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Observations of ULF waves in the solar corona and in the solar wind at the Earth's orbit

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ABSTRACT

Signs were looked for that would indicate a possible connection between plasma velocity oscillations observed in the region of solar coronal holes and magnetic field oscillations as recorded in the interplanetary medium. The problem appears to be quite important since the presence of large-scale ULF waves in the solar wind can increase geoeffectiveness of high speed streams in the interplanetary plasma. Observations of solar oscillations in the FeI 6569 Å spectral line in a coronal hole were taken as a basis. The measurements were carried out at the Horizontal Automated Solar Telescope of the Sayan Solar Observatory. High speed solar wind stream ejected from the coronal hole reached the Earth's orbit after approximately 60 h. The spectra of solar oscillations were compared with those of ultra low frequency (ULF) oscillations of the interplanetary magnetic field (IMF) at libration point $L1$. The oscillations were recorded with the ACE magnetometer when the leading edge of the high speed stream, bringing increased ULF wave activity, reached the Earth. The spectra of solar oscillations had a sharp peak at about 3.4–3.6 mHz. The spectrum of the solar wind ULF oscillations is much more complex, being formed by different sources. Nevertheless, ULF oscillations of the IMF often had peaks that were close in frequency to those of the solar oscillations. Analysis of the ULF wave spectra observed in the 92 high speed streams confirmed the presence of 3- and 5-min oscillations in the total wave spectrum. It is emphasized that the results cannot be regarded as proving a direct connection between solar oscillations and ULF waves at the Earth's orbit even though they do support such a possibility. Additional research is needed involving IMF wave trajectory calculations.

1. Introduction

Ultra low frequency (ULF) waves are commonly understood as electromagnetic waves in the frequency range 1 mHz–1 Hz. Waves and oscillations in this frequency range are observable everywhere, from the Earth's surface to the Sun's photosphere and chromosphere. Speaking of the Earth's magnetic field oscillations, the ULF range covers all types of geomagnetic pulsations. Their low-frequency portion (1–5 mHz) reflects large scale MHD waves travelling in the near-Earth plasma and having a wavelength comparable to magnetospheric dimensions. As shown by latest studies, these waves play a significant role in accelerating particles trapped in the geomagnetic field, resulting, in particular, in relativistic electron fluxes emerging in the outer radiation belt (Elkington et al., 1999; Liu et al., 1999; Kozyreva et al., 2007). In recent years, several papers have shown that fluctuations at discrete frequencies in the 1–10 mHz range are a common feature of the solar wind, in particular during high-velocity streams (Kepko et al., 2002; Kepko and Spence, 2003; Kessel et al., 2004; Villante et al., 2007; Viall et al., 2009). Potapov et al. (2012) traced the connection between high-energy electron fluxes in the magnetosphere and ULF oscillations in the solar wind and on the Earth based on solar cycle 23 data. They found ULF waves in the interplanetary environment and geomagnetic pulsations to be closely enough correlated, at least, on 24 h timescales. The question arises whether the 3–5-min oscillations observed in the Sun (Kobanov and Makarchik, 2004) are related to ULF waves registered in the solar wind near the Earth orbit. This is no idle question. Eselevich et al. (2009) predict magnetic disturbances on the Earth relying on the characteristics of magnetic fields transported away from the solar photosphere. The role of the most geoeffective parameter in this is played by the southward component of the interplanetary magnetic field (IMF). ULF waves, if they are in fact transported from the solar surface and transported by the solar wind to the Earth's orbit, might modulate the southward component magnitude of the IMF, thus affecting the geomagnetic disturbance regime. Their chief influence, however, may be expected to concern the dynamics of radiation–primarily, energetic electrons–trapped in the geomagnetic field.

The purpose of this work is to find features indicating a probable link between plasma speed fluctuations observable in solar coronal hole areas and magnetic field variations registered in

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the interplanetary environment and in the magnetosphere. This, as far as we know, is the first attempt to associate directly 3–5-min oscillations observed in the Sun with observations of ULF waves in the solar wind. Earlier, suppositions about possible solar sources of ULF oscillations in the solar wind were published (Kepko and Spence, 2003; Thomson et al., 2007).

