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ON THE POSSIBLE CONNECTION BETWEEN PHOTOSPHERIC 5-MIN OSCILLATION AND SOLAR FLARE MICROWAVE EMISSION

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Abstract. Dynamic spectra of low-frequency modulation of microwave emission from solar flares are obtained. Data of 15 bursts observed in 1989–2000 with Metsähovi radio telescope at 37 GHz have been used. During 13 bursts a 5-min modulation of the microwave emission intensity was detected with the frequency of $\nu_I = 3.2 \pm 0.24\ (1\sigma)$ mHz. Five bursts revealed a 5-min wave superimposed on a $\sim$1 Hz, linear frequency modulated signal generated, presumably, by coronal magnetic loop, this wave frequency is $\nu_{\mathrm{fm}} = 3.38 \pm 0.37\ (1\sigma)$ mHz. Both intensity and frequency modulations detected are in good agreement with the data on 5-min global oscillations of photosphere and with the data on the umbral velocity oscillations observed in the vicinity of sunspots. Possible role of p-mode photospheric oscillations in modulation of microwave burst emission is discussed.

1. Introduction

Solar atmosphere oscillates with a variety of periods ranging, mainly, within 3–60 min. These waves can be observed as sunspot umbral oscillations (Horn, Staude, and Landgraf, 1997), as a series of photospheric granulation images (Hoekzema, Brandt, and Rutten, 1998), as oscillatory modes in prominences (Sütterlin *et al.*, 1997), as oscillations of a hot soft X-ray loops (Kliem *et al.*, 2002), or as hot coronal EUV loop vibrations (Aschwanden *et al.*, 2002), and so on.

An outstanding oscillation mode, observed at different heights in solar atmosphere and even in the solar wind (Steffens and Nürnberger, 1998), is a 5-min period p-mode. Such phenomenon has a global character for the solar photosphere (Chaplin *et al.*, 1998), and is attributed to the stochastic generation of acoustic waves due to turbulence in the convection zone of the photosphere. It is suggested usually that acoustic waves can escape from convection zone into chromosphere owing to the "tunneling" effect (Brown, Mihalas, and Rohdes, 1986).

In the course of the observations of the Sun at microwaves the effects similar to changes of photospheric granulation images appear. The structures of radio sources above flocculae and sunspots vary in time which leads to the quasi-periodic pulsation of radio flux density with typical periods of 4–8 min (Kundu and Velusamy, 1974; Kislyakov, Nosov, and Tsvetkov, 1990). Note, that the event of chromospheric granulation, similar to that of the photosphere, has been found at the millimeter waveband (1.4–8 mm) (see e.g., Efanov, Moiseev, and Severny, 1974; Kislyakov *et al.*, 1975). Nevertheless, the temporal characteristics of the chromospheric granulation are still under study.

This paper is devoted to the new evidences of 5-min photosphere oscillations at microwaves during solar flare activity. Zaitsev *et al.* (2001a) have shown that in the dynamic spectra of low-frequency modulation of radio flux during flares the signals of 0.5–2 Hz with a frequency drift appear. Radio flux modulation of the flare active region – coronal magnetic loops (CML) – can be the result of eigen-oscillations of a loop. The frequency of such oscillations is proportional to the value of the electric current in a loop (Zaitsev *et al.*, 1998). Flare energy release occurs due to dissipation of the electric current, whereas the energy accumulation in a current-carrying loop is due to the current growing. Because the Q-factor of a loop – an equivalent electric circuit – is high enough, the deviation of modulation frequency follows to a linear law, e.g., radio flux density from a loop is modulated by a linear frequency modulation (LFM) signal. The sign of frequency drift corresponds to the phase of magnetic loop evolution: the frequency grows when the energy is accumulated and the frequency drops if the loop energy decreases (Zaitsev *et al.*, 2001b). In this paper, we are investigating many flare events when a slow modulation of microwave emission on the time scale of about flare duration (tens of minutes – hours) is accompanied by a fast quasi-periodic modulation with the period close to a 5-min photosphere oscillation. The results of observations of this new phenomenon are presented here and its possible connection with the 5-min acoustic oscillation of photosphere is discussed.

2. Data of Observations

We have used the selected data of solar radio bursts measured at 14-m radio telescope of Metsähovi Radio Observatory (Finland) at 37.5 GHz in 1989–2000. The angular resolution of antenna is 2.4 arc min. The sensitivity of the radio telescope amounts to $\sim$0.1 solar flux units (sfu), which is equivalent to the antenna temperature resolution of about 100 K. Radio flux digital data were obtained with a time resolution of 0.05 or 0.1 s depending of the operation mode of radio telescope. The digital data have been used for a time–frequency analysis in order to reveal the low-frequency modulations of the solar emission intensity. Two different methods were applied: the “sliding window” fast Fourier transform (FFT) and the Wigner-Ville nonlinear transform (WVT). The corresponding computer codes were described by Shkelev, Kislyakov, and Lupov (2002).

TABLE I

Eight-millimeter wavelength solar bursts list.

Date	Observation time (UT)	Time of burst peak (UT)	Peak intensity (sfu)	Group number	Active region position
06.22.1989	12:58–16:40	14:45	>40	5555	N25E60
05.19.1990	12:42–14:47	13:15	10.5	6064	S12W06
08.28.1990	08:20–10:50	09:06	>100	6233	N12E16
		09:10	45	6233	N12E16
		10:12	55	6233	N12E16
09.01.1990	06:40–8:20	07:14–07:16	3.0	6233	N13W34
03.23.1991	11:48–12:57	12:32	9.3	6555	S25E05
03.24.1991	10:01–11:34	10:18	8	6555	S25W03
		11:24	15	6555	S25W03
03.24.1991	13:41–15:11	14:11	>60	6555	S25W03
		14:18	50	6555	S25W03
05.07.1991	10:10–11:09	10:36	18	6615	S10W29
05.11.1991	12:09–14:02	∼13:20	>550	6615	S09W63
02.15.1992	08:56–09:58	09:32–09:41	>20	7056	S15W07
07.13.1992	06:55–08:20	08:07	≤10		
06.10.1993	05:43–07:10	06:25	100	7518	S11W85
06.27.1993	11:11–12:14	∼11:22	38	7530	S12E75
03.20.2000	10:29–11:32	10:54	6.0	8910	N22W32
03.23.2000	11:19–12:47	11:35	10	8910	N25W80
03.24.2000	10:35–11:39	11:27	3.0	8910	N23W85

