RADIO SIGNATURE OF FRAGMENTED ELECTRON INJECTION INTO A CORONAL LOOP

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Abstract. High-time-resolution observations of an unusual event of 1991 November 17, 07:04 UT at 2.5 and 2.85 GHz are presented. The event demonstrates sophisticated fine time structure including sudden reductions and quasi-periodic pulsations about various 'zero' levels. It is shown that the sudden reductions (≈30–100 ms) can be produced with upward-injected >100 keV electron beams filling the loss-cone. In such a case the acceleration is proceeding in a dense plasma layer with number density $n > 2.5 \times 10^{10}$ cm^{-3}. The shortest time scale of the fragmented injection is $\tau_{\rm inj}^{\rm min} \approx 30$ ms. Several different pulsating regimes arising due to the wave-particle and wave-wave interactions are considered. A theoretical mechanism with the nonlinear oscillations of Langmuir waves at the different steady-state levels provides the best agreement with the observed pulsations. The reduced steady-state level of the second train of pulsations is connected with the long (quasi-continuous) injection of electrons filling the loss-cone, which reduced the wave energy level. Physical parameters of the radio source were obtained. On the other hand, ECM nonlinear pulsations seem to be responsible for the radio pulsations observed in dMe stars.

1. Introduction

Ultra-fast time structures in the radio emission of solar flares contain important information on charged particle acceleration processes, on the particle dynamics in a flare, and on the emission mechanisms. The pioneer observations of the rapid fluctuations in microwave bursts (Droge, 1977; Slottje, 1978; Kaufmann *et al.*, 1980) have been explained in terms of the electron cyclotron maser (ECM) emission (Holman, Eichler, and Kundu, 1980; Melrose and Dulk, 1982; Vlahos, 1987). On some observational basis, Kaufmann *et al.* (1984), Benz (1985), Benz and Aschwanden (1991), and Vlahos (1993) have proposed an idea on the energy release fragmentation in flares. However, further observations revealed a variety of fine structures in microwave solar emission, and those cannot be understood in the framework of a single emission mechanism.

In the period from 1989 to 1993 we recorded at the Crimean Astrophysical Observatory about 150 events with superfine time structures at 2.5 and 2.85 GHz (Stepanov and Yurovsky, 1994; see also Stepanov and Yurovsky, 1990; Yurovsky, 1991, 1992a, b). In particular, broad-band pulsations, narrow-band spikes, and microwave 'type III bursts' were observed. The event of 17 November, 1991 is one of the most intriguing. We believe that the recurrent injections of high-energy particles into a magnetic trap are responsible for spectral and temporal

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peculiarities in that microwave burst. It is worth noting that the process of high-energy particle injection into magnetic traps is an important topic both in laboratory plasma physics (Roque and Gregory, 1972; Dimov *et al.*, 1993) and in astrophysical circumstances such as solar flares (Zaitsev and Stepanov, 1975; Benz and Kuijpers, 1976; Aschwanden *et al.*, 1993), stellar radio bursts (Bastian *et al.*, 1990), Earth's radiation belts (Vershinin *et al.*, 1972; Bespalov and Trakhtengertz, 1986), etc.

This paper considers the November 17, 1991 radio burst, which shows an irregular series of 30–100 ms sudden reductions and short trains ($\approx$1 s) of quasi-periodic pulsations. Section 2 presents the relevant observations at 2.5 and 2.85 GHz and the background. In Section 3 an attempt is described to explain the sudden reductions as the result of the loss cone filling with new injected electrons. Then, in Section 4, we compare various theoretical mechanisms of quasi-periodic radio pulsations and conclude that a model with the Langmuir wave-wave interaction fits the observations better. A discussion and the main conclusions are given in Section 5.

2. Observations

At 07:00–07:12 UT on November 17, 1991 a flare of GOES X-ray class M1.1, Hα importance SF, occurred in NOAA active region 6929 at heliographic coordinates S11 E86. The flare was accompanied by radio emission recorded in the range from 650 MHz to 9.3 GHz (*Solnechnye Dannye*, 1991; *Solar Geophysical Data*, 1992). Overall time profiles were measured at 2.5 and 2.85 GHz in the Katzively, Crimea, and in HXR range 25–100 keV by GRO (Aschwanden, 1993) and are shown in Figure 1(a–c).

Peaks of radio emission flux at 2.5 GHz (209 s.f.u.) and at 2.85 GHz (258 s.f.u.) occurred at 07:06:40 UT, simultaneously with the peak at 2.95 GHz ($\approx$200 s.f.u., station GORK). At the higher frequencies, 5.2, 9.1, 9.3 GHz, the peaks occurred at the time 07:08:12 UT synchronously with the maximum of the HXR emission recorded by GRO with 1.025 s time resolution in the 25–100 keV range.

