013, 158	H $\alpha$ 6563 Å	25	50

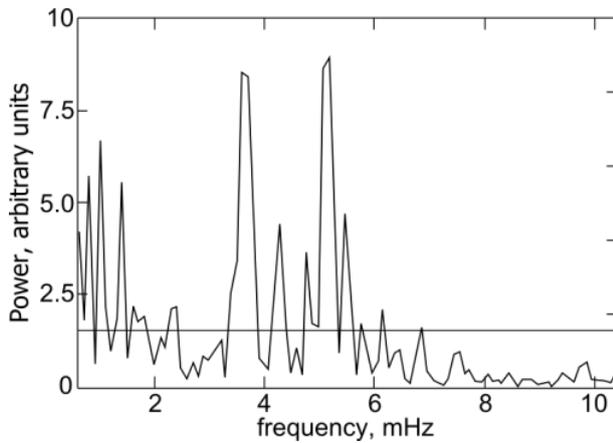


Figure 1. Typical H $\alpha$  profile half-width oscillation spectrum in a coronal hole. The main oscillation power is distributed in the 1.5–6.5 mHz range

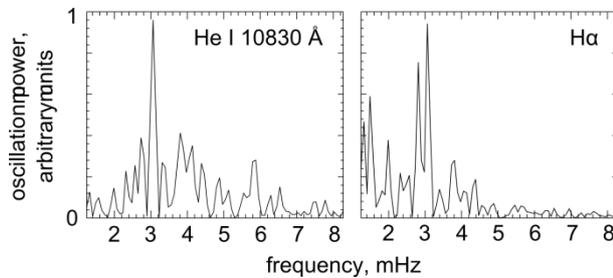


Figure 2. Chromospheric line profile half-width oscillation spectra in a facula

the magnetic field configuration in faculae – the faculae area is densely populated with magnetic fields of different slopes, which theoretically makes it possible to observe torsional Alfvén waves at any point of the solar disk.

### Active regions

Unlike faculae, there are oscillations with different periods in sunspot umbrae at different heights: five-minute oscillations dominate in the photosphere; and three-minute oscillations, in the chromosphere. Figure 3 presents typical spectra observed in the photosphere and chromosphere of sunspot umbrae. Over the entire surface of the sunspot and in its vicinity, the observed oscillation range is much wider. Oscillation power distributions in sunspot umbrae, penumbrae, and their vicinities have shown that the periods increase from inner umbrae to penumbrae and further through the outer boundaries in the vicinity of the sunspot,

where pronounced 10–12 min oscillations prevail [Kobanov, 2000b; Kobanov et al., 2013b; Kobanov et al., 2015].

Kolobov et al. [2016] have examined a circular region in the inner penumbra, where five-minute oscillations prevail in a wide range of heights, from the photosphere to the transition region (Figure 4).

The authors believe that the slope and strength of the magnetic field in this region determine conditions for propagation of five-minute oscillations between layers of the solar atmosphere.

Sych et al. [2009] have examined the possible connection between three-minute oscillations in sunspots and similar oscillations observed in flare light curves. The authors assumed that three-minute oscillations propagate from sunspots to flares, inducing there an energy release with this period.

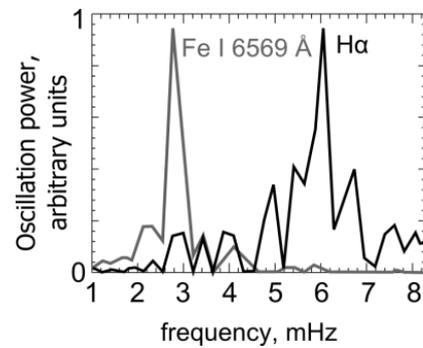


Figure 3. Umbral line-of-sight velocity oscillation spectra in the photosphere (Fe I 6569 Å) and chromosphere (H $\alpha$ )

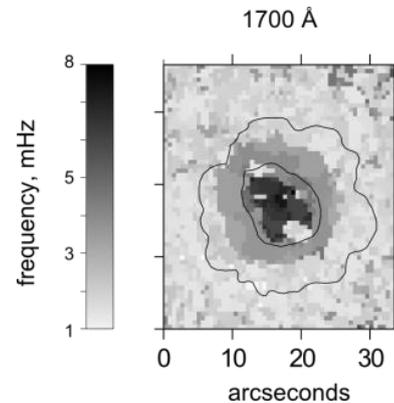


Figure 4. Distribution of dominant frequencies observed in a sunspot and its vicinity

Sych et al. [2012] have also studied three-minute oscillations observed in EUV channels and in a microwave range above sunspots. When analyzing their frequency characteristics, the authors found that the oscillation period can gradually change during one oscillation train. Two mechanisms were proposed: evolution of subphotospheric oscillation sources in the vicinity of sunspot and separation of pulses in magnetic tubes with different physical conditions.

One of the recent discoveries in oscillations in active regions is undamped transverse oscillations of coronal loops [Anfinogentov et al., 2015]. Periods of these oscillations can vary from 1 to 10 min, which corresponds approximately to loop eigenoscillation periods. They occur in almost all active regions and are likely to result from the interaction of loops with surrounding quasi-stationary streams [Nakariakov et al., 2016b].