In our previous paper (Zaitsev, Kislyakov, and Urpo, 2003), the 5-min oscillations in solar 8-mm wavelength emission were detected in two different modes: as a usual emission intensity (amplitude) modulation and as a sine-wave frequency modulation of the LFM signal. We have assumed this LFM signal to be generated by a CML responsible for the flare microwave emission. Several such events were analyzed whereas only few cases of the simultaneous intensity modulations were demonstrated. In this paper, we have considered 15 time profiles of the solar events that have taken place in 1989–2000.

The parameters of the bursts and their identification with the solar active regions are presented in Table I, according to the papers by Urpo *et al.* (1992a,b, 2003).

The date and the time of an observation are given in the first two columns. The 3rd column includes the time of the burst maximal intensity. Some events consisted of several bursts of comparable intensity. In this case, a corresponding number of moments are pointed out in the 3rd column and, respectively, several magnitudes are given in the 4th column presenting the burst intensities in sfu. Let us note that the papers by Urpo *et al.* (1992a,b, 2003) contain a more detailed description of the bursts than the one presented here. The last two columns of Table I include the optical data relevant to the corresponding event (the spots group number) and the active region coordinates determined by a radio mapping of the Sun (Urpo *et al.*, 1992a,b, 2003).

The time–frequency analysis of the burst profiles has been performed intentionally for the 5-min oscillations to be revealed. In order to improve the signal-to-noise ratio, the solar burst profiles were averaged on the time interval of 5–10 s (over 100 samples of data row). Besides, the burst profiles were approximated by polynomials in order to remove (by means of subtracting the approximating curve from a real-time profile) the powerful permanent constituents and, sequentially, to expand the dynamic range of the analysis of a comparatively weak modulations. The time–frequency analysis of intensity modulations was conducted using, mostly, the FFT. Figure 1a gives an example of a dynamic spectrum of the burst observed on 7 May, 1991, while Figure 1b presents this burst time profile. As it can be seen from Figure 1a, the dynamic spectrum of the burst shows a very intensive line at a frequency of $\nu_c \cong 2.5$ mHz.

The averaged spectrum of this line, in a relative spectral density (RSD) scale, is presented by Figure 2. Taking into account that this line is broad enough, and that the accuracy of its central frequency is not better than ±0.2 mHz, we can conclude that this line overlaps essentially the frequency $\nu_5 = 3.33$ mHz corresponding to the 5-min oscillations. It allows us to identify this line with the 5-min oscillations. We shall see below that in many cases the central frequencies of the detected lines are coincident, within the uncertainty of frequency determination, with the ν_5, however, in some cases we have to take into account the line width as well.

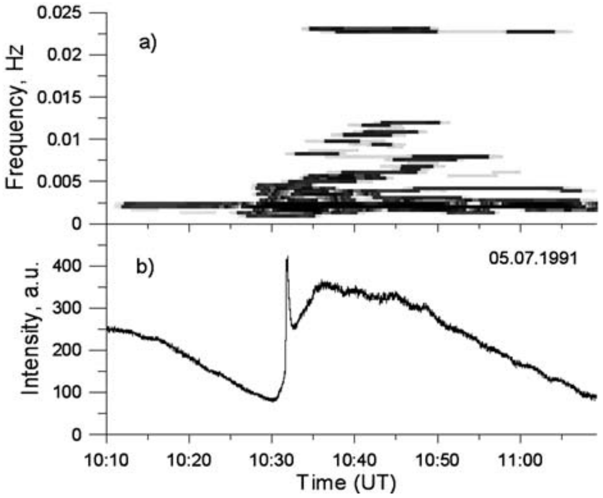

Figure 1. Low-frequency part of dynamic spectrum (a) and 8-mm burst time profile of the event observed on 07 May, 1991 (b).

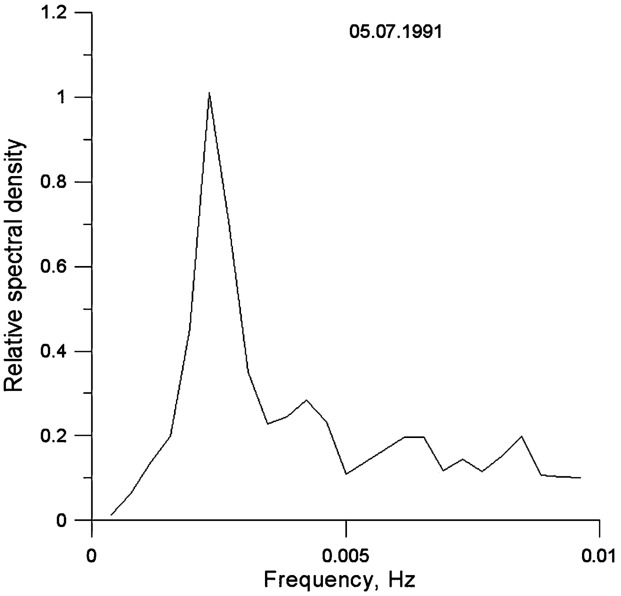

Figure 2. Microwave intensity oscillations: 2.5–2.7 mHz line spectrum observed on 07 May, 1991.