Superfine time structure ($\approx$10–100 ms) appeared at 07:05:30 UT and lasted over the whole impulsive phase at 2.5 and 2.85 GHz till 07:07:20 UT. It consisted of irregular absorption features (sudden reductions) at both frequencies lasting from 30 to 100 ms. Figures 2 and 3 show a small (6 s) part of the record 07:06:31–37 UT with sudden reductions and two short ($<$1 s) trains of broad-band pulsations. At the same time the HXR flux was enhanced, while the main HXR peaks were observed later, see Figure 1(c).

A cross-correlation study of all fragments 07:05:30–07:07:20 UT of the record shows (Figures 2 and 3 present small part of the data) that there is a 9–22 ms delay between the 2.85 and 2.5 GHz records, which corresponds to the frequency drift rate $\mathrm{d}f/\mathrm{d}t = -(16–39)$ GHz s^{-1}. In the first pulse train (period $\tau \approx 40$ ms) the delay was about 9 ms (Figure 2), i.e., close to the temporal resolution (the

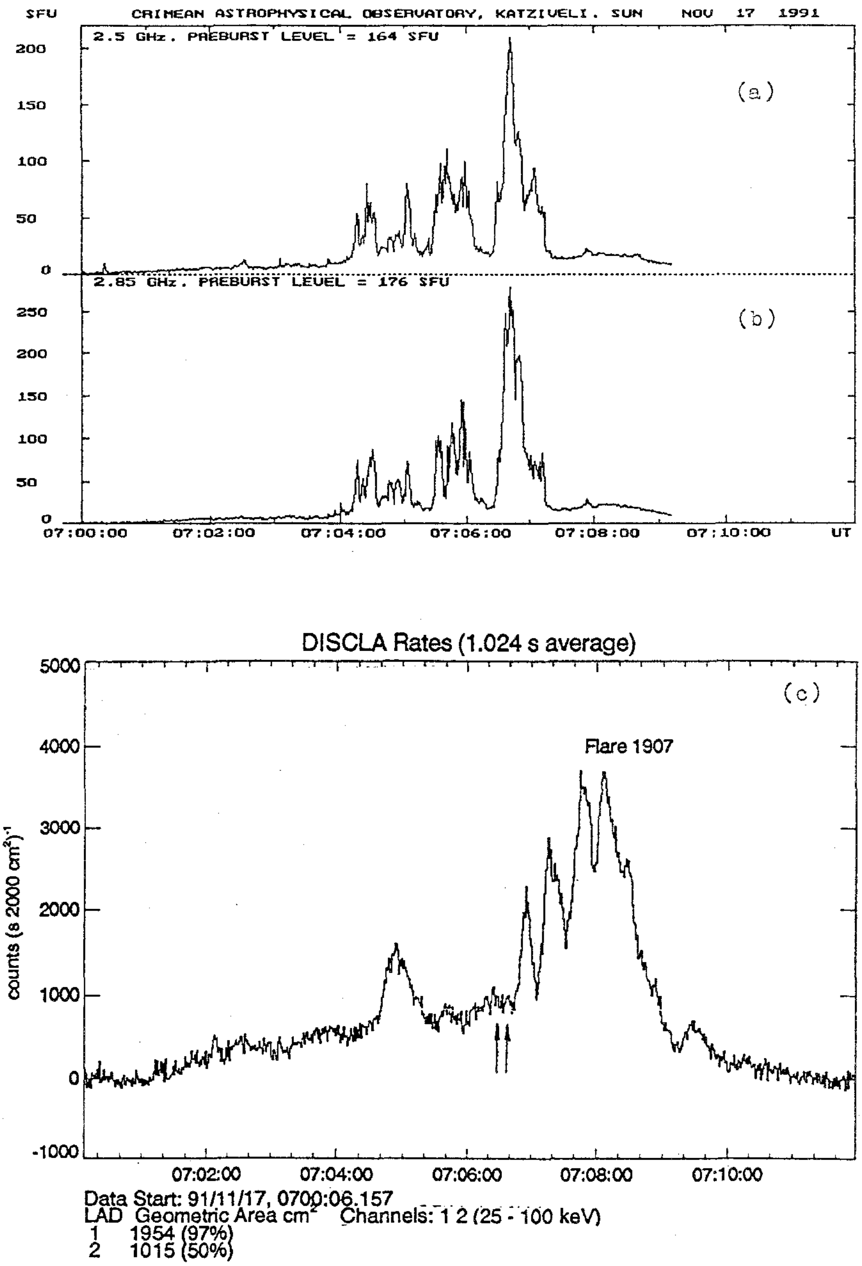
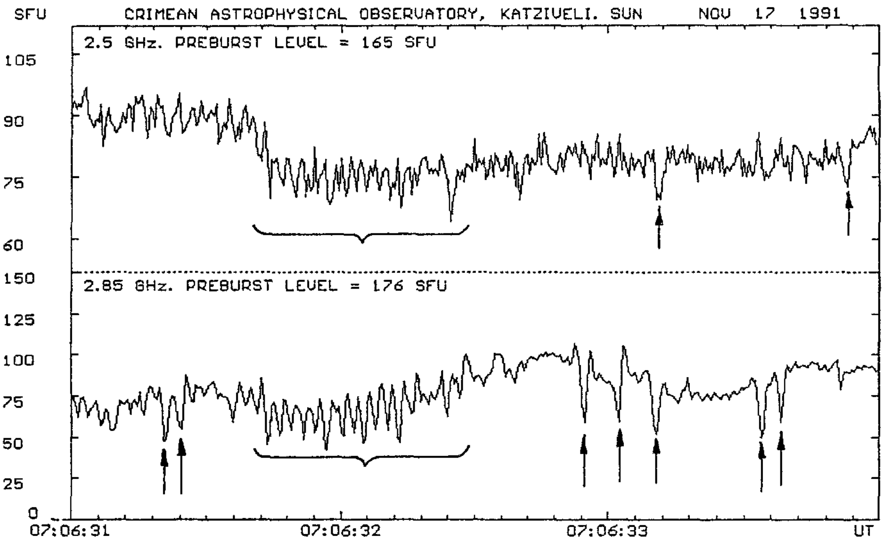