The 5-min solar oscillations were first discovered by Leighton et al. (1962). Later Ulrich (1970) interpreted them as standing acoustic waves. Global 5-min solar oscillations and 3-min sunspot umbra oscillations are well-known solar phenomena. It should be noted from the outset that identifying oscillations in the Sun registered by ground-based optical instruments with oscillations measured by satellite magnetometers in the neighbourhood of the Earth orbit, and even more so, on the Earth surface, is a very hard problem. Indeed, millihertz solar oscillations are measured sporadically, and patchily. Predicting which solar region is to host a coronal mass ejection capable of transporting ULF oscillations is so far impossible. In this respect, the most promising are coronal holes, for which it is possible to predict, with some degree of certainty, geoeffective high-speed streams. Even in this case, however, it is virtually impossible to pinpoint the particular spot and time on the solar surface where and when the ULF waves will be transported by the solar wind to the Earth magnetosphere. Therefore, we restrict ourselves to comparing the general wave characteristics measured in the coronal hole area to interplanetary ULF waves at the head of a high-speed solar wind stream arriving at the Earth’s orbit from this particular coronal hole. Additionally, we will present some statistical data concerning the spectra of ULF oscillations observable at the Earth's orbit. In this paper, we suppose that the frequency of waves on their way from the Sun to the Earth's orbit does not change, thus neglecting possible effects of the solar wind radial expansion.

2. Data used

Observation data obtained using the horizontal solar telescope ACT of the Sayan solar observatory are time series of spectrograms. The spectral slot was about 64″ high, 1″ wide. Exposure was 0.5–10 s long (in our case, 1 s). A photoelectric guiding system was used providing for a tracking accuracy of 1″. Registration was by a Princeton Instruments CCD camera (256 × 1024), cooled down to −15 °C. The telescope was aimed at an object in such a manner that the spectrograph in-slot cross the area of interest (in our case, a coronal hole) east-to-west; 256 CCD-matrix pixels covered 64″. Line-of-sight speed data were obtained by measuring the line Doppler shift found by measuring the mass centre shift of the line wings at a certain distance from the nucleus. For the Hα line this distance is ±0.5 Å, for the FeI 6569 Å line, ±0.05 Å.

The solar data were compared to interplanetary magnetic field (IMF) measurements close to the Earth's orbit by magnetometers onboard ACE and WIND spacecraft (SC), positioned near the libration point, $L1$ about 1.5 million km away from the Earth upstream the solar wind (SW) flow. ACE magnetometer 16-s or 1-s data for the three IMF components were used. Our interest focused on IMF ULF fluctuations, therefore the data were filtered using a band (1.5–6 mHz) Marmet filter in order to cut off irregular low-frequency variations. ULF wave amplitude A was estimated by means of hourly root mean square values of σ_i of the filtered data for each component $i=x, y, z$. These data were formed into $A=\sqrt{\sigma_x^2+\sigma_y^2+\sigma_z^2}$, used to evaluate the amplitude. The spectral density of solar oscillations and IMF fluctuations associated with HSS of 5–7 August 2005 have been evaluated over 1 h intervals by means of the fast Fourier transform (FFT) algorithm of 1-s values with a nominal spectral resolution $\Delta f \approx 0.28$ mHz, in the frequency range ≈0.6–8 mHz. When analyzing the IMF ULF spectral statistics we took 24 h of 16-s measurements for each HSS event, calculated spectral density by FFT with averaging in the frequency domain. The resulting spectral resolution was $\Delta f \approx 0.1$ mHz.

3. Results

The particular event selected for analysis was 4 August 2005 observation of 5-min variations in the Sun, in a coronal hole. The coordinates of the area observed in the Sun were 48° N 5° E. The 1-s resolution measurements concerned the FeI 6569 Å line, 04:47 to 05:47 UT 04.08.2005. 127 line-of-sight speed variation series have been obtained along the spectral slot. Oscillograms in Fig. 1 are an example of three time series of line-of-sight speed values. The thicker lines represent a smoothed curve obtained by calculating a running mean for 75 points. Fig. 2 shows the spectra of 26 individual, randomly chosen time series (thin grey lines) and a spectrum obtained by averaging the spectra of all 127 series. A conspicuous spectral-density maximum can be seen in the 3.3–3.6 mHz area, which corresponds to the 280–305 s, or 4.6–5.1 min, variation period. Let us attempt to find out whether these solar wind oscillations would be observed in the solar wind at Earth's orbit

Coronal holes are sources of high-speed solar wind streams. This therefore suggests that the oscillations we observed entered the interplanetary space with the solar plasma, travelling as MHD