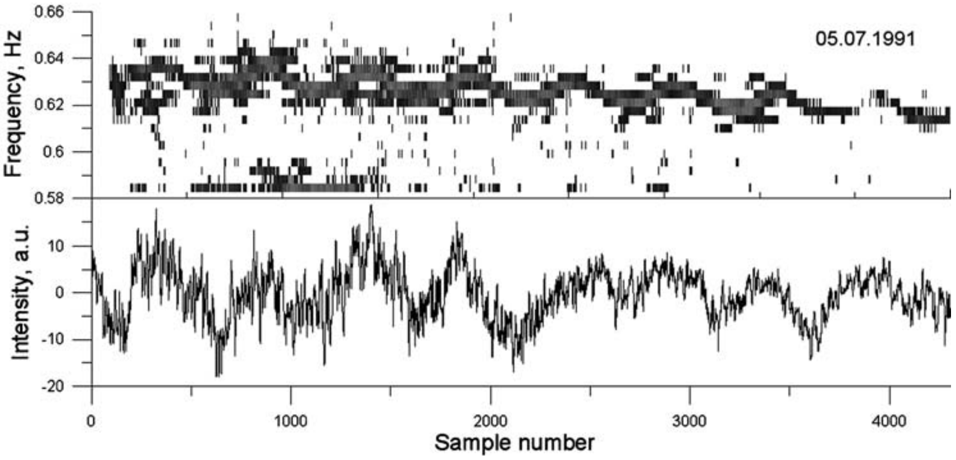

Figure 3. LFM signal frequency (the *top curve*) and the microwave intensity (the *bottom curve*) 5-min modulation observed on 07 May, 1991.

In conclusion of consideration of the event of 7 May, 1991, we have to mention the evident correlation between intensity and frequency oscillations as follows from Figure 3. The latter shows a sine wave (the top curve) with its frequency decreasing from ~0.64 to ~0.62 Hz. As it was mentioned above, such type LFM signals are attributed to the natural vibrations of coronal magnetic loops. The 0.6 Hz wave bears slow, quasi-periodic frequency deviations with the amplitude of 0.02 ± 0.002 Hz. The period of this slow modulation is estimated as 264 ± 24 s (Zaitsev, Kislyakov, and Urpo, 2003). Let us note that this LFM signal was detected using the WVT. The bottom curve in Figure 3 shows the correspondent part of the burst time profile where one can see the evident quasi-periodic intensity oscillations. Note, that this is a comparatively frequent case of the 5-min modulation visible by eye. The frequency and intensity modulations are, roughly, in phase and their frequencies are almost coincident within the measurement uncertainties. Besides, as it can be seen from Figure 1a, there is a slight increase of the intensity modulation frequency up to ~2.7 mHz at the end of the post-burst phase of time profile.

Another example of the solar emission intensity oscillations is presented in Figure 4a–c. Figure 4a illustrates the time profile of the burst observed on 13 July, 1992. The result of FFT time–frequency analysis of the burst can be seen from Figure 4b. The dynamic spectrum of Figure 4b shows two different parts. The lower part presents a powerful line with the central frequency of ~1.8 mHz at the very beginning of this oscillation, then its central frequency decreases down to ~1.2 mHz during the most intensive, final stage of oscillation. This lower part

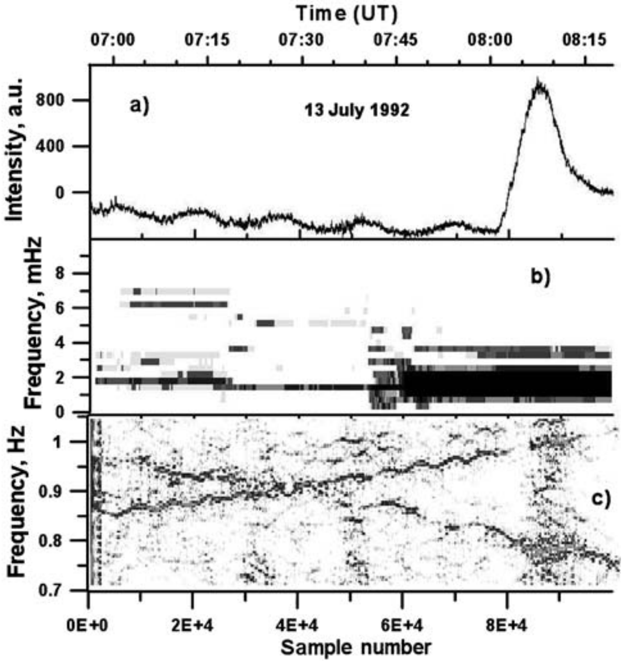

Figure 4. (a) Microwave time profile of event observed on 13 July, 1992. (b) Low-frequency part of its dynamic spectrum demonstrating the 3.2–3.4 mHz line (a 5-min oscillation) and a more powerful ~13.5-min line. (c) 1-Hz dynamic spectrum of the same event. One can see two LFM signals. The positive drift signal bears a 5-min modulation whereas the negative drift one is modulated by a 13.5-min oscillation.

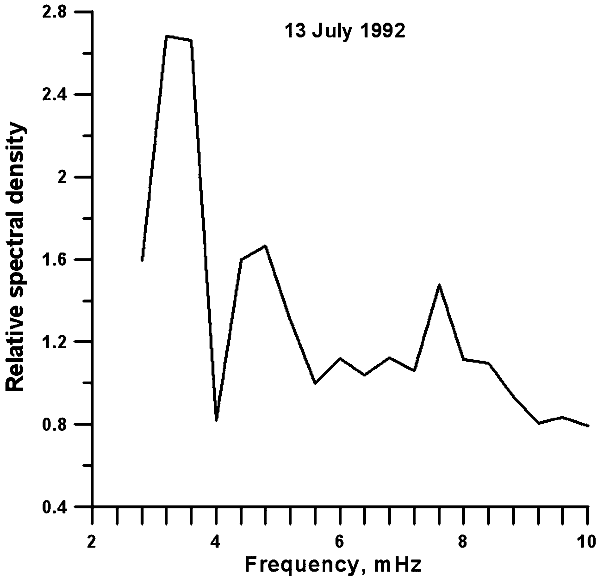

Figure 5. A 5-min modulation line spectrum observed on 13 July, 1992.

of dynamic spectrum is confirmed obviously by the event time profile itself. The second, upper part of the dynamic spectrum has no such visible confirmation as it presents substantially weaker oscillations. Here one can see a 5-min line with the frequency of ~3.2 mHz at the very beginning of event and, after a gap, its more intensive part with the frequency of ~3.4 mHz. There is also a hint of a line where frequency is decreasing from ~6.5 mHz at the start of the event to ~4 mHz at its end. Figure 5 shows averaged spectrum of 3.4 mHz line in RSD scale.