Fig. 1. Radio and hard X-ray observations of the November 17, 1991 07:04 UT flare. General view with 1 s resolution. (a) Radio flux at 2.5 GHz observed at the Crimean Astrophysical Observatory; (b) the same at 2.85 GHz; (c) CGRO hard X-ray flux in the 25–100 keV range. The arrows indicate the time interval plotted in Figures 2 and 3 with high time resolution.



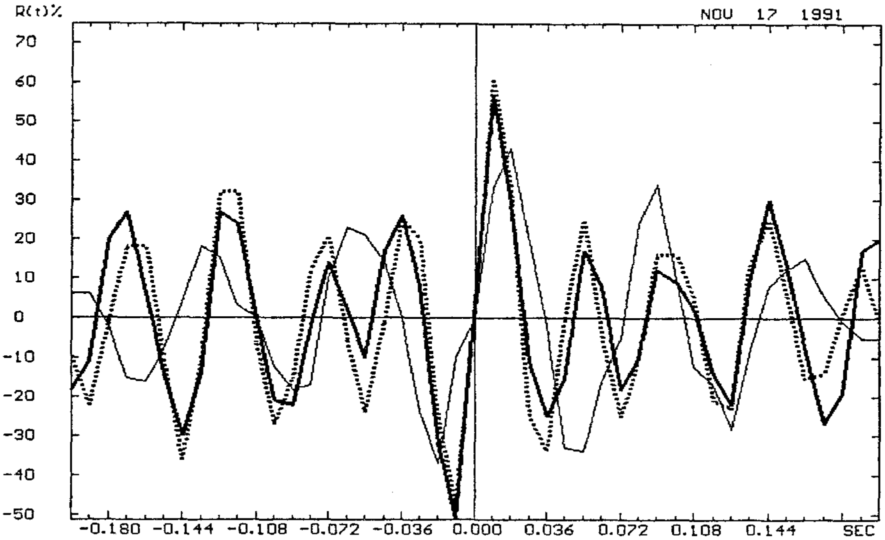


Fig. 2. *Top*: temporal profiles of the event of November 17, 1991 for the time interval 07:06:31–34 UT recorded at 2.5 and 2.85 GHz with sampling rate 110 s^{-1}. Irregular sudden 30–100 ms reductions are indicated by arrows and train of quasi-periodic pulsations near 07:06:32 UT is marked by curly brackets. *Bottom*: cross-correlation function for three shifted 1-s intervals for the fragment plotted above. The thick (07:06:31–32 UT) and dotted (07:06:31.5–32.5 UT) curves show 9 ms time delay and pulsating period ≈40 ms. The thin curve (07:06:33–34 UT) reveals an 18 ms delay (peaks at 2.5 GHz occur later).

sampling rate was 110 s^{-1}). In the second train in Figure 3 (period $\tau \approx$ 70–80 ms, 07:06:34.8–35.6 UT) one does not see any delay longer than 9 ms.