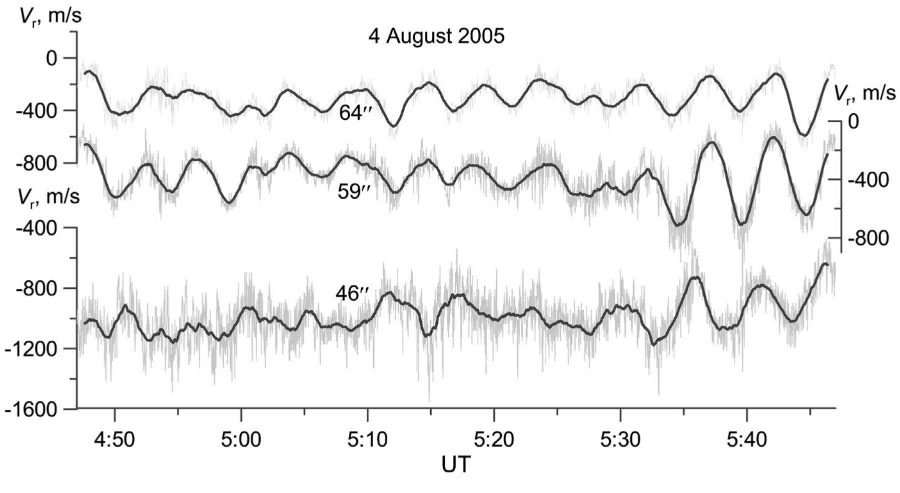

Fig. 1. Sample oscillograms for three time series of line-of-sight speed values as measured in FeI 6569 Å line.

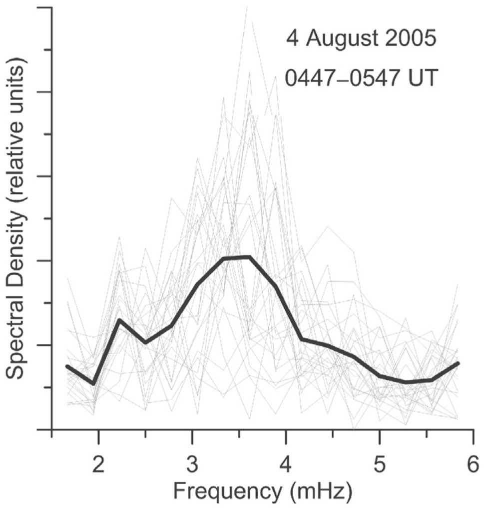

Fig. 2. Spectra for 26 individual randomly selected time series (thin grey lines) of solar oscillations, and the averaged spectrum for 127 series obtained from whole-slot spectrographic observations (black line).

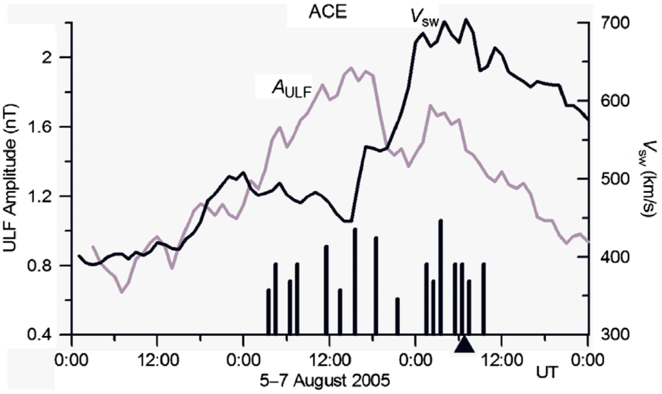

Fig. 3. High-speed solar wind stream from a coronal hole which passed over the Earth on 5–7 August 2005. The thicker black line indicates mean hourly SW speed values. The grey line shows the running mean of ULF oscillation amplitude over five hourly amplitudes. The bars show hours of 3-4 mHz ULF observations.

waves there. Of course, we cannot pinpoint the exact time and spot in space when and where these oscillations that were observed in the Sun must be observed in the vicinity of the Earth's magnetosphere, in case they are carried away from the solar surface into the solar wind. Rough estimates are possible, however. If the solar wind speed is assumed constant throughout to the Earth's orbit and equal 700 km/sec, coronal hole plasma should reach Earth's orbit after 2 days 11.5 h. It is known (Engebretson et al., 1998; Potapov et al., 2012), however, that ULF waves come before the SW speed peak, in the high-speed stream structure, therefore they should be expected earlier.