The event of 13 July, 1992 is remarkable also because it reveals the LFM signal with the quasi-periodic, 5-min modulation superimposed (Zaitsev, Kislyakov, and Urpo, 2003). Figure 4c shows the dynamic spectrum of two LFM signals detected in the course of time–frequency analysis of the burst time profile. One can see the LFM signal with a positive frequency drift (0.85 → 1.03 Hz); this signal is subject to the frequency deviation with the amplitude of 0.02 Hz whereas the period of this modulation amounts to 330 ± 10 s, i.e., corresponds to a 5-min oscillation. The second LFM signal has a negative frequency drift (0.96 → 0.75 Hz) and it also has a quasi-periodic frequency modulation with the period of ~13.5 min. Figure 4a and c shows in this case the remarkable negative correlation in the phases of intensity and frequency modulation.

The total results of the time–frequency analysis devoted to the search of 5-min intensity oscillation are compiled in Table II. The first two columns of this table give the date and the time of observation. The 3rd and 4th columns give the line frequency (with its uncertainty in brackets) and the line width at half intensity points. The time and duration of a 5-min oscillation are given in the 5th and 6th columns. The 7th

TABLE II

Solar emission intensity oscillations at 8 mm wavelength.

Date	Observation time (UT)	$F(\delta F)$ (mHz)	ΔF (mHz)	Oscillation time (UT)	ΔT (min)	RSD (Amplitude)	Comments
22.06.1989	12:58–16:40	3.1(0.2)	1.4	13:32–14:33	61	40.9(3.1)	Pre-burst stage
05.19.1990	12:42–14:47	3.0(0.1)	0.7	12:42–13:20	38	38(4.8)	GRF
08.28.1990	08:20–10:50			Not detected			
09.01.1990	06:40–8:20	3.4(0.1)	0.5	7:10–8:10	60	22(2.2)	Post-burst stage
03.23.1991	11:48–12:57	2.3(0.4)	1.2	11:58–12:44	46	21.8(1.1)	Post-burst stage
03.24.1991	10:01–11:34	4.2(0.2)	1.8	10:03–10:28	25	34(3.7)	Pre-burst stage
03.24.1991	13:41–15:11	3.3(0.2)	1.7	14:23–14:49	26	74.8(2.8)	Post-burst stage
05.07.1991	10:10–11:09	2.4(0.2)	0.9	10:12–11:08	56	1.0(0.04)	Post-burst stage
05.11.1991	12:09–14:02	3.8(0.2)	0.9	12:30–12:52	22	2.0(0.1)	Pre-burst stage
		3.3(0.2)	1.0	13:23–13:55	32	7.6(0.5)	Post-burst stage
02.15.1992	08:56–09:58	3.6(0.4)	3.2	08:56–09:58	62	3.1(0.05)	
07.13.92	06:55–08:20	3.2(0.2)	1.0	06:55–7:17	22	2.4(0.25)	
		3.4(0.2)	1.0	7:40–8:20	40	3.3(0.27)	
06.10.1993	05:43–07:10	3.4(0.1)	1.2	06:43–07:10	27	0.22(0.02)	Post-burst stage
06.27.1993	11:11–12:14	3.1(0.4)	2.6	11:04–11:26	22	33.1(2.6)	GRF
		2.7(0.4)	2.3	11:58–12:12	14	18.6(1.3)	
03.20.2000	10:29–11:32	3.1(0.4)	1.7	10:32–11:07	35	57(6.0)	
		2.3(0.4)	1.7	10:38–11:17	39	50(6.0)	
03.23.2000	11:19–12:47	2.3(0.4)	1.7	12:00–12:47	47	69(8.0)	GRF
03.24.2000	10:35–11:39			Not detected			GRF

column contains the peak RSD of a line. These values are comparable if they belong to the same observational session. Besides, the 7th column data make it possible to estimate the signal-to-noise ratio for a line (the rms errors are given in brackets). The last column presents information concerning the phase of development of the burst in question when the 5-min oscillations were detected.

As it follows from Table II data, the 5-min oscillations of solar 8 mm wavelength emission intensity can be considered as detected in 13 solar events from 15 events subject to investigation. The event of 28 August, 1990 has been accompanied with two powerful bursts of radio emission and they, probably, prevented the detection of a comparatively weak 5-min intensity modulation. Contrary to this case the event of 24 March, 2000 shows a low power burst; however, the search for 5-min line in this case was unsuccessful. We can, therefore, mention 17 cases of data reduction when the 5-min oscillation line was detected. In six cases, we identified the 5-min oscillations with a wide blending line whose center frequency was shifted from ν_5. In 11 cases, the detected line frequency is coincident with ν_5 within the