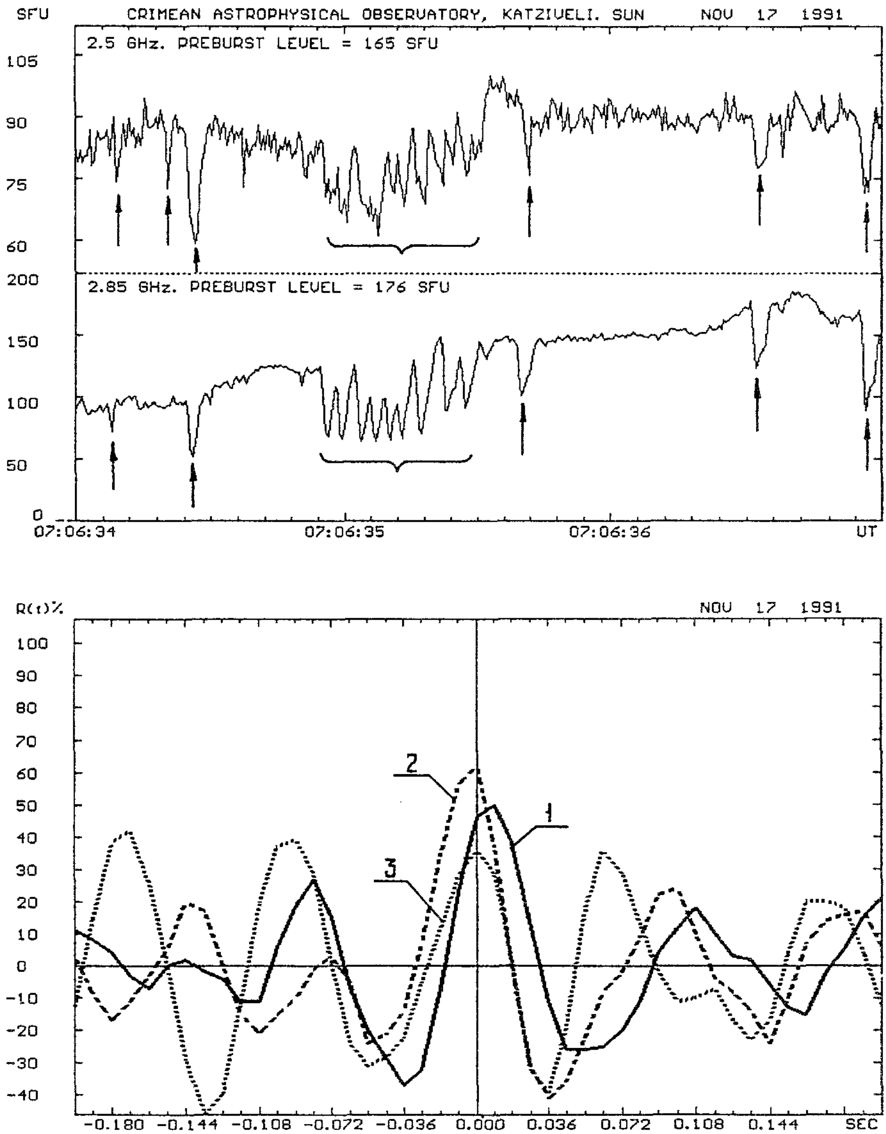


Fig. 3. *Top*: temporal profiles of event of November 17, 1991 for the time interval 07:06:34–37 UT recorded at 2.5 and 2.85 GHz with sampling rate 110 s^{-1}. Notice the reduction of the 'zero level' during the pulsating phase about 07:06:35 UT which is indicated by curly brackets. *Bottom*: cross-correlation function for three 1-s intervals for the fragment plotted above. Curve 1 (07:06:34–35 UT) shows 9 ms time delay. The delay is absent in the curves 2 (07:06:35–36 UT) and 3 (07:06:36–37 UT) within 9 ms time resolution.

It is important to note that the average burst level was suppressed during pulsating trains, which is clearly evident in the second train (Figure 3). In spite of this suppression, the overall burst level at 2.85 GHz increases above the pre-burst level of 176 s.f.u. from ≈80 s.f.u. at 07:06:31 UT to ≈200 s.f.u. at 07:06:37 UT.

3. Sudden Reductions

The observed radio emission is assumed to be generated by trapped fast particles due to a loss-cone instability. Then the most natural explanation of a single pulse in absorption is similar to that suggested by Zaitsev and Stepanov (1975) and Benz and Kuijpers (1976) for the sudden reductions in type IVdm bursts. A portion of the fast electrons being injected into the loss-cone reduces the overall anisotropy in the system 'trapped+injected particles'. That may produce either the quenching or the reduction of the involved loss-cone instability. When propagating through the inhomogeneous coronal loop, the electrons fill the loss-cone at different altitudes, providing the drifting pulse in absorption.