According to data from http://www.swpc.noaa.gov, high-speed SW stream from this coronal hole passed over the Earth on 5–7 August 2005, as evidenced by SW speed measurments by ACE. The thicker black line in Fig. 3 indicates mean hourly SW speed values. The plasma bulk speed exceeded 400 km/sec in the latter half of 5 August, reaching 500 km/s between 5 and 6 August, later dropping somewhat, reaching its maximum (for this stream) of over 700 km/s in the very beginning of 7 August. The black triangle in the time scale indicates the moment when the solar plasma is expected to arrive at Earth's orbit, if it was carried away at the moment the oscillations were observed and was transported by the high-speed stream at a constant speed of 700 km/s. This moment can be seen to be close to the moment the maximum SW speed was observed in the stream. The grey line denotes the running mean ULF wave amplitude over five hourly *A* values. The high-speed stream can be seen to result in intensified ULF oscillations in the solar wind. The main maximum of the ULF wave amplitude is about 15 h earlier than the SW speed peak. A second, smaller, increase in ULF oscillation amplitude coincided with the main SW speed maximum.

The spectrum of ULF oscillations is rather complex in the solar wind. It obviously comprises several sources, see for instance Parhi et al. (1999). Our goal is to try to determine the contribution from solar oscillations. Even a rough analysis of the pattern in which the oscillation characteristics are distributed along the spectral slot shows that these characteristics are not uniform. At some points, oscillations are narrow-band and have large amplitude, while at others, they are irregular and weak. Plasma from all of these points end up in different solar wind jets (microstreams) (Casalbuoni et al., 1999). Oscillations of solar origin may be expected to make a sizeable contribution to the general spectrum in some jets, while being lost against oscillations from other sources in other jets. We tried to find traces of 5-min solar oscillations in the 5–7 August 2005 high speed stream shown by the black curve in Fig. 3. To do this we used 1-s ACE magnetometer measurements. The data were filtered-out using a 1.5 mHz cut-off frequency Marmet filter in order to eliminate long-period IMF variations. Black vertical bars in Fig. 3 indicate the hours when the ULF spectrum had a spectral peak within the 3–4 mHz band. The bar height is proportional to the spectral density calculated as a sum of densities in the three IMF components. In Figs. 4 and 5 we show 4 examples of 1-h oscillograms and the spectra calculated for this event, respectively. It is clearly seen that oscillations in the solar wind at the Earth's orbit are more chaotic compared to oscillations on the solar surface. Waves with a period of about five minutes are clearly visible, however. The ULF wave spectrum in the solar wind is much wider than the spectrum of solar oscillations, of course. In some time intervals, the maximum in the frequency profile of the IMF oscillation amplitude may shift to other periods. The case is different for the solar oscillations – their periods chiefly tend to two values lying near 3 or 5 min (De Moortel et al. (2002); Kobanov and Sklyar, 2007). These values are, however, also characteristic for the solar wind.

To verify this, we measured the ULF spectra observed in the solar wind at a time when high-speed streams with increased ULF activity approached the Earth over 1999–2006.

We used data of the magnetometer (16 s resolution) and plasma analyzer onboard ACE, which was located near libration point $L1$ at the time. Events were selected where the mean daily solar wind speed exceeded 550 km/sec, and the mean daily ULF oscillation amplitude was above 2 nT, in the 1.5–6 mHz range.

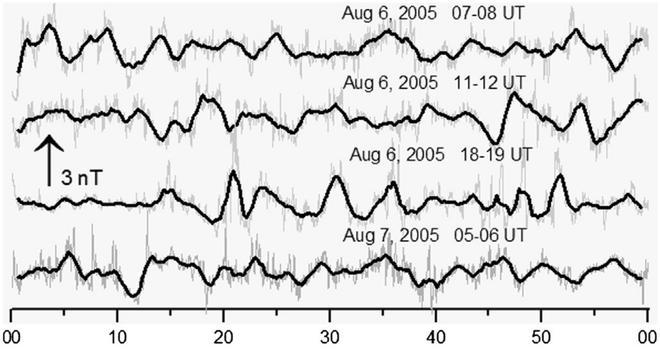

Fig. 4. Examples of hourly ULF-filtered IMF oscillograms for some of hours indicated in Fig. 3 by bars.