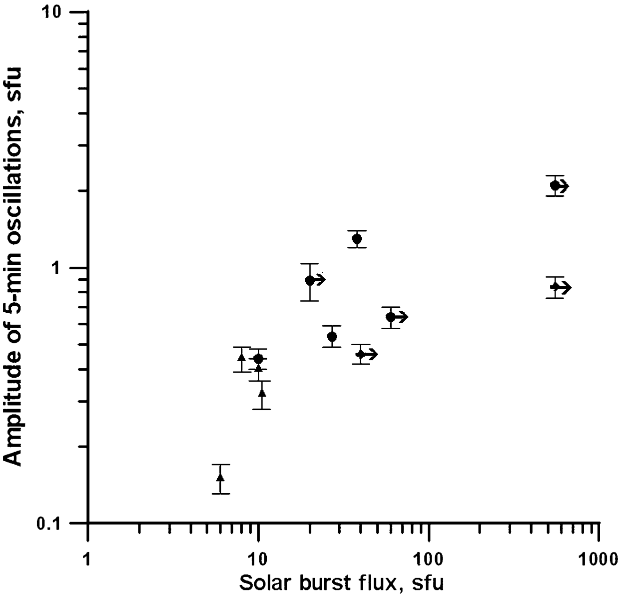

Figure 6. The absolute amplitude of a 5-min modulation observed during solar flares at 8-mm wavelength vs. the flare intensity (both in sfu). The *filled circles* denote the post-burst data whereas the *triangles* give the pre-burst points.

frequency measurement uncertainty. It is worth to note in this regard that the line of global acoustic oscillations of photosphere is wide enough as well (the energy spectrum width of the line is ~0.6 mHz while the center frequency is $\nu_{\mathrm{ph}} = 3.2 \pm 0.3$ mHz (Chaplin *et al.*, 1998). The latter is in perfect agreement with the frequency measurements of the 8-mm wavelength intensity oscillations as we can see later.

Let us note that the absolute amplitudes of a 5-min intensity modulation seem correlated with the peak flux intensity under microwave burst relevant (see the 4th column of Table I and the 7th column of Table II). Figure 6 presents the absolute amplitude of a 5-min intensity modulation versus the microwave burst intensity. Only the cases of ν_c coincident with ν_5 were considered. One can see that the post-burst amplitudes of a 5-min modulation (the filled circles) exceed, as a rule, the corresponding pre-burst values (the filled triangles). The arrows imply that the peak value of the burst intensity can be underestimated as the signal has gone off scale.

The solar emission intensity oscillations data can be compared with the 5-min oscillations detected as frequency modulated signals similar to those described above when considering the events of 7 May, 1991 and 13 July, 1992. Table III summarizes the 5-min oscillation data detected in a mode of frequency modulation of LFM signals and in a mode of pulse series of short LFM signals (chirps). The 1st column of Table III gives the date and time of observation. The 2nd column

TABLE III

Parameters of 5-min pulse and frequency modulation of solar microwave emission.

Date and time of event (UT)	Carrier frequency (Hz)	Period (s)	Frequency deviation (Hz)	Modulation type
06.22.89 (12:58–16:40)	1.35 → 1.8	311 ± 9	0.35–0.55	PM
05.19.90 (12:42–14:47)	1.2 → 1.5	291 ± 8	~0.3	PM
	1.5 → 1.8	207 ± 7	~0.3	PM
08.28.90 (08:20–10:50)	2.0 → 2.3	295 ± 10	0.05 ± 0.01	FM
09.01.90 (06:40–8:20)	1.75 → 2.0	328 ± 16	0.07 ± 0.015	FM
03.24.91 (10:01–11:34)	0.05–0.2		Not detected	
03.24.91 (13:41–15:11)	0.1–0.5		Not detected	
05.07.91 (10:10–11:10)	0.635 → 0.62	264 ± 24	0.02 ± 0.002	FM
07.13.92 (07:00–08:20)	0.85 → 1.03	330 ± 10	0.025 ± 0.002	FM
06.27.93 (11:10–12:15)	0.77 → 0.72	264 ± 24	0.02 ± 0.005	FM

presents the carrier frequencies of the LFM signals detected. The repetition periods under pulse modulation (PM) and the periods of quasi-periodic frequency modulation (FM) are given in the 3rd column. The frequency deviations under FM are presented in the 4th column whereas the last column indicates the type of 5-min modulation.

Let us consider the data of first two lines in Table III (the events of 22 June, 1989 and those of 19 May, 1990). Under events of 22 June, 1989, a long train of comparatively short (~58 s each) LFM pulses (chirps) was detected (Zaitsev *et al.*, 2001a,b, 2003) using the WVT. The repetition frequency of these chirps amounts to 311 ± 9 s and corresponds to the 5-min oscillation of photosphere. As it was argued by Zaitsev *et al.* (2001a,b, 2003), the carrier frequency of these chirps corresponds to a natural oscillation of the CML as a sequence of the fast magneto-sonic waves excited within magnetic tube. The 5-min repeated pulses can be attributed to the kink-mode (Zaitsev *et al.*, 2001a,b, 2003) of loop oscillation possibly synchronized with the acoustic waves of photosphere. This possibility will be discussed in more detail below.

The event of 19 May, 1990 demonstrates two independent trains of chirps occupying the adjacent carrier frequency intervals: 1.2–1.5 and 1.5–1.8 Hz (Zaitsev *et al.*, 2001a,b, 2003). The lower interval pulses have the duration of ~200 s and the repetition period of 291 ± 8 s; the latter is very close to the 5-min oscillation of photosphere. The upper interval pulses are more short (~120 s each) and are more frequent (the repetition period is 207 ± 7 s). The last period can be considered as corresponding to the 3-min oscillation typical for the lower chromosphere. We note that the 5-min intensity oscillations were certainly detected during both chirp events (22 June, 1989 and 19 May, 1990) as follows from the data of Table II.

The LFM signals of long duration are cited in the rest of the Table III. Two events we have discussed already; there are only three other cases when a 5-min frequency modulation was detected: 28 August, 1990, 01 September, 1990, and 27 June, 1993. As the FFT as the WVT were applied. These LFM signals 5-min frequency modulation was described by Zaitsev, Kislyakov, and Urpo (2003). We added only two cases when the slow LFM signals were detected whereas a 5-min FM was absent (two observing sessions on 24 March, 1991). We can also mention that the 5-min intensity oscillations were not detected only in the case of event of 28 August, 1990. The probable reason was pointed out above.