In the November 17, 1991 event the frequency drift is negative, $\mathrm{d}f/\mathrm{d}t < 0$ (similar to the absorption bursts in type IV radio emission). This implies the upward injection of electrons into a magnetic loop. Thus, the acceleration process takes place in a relatively dense layer of the solar atmosphere with electron plasma frequency $f_p > 2.85$ or 1.43 GHz. According to the formula

$$v_b \approx 2\frac{L_n}{f}\left|\frac{\mathrm{d}f}{\mathrm{d}t}\right| , \tag{1}$$

the measured frequency drift rate of 16–39 GHz s^{-1} with $f \approx 3$ GHz and density scale length $L_n \approx 10^9$ cm corresponds to a characteristic velocity of injected electrons $v_b \approx (1.1\text{–}2.5) \times 10^{10}$ cm s^{-1} or an electron energy ≈40–400 keV. The estimated group delay is about 1 ms for our case, and much less than the observed time delay.

It should be noted that the number density of the injected electrons n_2 could be rather small relative to the number density of the trapped electrons, n_1, to provide observable reductions, especially if the instability operates just above its threshold. For example, the condition for quenching the loss-cone instability upper hybrid waves is (Zaitsev and Stepanov, 1975)

$$\frac{n_2}{n_1} > \frac{1 - 2k_{\parallel}^2/k_{\perp}^2 - m\omega^2/k^2T_1}{2(1 + k_{\parallel}^2/k_{\perp}^2)} \exp\left(\frac{m\omega^2}{k^2T_1}\left(1 - \frac{T_1}{T_2}\right)\right) , \tag{2}$$

where T_1 and T_2 are the characteristic energies of the trapped and injected fast electrons, $\omega = (\omega_p^2 + \omega_B^2)^{1/2}$ is the upper hybrid frequency, k is the wave number of the plasma waves. If $k_{\parallel}^2 \ll k_{\perp}^2, T_1 \approx T_2$ and $m\omega^2/2k^2T \approx 0.3$; then Equation (2) yields $n_2/n_1 > 0.2$.

Observed single absorption pulses are quite short, so the duration of the injections should be about 30 ms. Note that the duration of absorption pulses in type IV bursts is $\approx$1 s. The effective growth rate $\gamma_{\text{eff}} = \gamma - \nu_{\text{eff}}$, where γ is the linear growth rate, ν_{eff} is the effective damping rate of the waves, which is of the same order of magnitude as ν_{eff}. That follows from the approximate equality of the decay time (τ_d) to the growth time (τ_g) during a pulse, so that $\tau_d \approx \tau_g \approx \nu_{\text{eff}}^{-1}$.

As is shown in Section 4, the emission mechanism in the event is the coalescence of two Langmuir waves into a transverse wave, $l + l' \Rightarrow t(2\omega_p)$. Thus, it is possible to estimate the background plasma density in the radio source, $n \approx 2.5 \times 10^{10}\ \text{cm}^{-3}$; then from the effective collisional damping rate,

$$\nu_{\text{eff}} = \nu_{ei} \approx \frac{60n}{T^{3/2}}, \tag{3}$$

it follows that the temperature of the background plasma $T \approx 10^7$ K. The observed absorption bursts with negative frequency drift are explained usually as the result of recurrent upward injections quite similar both for solar radio emission (Slottje, 1981; Aschwanden *et al.*, 1993) and for flares on red dwarf stars such as YZ Canis Minoris (Bastian *et al.*, 1990). These injections last some tens of milliseconds in both cases.

4. Quasi-Periodic Pulsations

Let us proceed now to the pulsating parts in the November 17, 1991 event. We doubt if these pulsations are due to quasi-periodic injection of particles into the trap, because the time delay between the 2.85 and 2.5 GHz records is practically zero (<9 ms, Figure 3). Global MHD oscillations do not fit the observations either, as they imply a characteristic period $\tau_{\text{MHD}} \approx R/c_{\text{A}} \approx$ 1–10 s for appropriate values of the trap scales, R, and Alfvén speed c_{A}.

Actually, several pulsating regimes are possible in the process of interactions between high-energy particles and waves in a magnetic trap (see the review by Aschwanden, 1987). They are the relaxation oscillations due to wave–particle interaction or the nonlinear oscillations due to wave–wave interactions. In the latter case the interacting waves can either be plasma, or electromagnetic waves, or a combination of them.