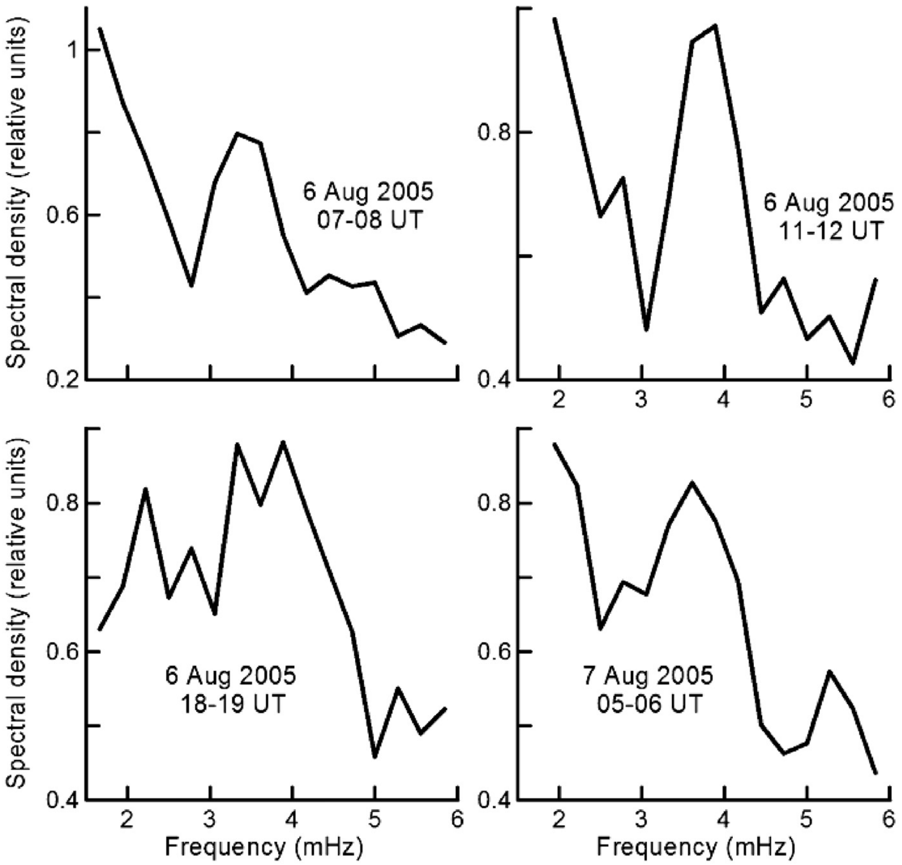

Fig. 5. Examples of hourly oscillation spectra for the same hours as in Fig. 4.

These events were 92 in the eight years (see Table A1 in Appendix A). The selection did not distinguish between high-speed streams from coronal holes and those resulting from coronal mass ejections. A 24 h interval of the most intense oscillations was selected for each event. Sometimes this interval included the peak speed of the stream, but sometimes the interval of intense ULF waves was considerably, by more than 24 h, ahead of the speed maximum. Fast Fourier transform of a time series of 16-second values of the IMF B_z-component was performed in order to calculate the oscillation spectrum. The location of characteristic spectral peaks in the relevant frequency range was registered. To select conventionally significant spectral peaks, we used the following algorithm: (1) plot the frequency dependence of the obtained spectral density $S(f)$ in logarithmic coordinates, (2) calculate and plot a line approximating the spectrum by the power function $\ln S(f)=A\cdot\ln f+B$, where $A<0$ and $B<0$, (3) plot a second line, given by the equation $\ln S(f)=A\cdot\ln f+B^*$, where $B^*=B+\ln 1.5$, this corresponds to a spectral density level that was1.5 times higher than the average level for this event; (4) if some spectral peak is beyond the second line above the first one, this peak is considered significant, and its frequency is tabulated (see Table A1 in Appendix A).

A sample oscillation spectrum for the time interval 1200 UT 21October 2001 to 1200 UT 22 October 2001 is shown in Fig. 6. The power approximation is shown by a solid straight line; the dashed line is an additional line to single out significant peaks. There are two peaks in this case: 2.5 mHz and 3.2 mHz. The oscillation period corresponding to one of these, $T_2=1000/3.2\ \text{mHz}=312\ \text{s}=5.2$ min is close to the 5-min period characteristic for solar oscillations. Overall, of the 92 events, 78 cases show oscillations ranging 3.33 ± 0.5 mHz (periods of 4.4 to 5.9 min), in 83 cases the oscillations ranged 5.55 ± 0.5 mHz (periods of 2.8 to 3.3 min). Meanwhile, all of the 92 events witnessed oscillations close to 3 or/and 5 min.