3. Discussion

The data mentioned in the previous section can be used for a comparative study of radio observations of FM with the measurements of solar low-degree p-modes (Chaplin *et al.*, 1998). Therewith it should be noted that the Birmingham Solar-Oscillations Network (BiSON) collected the data of multi-month synchronous observations at six BiSON sites (Chaplin *et al.*, 1998). In this context, the statistical analysis of the parameters in Tables II and III seems desirable. The mean value of the period of frequency modulation of solar flare microwave emission is $T_{\mathrm{fm}} = 296.2 \pm 32.5\ (1\sigma)$ s, so the frequency is $\nu_{\mathrm{fm}} = 3.38 \pm 0.37\ (1\sigma)$ mHz. Note that the deviation standard of T_{fm} is substantially higher than a separate measurement accuracy of data in Table III. Power spectrum of the photosphere low-degree ($l = 0$) p-mode has a maximum near $\nu_{\mathrm{ph}} = 3.2 \pm 0.3$ mHz which fits well to the mean frequency of FM radio signal ν_{fm}. The bandwidth of the energy spectrum of photosphere acoustic oscillations is about 0.6 mHz (Chaplin *et al.*, 1998). Hence, it seems that resonant line of 5-min oscillations, observed in a FM mode at microwaves, has the same or even larger Q-factor ($Q \geq 10$) compared to the resonant curve of overall photosphere oscillations.

As to the 5-min line intensity oscillations at microwaves (Table II), the average on 12 measurements of their central frequencies ν_{c} amounts to $\nu_{\mathrm{I}} = 3.2 \pm 0.24\ (1\sigma)$ mHz. The selected values of ν_{c} ranged within 2.7–3.8 mHz. The mean Q-factor of these lines is about 3, slightly lower than the Q-factor of acoustic oscillations. These results are also in a satisfactory agreement with the optical observations.

However, this comparison is quite formal for the following reasons. First, the cited photospheric oscillations have a global character whereas the data on power spectra were obtained in 1989–2000, near the solar activity cycles 22/23. Solar microwave bursts are generated as a rule in flaring magnetic loops and were observed in the period close to the maximum of solar activity (cycle no. 22). Second, the energy spectrum of the photosphere oscillations is more proved statistically because multi-month observations have been used, whereas microwave solar bursts under investigation have a typical duration of about hour and we have used 15 events for the analysis only. Therefore, it is natural to compare our results with the study of sunspot umbrae oscillations (Horn, Staude, and Landgraf, 1997). According to the latter paper, the spectral density of the mean squared velocity $\langle v_s^2 \rangle$ peaks at $\nu_s \approx 3$ mHz. The half intensity width of the $\langle v_s^2 \rangle(\nu)$ curve is $\Delta\nu_s \approx 0.37$ mHz being in good agreement, if to take into account the accuracy of measurements, with the microwave 5-min line width. Note that overall 5-min oscillation of the photosphere leads to $\Delta\nu_{\mathrm{ph}} \sim 0.6$ mHz.

We can conclude that coincidence of periods of FM radio signals, a 5-min oscillation at microwaves, and photosphere oscillations cannot be considered as an occasional event. In this context, it is necessary to discuss the possible mechanisms of relation between photosphere oscillations and corresponding MW modulations generated in solar magnetic loops.

Essential, that the 5-min acoustic waves do not penetrate directly into corona being reflected by the chromosphere transition region (Wedemeyer *et al.*, 2004 and references therein), as their frequency is lower than the acoustic wave cutoff frequency

$$\omega_s = g\gamma/2c_s, \tag{1}$$

where g is the gravity, γ is the specific heat ratio, and c_s is the sound velocity. Under $T \approx 5000$ K, Equation (1) gives the acoustic cutoff frequency $\omega_s/2\pi \approx 5$ mHz exceeding the frequency of a 5-min photospheric oscillation. It implies that this wave is reflected from the layer of temperature minimum.

On the other hand, we can see the different evidences of the presence of 5-min oscillations in the solar corona. As it was shown above, this presence is manifested in the microwave emission of the flare regions as an intensity- and FM-modulations arising, probably, within coronal magnetic loops. In this regard, we discuss below three possible ways for the acoustic 5-min waves to penetrate to the coronal levels: (1) a tunnel effect, (2) the plasma heating within the CML, and (3) the CML electric current modulation by a photospheric oscillation.

3.1. TUNNEL EFFECT

Regardless of the main part of a 5-min photospheric wave energy being reflected from the temperature minimum region, this wave can seep partly through the barrier as a combination of non-propagating and evanescent modes of waves analogous to the wave penetration through the quantum-mechanical barrier. This process is known as a wave tunnel effect, it was considered as applied to the 5-min photospheric oscillation by Zhugzhda (1972). However, the wave energy decreases exponentially if the length of a penetrating wave is small in comparison to the barrier extension in space. As it is very well known (see e.g., Wedemeyer *et al.*, 2004 and references therein), the 5 min oscillations form a standing wave governing the periodic velocity shifts under heights $h_c \leq 500$ km over the photosphere. The acoustic cutoff frequency is ∼5 mHz, and the 5-min wave becomes evanescent under $h_c \sim 1000$ km. In this region, a 3-min period of acoustic oscillations is dominant (Wedemeyer *et al.*, 2004).

3.2. CML PLASMA HEATING

The second opportunity of the photospheric oscillations impact on a CML microwave emission could be connected with the 5 min acoustic wave penetration into the loop through the heated foot points. The CML foot points can be heated essentially due to strong electric current inside a loop or due to a flare. Both the reasons, in turn, can smooth the sharp temperature gradient, thus making it possible to transport the 5-min oscillations into CML.