4.1. Oscillatory Wave–Particle Interactions

Initially the relaxation oscillations were studied by Bespalov and Trakhtengertz (1986, see their review and references therein) for the case of interaction between electrons and whistler waves in Earth's radiation belts. Qualitatively, this mechanism works as follows. The onset of a source of high-energy particles produces their accumulation in a trap. When the linear growth rate exceeds the threshold of instability, the waves start to grow. Sometimes the rapidly growing turbulence provides strong quasi-linear diffusion. The system passes by its steady state defined by the condition of the equality of the wave growth rate and the damping rate or escape rate, while particle losses are being compensated by their source. Thus, the relaxation of the system towards the steady state is being accompanied by oscillations of the involved plasma parameters. Bardakov and Stepanov (1979) and Aschwanden and Benz (1988b) have explained some kinds of solar radio pulsations in terms of relaxation oscillations.

Of particular interest are models of the pulsating regime of electromagnetic wave direct amplification; these waves can escape freely from the source and reach the Earth. Aschwanden and Benz (1988a, b) studied a pulsating regime of an electron cyclotron maser (ECM) operating close to the steady state. The dynamics of the system are described by the following equations for the wave energy density (where nonlinear wave–wave interactions are neglected) and for the emitting electron distribution function including the terms with the electron source (J) and electron losses (L) as well as their quasi-linear diffusion on transverse waves:

$$\begin{aligned} \frac{\partial W(\mathbf{k}, t)}{\partial t} + \mathbf{v}_g \frac{\partial W}{\partial \mathbf{r}} &= \gamma[f(\mathbf{p}, t)]W - \nu_{\text{eff}} W \,, \\ \frac{\partial f(\mathbf{p}, t)}{\partial t} &= \frac{\partial}{\partial p_i} D_{ij}[W(\mathbf{k}, t)] \frac{\partial f}{\partial p_j} + J(\mathbf{p}, t) - L(\mathbf{p}, t) \,. \end{aligned} \tag{4}$$

In the vicinity of a steady state ($\partial W/\partial t = 0$, $\partial f/\partial t = 0$) relaxation oscillations with the period

$$\tau = 2\pi(\tau_{\text{diff}}/\gamma)^{1/2} \tag{5}$$

may arise; here $\tau_{\text{diff}} \approx p^2/D$ is the characteristic diffusion time and γ^{-1} is the characteristic time of wave growth. The natural property of such a regime is the irregular behavior of the pulsation amplitude and of the period. This is exactly what we do typically observe in the decimetric and microwave pulsations. The bandwidth of the pulsations is determined by the magnetic field inhomogeneity in the emitting source. According to Equation (5) the model predicts the simple dependence

$$F \approx \tau^2 \,; \tag{6}$$

here F is the radio flux.

However, dependence (6) does not fit observations of the November 17, 1991 event. Figures 2 and 3 show that the period in the second train is about twice as large as that in the first one, while the flux variation is only 25%. Futhermore, the model has some important limitations. For example, if $Y = \omega_p/\omega_b > 0.3$, the plasma low-hybrid waves or Z-mode waves may dominate and affect the particle distribution rather than transverse O1 or X2 waves (see, e.g., Fleishman and Yastrebov, 1994b). In the opposite case, $Y < 0.3$, that when our pulsations are responsible for the periods close to 40–80 ms, there appears a strong dependence of period on the parameter Y (Ashwanden and Benz, 1988b), which should probably destroy the pulsating regime. Consequently the model of relaxation oscillations does not fit the observations of the particular November 17, 1991 event.

4.2. Nonlinear pulsations of ECM

The pulsating regime of ECM is also possible if there are reasons to neglect the back influence of transverse waves on emitting particles. This is the case if the nonlinear wave–wave interactions become important sooner than the quasi-linear relaxation and have to be taken into account (Trakhtengertz, 1968). Let us assume that the stimulated scattering of transverse waves with thermal ions is the main nonlinear effect (Fleishman, 1994). Then the respective equation (see Equations (9) and (16) in Fleishman (1994) for details),

$$\frac{\mathrm{d}W(\mathrm{k},\, t)}{\mathrm{d}t} = \gamma W - W \int \mathrm{dk} W' K \left(\frac{\omega - \omega'}{|k_z - k_z'|\, v_{Ti}} \right) , \tag{7}$$

can be considerably simplified if the width of the excited wave spectrum is more narrow than the core in the integral in Equation (7). This condition is fulfilled if

$$\frac{\Delta\omega}{\omega} < \frac{v_{Ti}}{c} \leq 10^{-3} . \tag{8}$$

No power-law momentum distributions of particles is able to produce the peaks of the required sharpness (Fleishman and Yastrebov, 1994a), however those could be provided with the Maxwellian distribution with a loss-cone (e.g., Ashwanden and Benz, 1988a). Then the integral in (7) may be transformed as

$$\int \mathrm{d}\omega' \int \mathrm{dk}' W^{\mathrm{res}}(\omega',\, \mathrm{k}') \equiv W^{\mathrm{res}} \approx \Delta\omega W^{\mathrm{res}}_{\mathrm{max}}(\omega) , \tag{9}$$