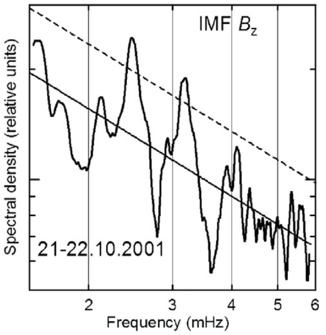

Fig. 6. Sample IMF oscillation spectrum in high speed solar wind stream of 21–22 October 2001.

4. Discussion and conclusions

Without any doubt, MHD waves play an important role in physical processes in the Sun, the solar wind, planetary magnetospheres. Indeed, it is commonly accepted that these waves are the major factor heating the solar plasma in the chromosphere (Veselovsky and Kropotkin, 2010). If MHD - primarily, Alfvén waves are ignored, it is impossible to explain solar wind properties. In magnetospheres, ULF oscillations and waves participate in redistribution of charged particles, they are a major mechanism for particle acceleration. Additionally, they directly contribute to magnetic turbulence in the magnetosphere unrelated to

Table A1
Dates of the SW high-speed streams selected for statistical analysis and spectral peak frequencies within four ULF frequency intervals.

N	Year	Month	HSS first day	HSS last day	Day of max ULF ampl.	Day of max SW speed	HSS duration	Spectral peak frequencies			
								1.5–2.7	2.8–3.8	3.9–4.9	5.0–6.0
1	1999	1	12	17	14	15	6	2.4	2.8		5.9
2		5	17	22	18	19	6	2.6	3.6	4.8	5.6
3		8	14	21	16	19	8	2.5	3.8	4	5.5
4		10	7	19	10	15	13	2.5	3.1	4.4	5.6
5			20	26	21	23	7	2.3	3.1	4.1	
6		12	1	11	4	5	11	2	3.4	4.7	5.5
7			29	5	31	1	8	2	3.8	4.6	5.7
8	2000	1	10	18	11	12	9	1.8	3	4.8	5.9
9			26	31	27	28	6	1.7	3.6		5.4
10		2	4	8	6	7	5	2.1	3.4	4.4	5.4
11			10	15	12	14	6	2	3.4	4.9	5.2
12			22	27	24	25	6	2.8	3.3	4.5	5.5
13		3	20	27	22	24	8	1.6	2.9	4.5	5.4
14		5	22	27	24	24	6	2.1	3.3	4.1	5.7
15		6	6	9	8	8	4	2.3	2.8	4.6	5.1
16		7	12	17	15	15	6	2.6	3.2	4.2	5.5
17		9	16	20	17	18	5		2.9	4.3	5.3
18		11	8	16	10	11	9	2.6	3	4.9	5.1
19		12	5	15	8	9	11	2.2	3.4	4.4	5.4
20	2001	3	26	30	27	28	5	2.5	3.2	4.2	5.7
21			30	4	31	1	6	2.4	3.9		5.9
22		4	3	6	4	5	4	2.7	3.6	4.8	5.2
23			10	15	11	13	6	2.5	3.7	4.7	5.5
24			27	30	28	28	4	2.7	3.8	4.7	5.3
25		10	18	24	21	22	7	2.5	3.2		
26		11	4	10	6	7	7	1.7	3.6	4.4	5.5
27			21	28	24	24	8	2.5	3.1	4.6	5.1
28	2002	1	9	16	10	11	8	1.9	3.3	4.9	5.7
29		2	3	9	5	6	7	2		4.8	5.1
30		3	3	8	4	5	6	2.6	3.6	4.9	5.6
31			29	3	30	1	6	2.4	3.3	4.3	5.6
32		4	18	21	19	20	4	2.6	3	4.3	5.2
33		5	22	25	23	24	4	1.8	3.2	4.3	5.6
34		10	23	26	24	25	4	2.2	3.5	4.3	5.4
35		11	4	8	5	6	5	1.8	3.3	4.2	5.1
36			9	14	11	12	6	2.2	3.4	4.2	5.3
37			18	24	21	21	7	2.1		4.5	5.4
38		12	6	11	7	8	6	2.6		3.9	5.9
39			26	31	27	28	6	2.3	3.8		5.8
40	2003	1	2	5	3	4	4	2.2	3.3	4.2	5.7
41			16	22	18	21	7	2.7	3.7		5
42		2	12	19	14	18	8	2.2			5.4
43			19	22	20	20	4	2.6	2.9		5.8
44		3	10	24	14	18	15	2.1	3.7	4	5.7
45			29	3	30	31	6		3.3	4.3	5.6
46		4	7	13	10	11	7	1.6	3.2	4.4	5.7
47		5	4	10	5	9	7		3.7	4.4	5.1
48			26	1	29	31	7	2.4	3	4.9	5.3
49		6	1	5	2	3	5	2.6	3.1	3.9	
50			5	12	7	8	8	1.8	3.3	4.5	5.4
51			16	21	18	19	6	1.6	3.3		