### OSCILLATIONS IN THE MAGNETOSPHERE

Geomagnetic waves, or pulsations, can be regularly observed in any part of Earth's magnetosphere. Stable periodic and quasiperiodic pulsations are usually referred to as Pc, or continuous pulsations. Compared to other similar pulsations, Pc5 waves (periods of 150 to 600 s) have much higher amplitudes. At high latitudes, they can reach hundreds of nanotesla even under moderately disturbed geomagnetic conditions.

Pc5 waves can have both internal and external magnetospheric sources. The azimuthal structure of oscillations is often considered as an indicator of their origin: waves generated within the magnetosphere usually feature a high azimuthal wave number  $m$ ; waves with sources in SW or at the magnetopause usually exhibit low  $m$  values because waves with high  $m$  cannot effectively penetrate into the magnetosphere [Guglielmi, Potapov, 1984; Leonovich et al., 2015].

Long-period pulsations of another type – Pi2 – are irregular pulsations with dominant periods of 40 to 150 s. They represent isolated wave packets and are more common than Pc5 [Lipko et al., 2002]. Pi2 are often observed in 5–10 min series. They usually occur during geomagnetic storms and substorms. They can accompany all phases of magnetic storms generated by continuous substorm activity [Zolotukhina et al., 2000]. At midlatitudes, Pi2 pulsations can be observed in a wide longitude sector, including the dayside magnetosphere. The region of Pi2 surface observation often corresponds approximately to the plasmopause footprint. Rakhmatulin et al. [2000], using a network of mid-latitude observatories, have determined a stable maximum of Pi2 occurrence around noon. In the nightside magnetosphere, however, high-latitude pulsations predominate over mid-latitude ones. The presence of the secondary longitudinal maximum and the differences between Pi2 generation patterns in different regions confirm the assumption about multiple sources of these pulsations [Rakhmatulin, 2009].

The hypothesis about penetration of SW-driven oscillations into the magnetosphere was made in the 1970s [Guglielmi, 1972; Troitskaya et al., 1971]; then it was developed and supported by many researchers [Potapov,

Mazur, 1994]. The most frequently discussed mechanism of externally generated waves is the Kelvin–Helmholtz instability forming at the magnetopause under the influence of high-speed SW [Lee et al., 1981; Mishin, Tomozov, 2016]. While the magnetopause is an integral part of the magnetosphere, surface waves propagating in it and causing internal magnetospheric oscillations are also external sources since they are a direct consequence of the interaction between the magnetosphere and SW inhomogeneities [Yumoto, 1988]. Fast magnetosonic (FMS) waves excited by this process propagate into the magnetosphere and generate Alfvén waves on resonance magnetic shells, where the frequency of local Alfvén oscillations coincides with the frequency of the FMS wave exciting these oscillations [Mishin, 1981, 1993; Dmitrienko, 2010]. This hypothesis is supported by many features of magnetospheric waves: peculiarities of polarization pattern, preferential antisunward propagation [Olson, Rostoker, 1978], dependence of pulsation observation probability on SW speed [Nosé et al., 1995], etc.

Among other scenarios, a direct penetration of ULF waves from an interplanetary medium into the magnetosphere is often discussed [Mazur, 2010; Stephenson, Walker, 2002]. Potapov and Polyushkina [2010] have shown diurnal magnetic field spectra in a geostationary orbit, whose peaks are similar to those in the SW magnetic field spectrum (Figure 5). The authors assumed that the MHD waves penetrated directly into the magnetosphere. Wright and Rickard [1995] have demonstrated the possibility of exciting magnetospheric waves with discrete frequencies (the so-called magic frequencies) by the broadband oscillation spectrum in SW. This unusual feature can be explained by the model of FMS-wave resonator forming in the near plasma sheet [Mazur, Leonovich, 2006]. It is explained by the magnetospheric wave resonator model ascribing dominant resonance frequencies to eigenoscillations of the magnetosphere as a whole.

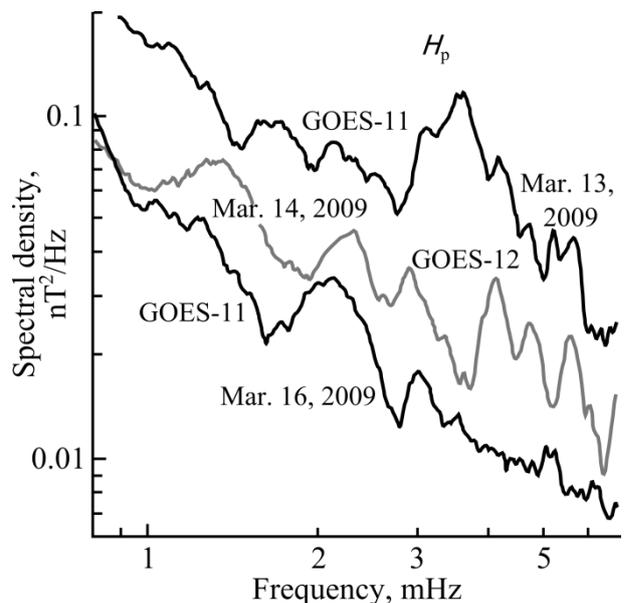


Figure 5. Three diurnal spectra of oscillations in magnetic field  $H_p$  component

Some authors suggest that these spectrum peaks prevail in SW pressure fluctuations rather than necessarily originate within the magnetosphere [Kepko et al., 2002; Viall et al., 2009]. Mishin et al. [2003] have identified the dependence of periods of pulsations caused by SW pressure fluctuations as the fourth power of the distance to the subsolar point of the magnetosphere.