where W^{res} is the energy density of resonant (amplified) transverse waves. After integrating over the unstable (resonant) range and then over the non-resonant range (where the wave damping occurs), Equation (7) can be reduced to the familiar equations of the Lotka–Volterra type:

$$\frac{\mathrm{d}w}{\mathrm{d}t} = \gamma w - \zeta w w^* , \qquad \frac{\mathrm{d}w^*}{\mathrm{d}t} = -\tilde{\gamma} w^* + \zeta w w^* , \tag{10}$$

where γ is the growth rate in the resonant range, $\tilde{\gamma}$ is the damping rate in the non-resonant range, $w(w^*) = W(W^*)/nT$,

$$\zeta \approx 5 \times 10^{-3} \omega . \tag{11}$$

The value of (11) was calculated assuming that the electron and ion temperatures are equal ($T_e = T_i$) and $n_\sigma^2 \ll 1$ (n_σ is the refraction index of the wave σ).

Equations (10) are known to have a periodic solution which corresponds to the closed phase trajectories around a center-type singular point:

$$w_0 = \tilde{\gamma}/\zeta\,, \qquad w_0^* = \gamma/\zeta\,. \tag{12}$$

The respective period of small oscillations is

$$\tau = 2\pi(\tilde{\gamma}\gamma)^{-1/2}\,. \tag{13}$$

We have neglected here possible variations of the electron distribution function and assumed that the source scale, L, is large enough for the oscillations to be synchronous (Zaitsev, 1971):

$$L^2 \gg v_g^2/\tilde{\gamma}\gamma\,. \tag{14}$$

Now we are ready to determine the model parameter fitting to the observations. Let us choose $Y < 0.3$, which means that the fundamental X-mode (X1) dominates and $\omega \approx \omega_B$. The growth rate $\gamma = \alpha\omega_B$ may be found from (13). For $\tau \approx 40$ ms and $\tilde{\gamma} \approx \gamma$ we obtain $\gamma \approx 10^{-8}\omega_B$. Then, Equation (12) yields the level of electromagnetic turbulence:

$$w \approx w^* \approx 2 \times 10^{-6}\,. \tag{15}$$

The brightness temperature can be determined from Equations (8) and (15) as follows:

$$\frac{T_b}{T} = w\frac{c^3}{\Delta\omega\,\omega^2} \approx 2 \times 10^7\,. \tag{16}$$

For the reasonable temperature range $T = 10^6$–10^7 K, we have

$$T_b \approx 2 \times (10^{13}\text{–}10^{14})\ \mathrm{K}\,. \tag{17}$$

On the other hand, the brightness temperature is connected with the observed flux as

$$T_b = 1.4 \times 10^{10}\frac{F_{\mathrm{s.f.u.}}}{f_{\mathrm{GHz}}^2 L_8^2}\ \mathrm{K}\,, \tag{18}$$

where $L_8 = L_{\mathrm{cm}}/10^8$. Substituting $F \approx 100$ s.f.u. and T_b from Equation (17) into (18) we find the scale of the source to be

$$L \approx (0.3\text{–}1) \times 10^7\ \mathrm{cm}\,. \tag{19}$$

The energy density may reach the value in Equation (15) if the source has a high enough optical depth $\tau = \gamma L/v_g$, so that the waves are actually amplified up to this level over the length (19), $\exp(\gamma L/v_g) > 10^7$. This requirement restricts the group speed of waves:

$$v_g < \gamma L/15 \approx 10^8 \text{ cm s}^{-1} . \tag{20}$$

The value of v_g together with $L > 10^6$ cm provides the correctness of inequality (14). One might note that this mechanism requires the magnetic field inhomogeneity to remain quite small, $\delta B/B < 10^{-3}$ over the scale L.

The ECM pulsation model does satisfy the observations under some extreme assumptions on the source parameters: (i) the small group velocity $v_g < 10^8$ cm s^{-1}, which is only reasonable just above the cut-off frequency; (ii) the narrow-band emission of excited peaks $\Delta\omega/\omega < 10^{-3}$; (iii) quite uniform magnetic field $\delta B < 10^{-3}B$ over $L \approx 10^7$ cm. These conditions are scarcely to be expected in the case of solar microwave bursts, while they may take place in the red dwarf coronae, where there are higher magnetic fields and longer magnetic loops.