Table A1 (*continued*)

N	Year	Month	HSS first day	HSS last day	Day of max ULF ampl.	Day of max SW speed	HSS duration	Spectral peak frequencies			
								1.5–2.7	2.8–3.8	3.9–4.9	5.0–6.0
52			25	30	28	30	7	2	3	4	5.3
53		7	15	18	16	17	4	2.7	3.8	4.4	5.4
54			25	28	26	27	4	1.8	3.1	4.3	5.6
55		8	5	10	8	8	6	2.4	3.1	4.5	
56			19	24	21	22	6	2.4	3.7	4.3	5.3
57		9	7	12	9	10	6	1.8	3.6	3.9	5.7
58			15	20	17	18	6		2.9	4.4	5.8
59		10	12	17	14	15	6	1.5	3.8	4.1	5.2
60			27	2	29	31	7	1.8	3.3	3.9	5.4
61		11	3	6	4	4	4	2.4	2.9	4.3	
62			8	14	11	11	7	2	3.8	4.5	5.2
63			14	19	15	17	6	1.7	3.1	4.4	5.5
64			19	21	20	20	4	2.5	3.2	4.5	5.3
65			21	28	23	25	8	2.6	3.5	4.9	5.7
66		12	19	25	20	22	7	1.9	2.9	4.7	5.4
67	2004	1	1	8	3	7	8	2.2	3.8	4.3	5.4
68			21	24	22	22	4	1.7	3	4.3	5.1
69		2	10	14	12	13	5	1.8	3.7	4	5.9
70		3	24	31	27	28	8	1.7	3.8		5.4
71		11	6	13	7	10	8	2.4		4.1	5
72			28	4	29	30	7	2	3.1		5.4
73		12	15	20	17	17	6	2.3		3.9	5
74	2005	1	31	6	2	2	7	1.7		4.1	5.7
75			11	16	12	13	6	2.2			5.4
76			16	20	18	19	5	2.2	3.5	4.1	5.2
77			20	25	21	22	6	2.2	3.4	4.9	5.8
78			27	1	29	31	6	2.5		4.4	5.6
79		3	23	28	25	26	6	2.7		4	5.1
80		5	5	10	8	8	6	2.1	3.5	4.8	5.9
81			14	17	15	15	4	1.8		4.5	5.9
82		6	22	27	23	25	6	2.4	3		
83		7	8	15	10	13	8	1.8	3.2	4.9	5.8
84		8	23	27	24	25	5	2.4	3		5.5
85		9	8	14	11	12	7		3		
86		10	6	12	8	8	7	2.2		4.5	5.1
87	2006	4	8	12	9	10	5	1.6	2.8	4.7	5.3
88		8	6	10	7	8	5	1.8	3.8	4.1	5.9
89			26	31	27	28	6	2	3.4	4.8	
90		9	22	29	24	25	8	2		4.2	5.3
91		12	5	9	6	8	5	2.1	3		5.1
92			13	18	14	14	6	2.3			5.8
Number of spectral peaks in the selected frequency intervals:								87	78	76	83

Day_first is date of the 1st day of HSS; Day_last is date of the last day of HSS; D_Amax is date of a day when the daily ULF amplitude is maximal; D_Vmax is date of a day when the daily SW speed is maximal; N_of_days is the length of a HSS; 1.5–2.7—this column contains frequency of spectral peaks within 1.5–2.7 mHz range; 2.8–3.8—this column contains frequency of spectral peaks within 2.8–3.8 mHz range; 3.9–4.9—this column contains frequency of spectral peaks within 3.9–4.9 mHz range; 5.0-6.0—this column contains frequency of spectral peaks within 5.0-6.0 mHz range; If no value is in a column, there is no spectral peak in the corresponding range.