3.3. MODULATION OF ELECTRIC CURRENT WITHIN CML

Taking into account the discussion of two above-mentioned ways for acoustic waves to affect the microwave emission of a CML, we consider the third one, as more plausible, in detail. The converging convective plasma flows can form magnetic loops with footpoints at the nodes of several supergranulation cells. In the course of this process, the electromotive force $(\vec{V} \times \vec{B})c^{-1}$ produces a loop electric current flowing through the corona, from one foot-point of the loop to another, and closing through the photosphere (Figure 7). This electric current bearing magnetic loop can be considered as an equivalent electric circuit (Zaitsev *et al.*, 1998). The resonant frequency of this circuit lies usually near 1 Hz. The circuit natural oscillations modulate the CML microwave emission intensity just due to the electric current periodic changes. Periodic modulation can be detected by means of spectral

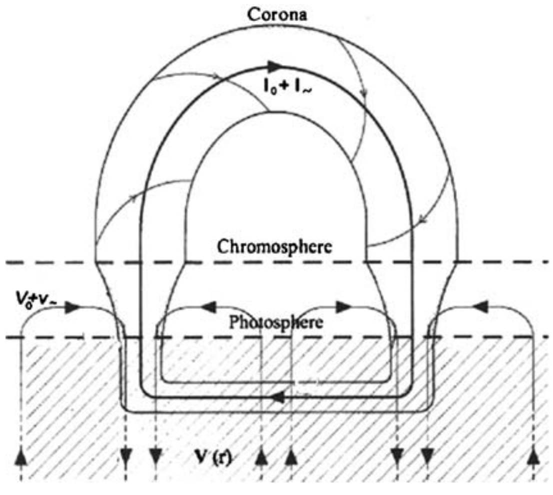

Figure 7. Coronal magnetic loop interaction with the acoustic waves in photosphere.

analysis of the microwave intensity time series, and presents a narrow band, linear frequency modulated signal. The frequency of LFM signal is proportional to the CML electric current magnitude (Zaitsev *et al.*, 1998): $\omega = AI$, while the current I, in turn, is proportional to the velocity of photospheric convection (Khodachenko and Zaitsev, 2002) according to the expression $I = DV$. The constants A and D are dependent on the loop geometry and plasma parameters. The 5-min photospheric velocity oscillation causes the adiabatic change of the current magnitude thus resulting in synchronous frequency modulation of LFM signal. That is the parametric interaction between natural oscillations of a CML (as an equivalent electric circuit) and of a slower 5-min oscillation of photosphere.

The slow (in comparison with the LFM period) oscillation of a circuit current can be described by the following equation (Zaitsev *et al.*, 1998, 2001b)

$$\frac{L}{c^2}\frac{\partial I}{\partial t} + R(I) \quad I = \frac{|V_{\mathrm{r}}|h}{rc^2}I, \tag{2}$$

where L is the inductance; $R(I)$ is a circuit resistance depending, under the loop self-consistent model, of the current magnitude (Zaitsev *et al.*, 1998); V_{r} is the convection velocity in loop foot points; $2r$ is the loop thickness; h is a height interval where the electromotive force acts. Under $I = I_0$ (stationary case) $R(I_0) = |V_{\mathrm{r}0}|h/(rc^2)$ and one can obtain the steady-state current magnitude.

Assuming $|V_{\mathrm{r}}| = V_0 + V_{\sim}\sin(\Omega t)$ and $I = I_0 + I_{\sim}$, one can make a linear approximation to Equation (2) in vicinity of a steady state:

$$\frac{\partial I}{\partial t} + \frac{2R(I_0)c^2}{L}I_{\sim} = \frac{V_{\sim}hI_0}{rL}\sin\,\Omega t. \tag{3}$$

Using Equation (3) we obtain the steady-state oscillation induced by the photosphere

$$I_{\sim} = \frac{V_{\sim}hI_0}{\sqrt{4R^2(I_0)c^2 + \Omega^2L^2}}\sin(\Omega t - \gamma), \quad \text{and} \quad \tan\gamma = \frac{\Omega L}{2R(I_0)c^2}. \tag{4}$$

Therefore, the convection velocity and the current oscillation amplitudes are connected in accordance with the expression

$$\frac{I_{\sim}^{\mathrm{m}}}{I_0} = \frac{hV_0}{\sqrt{4h^2V_0^2 + \Omega^2L^2r^2}}\frac{V_{\sim}}{V_0} \cong \frac{hV_0}{\Omega Lr}\frac{V_{\sim}}{V_0}. \tag{5}$$

The observed LFM signal reciprocal frequency deviation equals to $\Delta\omega/\omega = I_{\sim}^{\mathrm{m}}/I_0 \cong 10^{-2}$. Adopting $\Omega = 2 \times 10^{-2}$ (it corresponds to the period $T = 2\pi/\Omega \cong 5$ min), $L = (1/4) \times 10^9$ cm, $r = 10^7$ cm, $h = 10^8$ cm, and $V_0 = 10^5$ cm s^{-1}, we obtain from Equation (5) the reciprocal amplitude of convection velocity oscillations: $V_{\sim}/V_0 = 0.2/0.8$. The observed velocity amplitudes under 5-min oscillation range within 0.1–0.4 km s^{-1} with the mean value in photosphere about 0.4 km s^{-1} (Leighton, 1960). These velocities are sufficient to provide the ratio $V_{\sim}/V_0$ necessary for a 5-min modulation of the microwave emission.

Modulation effect inside a coronal magnetic loop due to 5-min photospheric oscillations can be amplified also owing to the acoustic wave frequency coincidence with the natural acoustic frequency of the loop, i.e., under condition $\nu_{\mathrm{ph}} \approx 3\,\mathrm{mHz}$ $\approx c_s/\ell$, where ℓ is the loop length and c_s is the loop sound velocity. This is the case of resonance under acoustic loop excitation with the photospheric oscillations as an external source. One can estimate the parameters of a possible candidate-loop if to adopt $c_s = 10^7\,\mathrm{cm\,s^{-1}}$ and $\Omega = 2 \times 10^{-2}$, then the resonant length of a loop turns to be equal to $\ell \cong 3 \times 10^9$ cm. Such loops are expected to produce an outstanding respond to the photospheric oscillations in comparison with the loops of non-resonant lengths.