Another possible manifestation of the mechanisms of pulsation energy transfer from the solar atmosphere to Earth's magnetosphere can be observed in the 0.1–5 Hz frequency range (Pc1-2 pulsations): the so-called serpentine emission (SE) [Guglielmi, Dovbnya, 1973] is recorded in polar caps and represents ion-cyclotron waves, which feature deep frequency modulation. The assumption about the external magnetospheric source of these oscillations was made on the basis of observations showing characteristic five-minute modulation of oscillations, which is probably associated with five-minute oscillations recorded in the solar photosphere [Guglielmi et al., 2015]. It is, however, obvious that generation of this emission is not well understood and the assumption that these oscillations penetrate from SW into the magnetosphere needs further theoretical justification [Dovbnya, Potapov, 2018].

In some cases, the phenomena recorded in near-Earth space can be interpreted as a response to the oscillations occurring on the Sun. Hayes et al. [2017] have examined the example when electron density variations in the ionosphere echo quasiperiodic pulsations in X rays of solar flares. The period of the X-ray pulsations was ~20 min; the delay of the ionospheric response, ~90 s. While this case could not be a typical example of earthward oscillation energy transfer by MHD waves, it shows how solar oscillations can generate ionospheric oscillations. Waves in near-Earth space can also be caused by variations of SW parameters. Zolotukhina [2009] has shown that SW pressure fluctuations can excite magnetospheric oscillations.

Comparing small-scale phenomena on the Sun with specific ionospheric and magnetospheric responses to them is a difficult task. Potapov et al. [2013] have analyzed spectral oscillations at bases of coronal holes and spectral peaks of interplanetary magnetic field variations (Figure 6). They tried to analyze to what extent solar photospheric oscillations contribute to SW oscillations in Earth's orbit.

Chromospheric line profiles exhibit pronounced half-width oscillations, which can be attributed to Alfvén waves. Spectral peaks of these oscillations range from 2 to 6 mHz. In SW, which feature Alfvén waves, these peaks can also be detected, although, in general, SW spectra have a more complex frequency distribution and irregular behavior.

Characteristics of oscillations observed in different media indicate that Alfvén waves generated in the solar chromosphere and transported by SW can provide the energy for the Alfvén resonance of magnetospheric field lines.

## CONCLUSIONS

The brief analysis of observations made at ISTP SB RAS has shown that oscillation spectra in the solar chromosphere and Earth's magnetosphere have much in

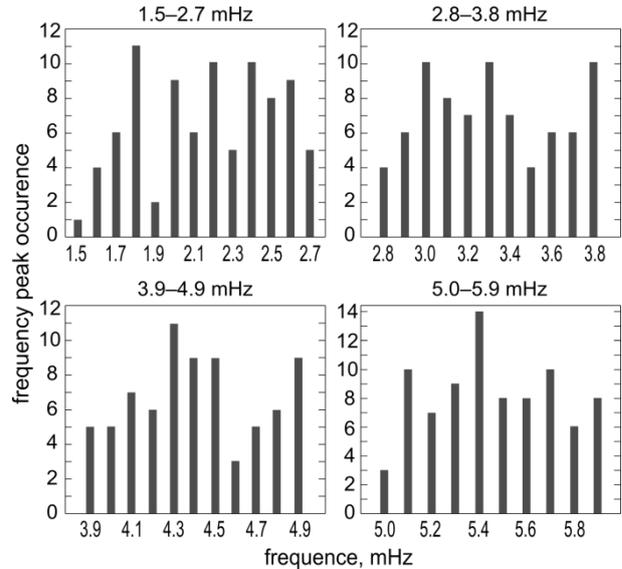


Figure 6. Distribution of peaks in different frequency ranges observed in high-speed SW streams between 1999 and 2006. The histograms are based on data obtained by Potapov et al. [2013]

common. This is another argument for joining the two formally distant areas of research. It is hoped that in the near future these areas will be enriched with new ideas and approaches to the problems under study [Nakariakov et al., 2016a].

The connection between solar and magnetospheric oscillations is generally searched for in the five-minute range, which is obviously due to the prevalence of five-minute oscillations in the solar atmosphere. The spectra of the observed solar and magnetospheric oscillations are, however, much richer.

We think that much attention should be paid to three-minute oscillations common in the solar chromosphere and to 10–15 min oscillations observed both in the Doppler velocity and in different solar structures.

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