reconnection at the magnetopause (Potapov et al., 2009). The nature of the oscillations is generally different in the above regions, as are the wave sources. A number of cases, however, exhibit a clear connection between oscillations observed in different media. For example, Kepko and Spence (2003) (see also Kepko et al., 2002) found eight cases of high correlation between ULF spectra of the SW pressure oscillations and magnetic oscillations inside the magnetosphere in the frequency range of 0.5–2 mHz. They interpreted this founding as an evidence for the forced magnetosphere breathing under action of slow (period T>10 min) SW pressure fluctuations. For higher frequencies, 2–5 mHz, high and stable (throughout the solar cycle) correlation between wave amplitudes in the solar wind and on ground was found in (Potapov et al., 2012) suggesting direct penetration of these oscillations into the magnetosphere that serves as a passive or active filter. In this paper, we made an attempt to find any signs of the possibility that solar atmospheric oscillations observable by telescopes may contribute to the MHD wave spectrum of the solar wind at the Earth's orbit. If this hypothesis is proved, then the Sun does exert some wave influence on near-Earth space in the ULF range. In some cases, this might even be a resonant influence if the frequency of oscillations carried away from the Sun coincides with the eigenfrequency of one of the magnetospheric resonators. Earlier, a number of authors (Riley and Sonett, 1996; Thomson et al., 2001, 2007) tried to find correspondence between the SW fluctuations and solar *g*- and *p*-mode oscillations in the lower frequency range (up to 3 mHz), without direct comparison with these oscillations, though.

The results of our analysis provide certain evidence in support of the above hypothesis. This includes, first, the presence of a spectral peak in the spectrum of ULF oscillations measured at Earth's orbit, in the high-speed stream coming from a coronal hole – at the same frequency that oscillations were observed by a solar telescope two days earlier, in the FeI 6569 Å line, in the same coronal hole. Second, spectral peaks have been discovered with frequencies close to 5- and 3-min oscillations based on data from 92 high-speed streams from coronal holes and coronal mass ejections. Both the 5 and 3 min periods are characteristic of solar atmospheric waves. The former is often observed in the quiet Sun (photosphere) including coronal holes, while the latter is often observed above the sunspot umbrae (chromosphere) (Su et al., 2013).

It should be noted that we use here a technique of analysis similar to that implemented by (Viall et al., 2009) for calculation of the occurrence distributions of statistically significant apparent frequencies of periodic solar wind number density structures in the 0.5–5.0 mHz frequency range during 1995–2005. However, the results are different. Viall et al. (2009) do not mention frequencies between 2.8 and 3.8 mHz as the most probable: oscillations in this range have enhanced occurrence only in six of the nine overlaid three-year intervals (see Fig. 6 in (Viall et al., 2009)). The reason lies, to our mind, in different nature of initial data taken for the two analyses. We use magnetic observations during passing the Earth's orbit by the high-speed streams; Viall et al. (2009) took continuous measurements of the SW plasma density. As a result, first, frequency content of the solar wind ULF waves could be quite different within the HSS structure and in the background SW plasma. Second, plasma density fluctuations only reflect compressional disturbances in the SW, as opposed to magnetic oscillations that are characteristic of both compressional and Alfven-type waves. It is well known that Alfven waves are common in the high-speed streams (Borovsky and Denton, 2010).

At the same time, these results cannot be regarded as evidence of a direct link between solar oscillations and solar wind waves at the Earth's orbit. The oscillation spectrum at libration point *L*1, the measurement site, proved much more complex than the oscillation spectrum in the solar atmosphere. Therefore, the chief conclusion of this paper may be formulated as follows: it demonstrates the possibility that oscillations originating in the Sun and observed as Doppler shifts of spectral lines for various elements may contribute to the ULF wave spectrum at the Earth's orbit. Making more definite conclusions proving or rejecting this hypothesis would require additional research including, e.g. wave trajectory calculations in the interplanetary medium if we assume not only transportation of waves by the solar wind, but their propagation as well. Studies, both theoretical and experimental, of the ULF wave spectrum evolution in the solar wind between the Sun and the Earth would also be fruitful.

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Appendix A. A list of the SW high-speed streams selected for statistical analysis

See Table A1.

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