We can try now to find the reason of a 5-min modulation of the microwave emission intensity and of the CML natural LCR-oscillation frequency. That is the acoustic oscillation of the loop as a whole with the period of $T \approx \ell/\mathrm{c}_s$ or the loop electric current modulated by 5-min oscillation of the photosphere. The observational results, at least in the cases of the modulation of natural frequency of LCR-oscillation revealed, support the second possibility. Indeed, the observed variations of a loop's oscillation frequency correspond to the changes of magnetic field of the order of $\Delta B/B \approx \Delta I/I \approx 10^{-2}$. Such strong variations cannot be produced by an excitation of acoustic waves in the loop as its diamagnetic plasma requires in this case the acoustic wave with the reciprocal pressure amplitude of $\Delta p/p \approx (1/2\beta)(\Delta B/B) \approx 5 \times 10^{-3}/\beta$, where $\beta = 8\pi p/B^2$ is the ratio of gas-kinetic pressure to magnetic field pressure in the loop. Under typical flaring magnetic loop parameters ($B \approx 10^2$ G, $n \approx 10^9$–$10^{10}\,\mathrm{cm}^{-3}$, $T \approx 10^6$ K), it gives $\Delta p/p = 1.4/14$ unlikely for an acoustic oscillations and more appropriate for strong shock waves.

One can obtain the analogous estimations using the data on 5-min microwave emission intensity oscillations during a flare if to adopt the gyro-synchrotron mechanism of this emission generation (Dulk, 1985). If the fast electrons responsible for microwave emission have a power energy spectrum $f(E) \propto E^{-\delta}$, then their microwave emission intensity is proportional to $B(\nu/\nu_{\mathrm{B}})^{-1.22+0.9\delta} \propto B^{-0.22+0.9\delta}$. Under typical spectrum indices within $2 \leq \delta \leq 7$, the radio emission flux is dependent on the source magnetic field as $F_\nu \propto B^{(1.58/6.08)}$. As it follows from Tables I and II data, the reciprocal amplitudes of 5-min oscillation of microwave emission burst flux range within (0.015/4)% and are correspondent to the relative variations of the loop magnetic field of the order of $\Delta B/B \approx 2(10^{-3}/10^{-2})$. Such magnetic field variations are too strong in order to be produced by a direct acoustic wave excitation within CML as it requires the acoustic wave pressure variations of the order of $\Delta p/p \approx 0.3/3$, what is improbable.

Thus, it is more likely that a 5-min modulation of the flare microwave emission is connected with the loop electric current modulation due to 5-min oscillations of the photospheric convection velocity. The current modulation produces, in turn, the variations of the natural oscillation frequency of a flaring loop as an equivalent electric circuit, and the microwave emission intensity modulation, which is, assuming the gyro-synchrotron mechanism of emission, in phase with the frequency modulation (see Figures 3 and 6).

Therefore, one can conclude that the microwave 5-min oscillations manifest a new type CML-photosphere connection. In this case, we can consider the parametric interaction of the natural oscillations of CML as an equivalent electric circuit with the acoustic 5-min oscillation of the photosphere. This interaction results from the loop electric current modulation (and, sequentially, the LCR-oscillation frequency modulation) by the photospheric acoustic waves.

Note that the relation between the photospheric oscillations and parameters of solar microwave emission is not well understood yet. It is known that solar active region can contain a number of magnetic loops. In this situation, a loop–loop interaction is possible and the modulation of loop eigen-modes can be the result of such coalescence (Zaitsev and Khodachenko, 1997). It is possible, that the double LFM signals observed sometimes in the microwave emission during solar flare (see e.g., Figure 4) are connected with the loop–loop interaction (Khodachenko *et al.*, 2005). In addition, the changes in the structure of the emission source can be more effective similar to the processes observed in the photosphere (Hoekzema, Brandt, and Rutten, 1998).

4. Conclusions

Based on the analysis of 15 selected solar microwave events observed at 8-mm wavelength using the 14-m radio telescope of Metsähovi in 1990–2000 (Table I), we revealed 5-min frequency and intensity modulations and can make the following conclusions:

1. Periods of “5-min” frequency modulation are within 260–330 s and the frequency deviation occupied the interval 0.02–0.07 Hz. The average value of frequency modulation is $\nu_{\mathrm{fm}} = 3.38 \pm 0.37\ (1\sigma)$ mHz and is coincident, within the measurement uncertainty, with ν_5. A 5-min intensity modulation was detected during 13 bursts (the line identified in 17 cases) and was present in almost all cases (excluding one) when the frequency modulation was observed. The average value of frequency of intensity modulation turns out to be equal to $\nu_{\mathrm{I}} = 3.2 \pm 0.24\ (1\sigma)$ mHz. Both values (ν_{fm} and ν_{I}) are in good agreement as with the global photospheric oscillations ($\nu_{\mathrm{ph}} = 3.2 \pm 0.3$ mHz) as with the sunspot velocities oscillations ($\nu_{\mathrm{s}} \approx 3 \pm 0.37$ mHz).
2. Correlation between spectral density of FM waves and the flux density of solar microwave emission is found. In some cases, the changes in frequency deviation and FM were synchronized with oscillations of the microwave emission level. The absolute amplitudes of a 5-min intensity modulation are correlated with the relevant microwave burst intensities. All these connections cannot be an instrumental factor and support the solar origin of a 5-min modulation described above.

3. We interpret the microwave “5-min” modulation as the modulation of the CML – sources of flare microwave emission – electric current (and, sequentially, the LCR-oscillation frequency modulation) by the photospheric acoustic waves. Both frequency and Q-factor of line of “5-min” modulation are very close to the corresponding parameters of 5-min photospheric oscillations. This is strong indication on the generic connection of solar photosphere with the chromosphere and low corona where the sources of microwave emission are located. This connection can be realized also via the CML, which is closed through the photosphere. Detection of 5-min MHD oscillations in microwave emission from two coronal magnetic loops (Zaitsev *et al.*, 2001a) strongly supports this suggestion.

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