Actually, this model properly explains the 100% circularly polarized pulsations with a period of 0.3–0.7 s observed in AD Leo radio emission at 1.415 GHz by Bastian *et al.* (1990). The measured flux ($\approx$0.1 Jy) corresponds to 10^7 s.f.u. being observed from a distance of 1 AU, and the respective brightness temperature is 10^{13} K, at least. Assuming that the typical coronal temperatures of the red dwarfs are of the order of 10^7 K, and the other parameters are $Y \approx 0.3$ ($B \approx 500$ G, $n \approx 3 \times 10^9$ cm^{-3} for $f_B \approx f \approx 1.4$ GHz, see Bastian *et al.*, 1990), one might obtain a transverse wave damping rate $\tilde{\gamma} \approx \nu_{ei}(\omega_p/\omega)^2 \approx 0.1$ s^{-1}. Then Equation (13) yields the appropriate value of the growth rate $\gamma \approx 10^{-7}\omega_B \approx 10^3$ s^{-1} for the pulsation period of about 500 ms. This value implies a brightness temperature $\approx 10^{15}$ K and source scale $\approx 10^9$ cm for the group velocity (0.3–1)c. Thus, we have reasonable values for the relevant physical parameters to explain these highly polarized pulsations.

It is worth noting that there are some other nonlinear effects capable of providing the ESM pulsations (Fleishman, 1994), e.g., Raman scattering of transverse waves on low-frequency plasma waves. However, those require some specific conditions to be satisfied.

4.3. Nonlinear Oscillations of Langmuir Waves and Their Conversion into Electromagnetic Waves

Equations (10) were deduced by Trakhtengertz (1968) and Zaitsev (1971) for longitudinal waves and have already been applied to the phenomenon of solar radio pulsations (Zaitsev, Stepanov, and Sterlin, 1985; Aschwanden, 1987; Stepanov and Yurovsky, 1990). For the upper hybrid waves in the case $Y \gg 1$ one has $\zeta_p \approx \omega_p/40$ and $\gamma \approx 10^{-8}\omega_p$ instead of (11). This value of γ is close to the damping rate of the plasma waves (see Section 3), which corresponds to the temperature of the background plasma $T \approx 10^7$ K. The energy density of Langmuir waves in the steady-state condition can be found from the expression

$$w_l = \frac{W^l}{nT} \approx \frac{100}{f_T} , \tag{21}$$

which gives $w_l \approx 10^{-6}$ in our case.

While the plasma wave conversion can provide radio emission at fundamental and second harmonics of the plasma frequency $\omega_p = 2\pi f_p$, the coalescence process $l + l' \Rightarrow t(2\omega_p)$ is most efficient in the flaring loops (Zaitsev and Stepanov, 1983). It is easy to show that the optical depth due to both free-free absorption and the decay process $t(2\omega_p) \Rightarrow l + l'$ is less than unity, so the respective brightness temperature is defined by the expression (Zaitsev and Stepanov, 1983)

$$T_b(f \approx 2f_p) = a_\omega L = \frac{(2\pi)^3}{15\sqrt{3}} \frac{c^3 L}{f_p^2 v_{ph}} \frac{w^2}{\xi^2} nT \; , \tag{22}$$

where $\xi = (c/\omega_p)^3 (\Delta k)^3 \approx 400$ relates to the phase volume of the plasma waves. From (18) and (22) one obtains the following expression for characteristic source scale L:

$$L = \frac{10^{15}}{2\pi} \left(\frac{F_{\text{s.f.u.}} v_{ph} \xi}{c^3 w_l^2 nT} \right)^{1/3} \text{cm} \approx 5 \times 10^7 \text{ cm} \; ; \tag{23}$$

Now the brightness temperature, T_b, may be found either from (18) or (22) as $T_b \approx 8 \times 10^{11}$ K. The Langmuir waves are actually amplified in a source of scale (23) if the respective optical depth is large enough. This requires their group velocity to be

$$v_g < \gamma L/5 \approx 10^9 \text{ cm s}^{-1} \; . \tag{24}$$

Actually, the group velocity range is

$$v_g = 10^8\text{–}10^9 \text{ cm s}^{-1} \; , \tag{25}$$

if the Langmuir waves are excited with the fast particles in the plasma with $T \approx 10^7$ K; so the condition (24) is easily satisfied. Finally, the plasma could be somewhat more inhomogeneous than the magnetic field considered in Section 4.2, because this model is not as critical to the width of spectra of the excited Langmuir waves ($\Delta k/k < 0.3$).

The period of small oscillations around the center-type singular point is $\tau_s \approx 2\pi/\gamma$ (the larger the growth rate the smaller the oscillation period). In the event under consideration the period is growing with the flux. To understand this one may note that the period of large oscillations is $\tau_l = \tilde{\gamma}^{-1} \ln[\gamma/\zeta w^*(t = 0)]$ (Zaitsev, 1971) and that may be sometimes larger than τ_s. Thus the observed period, τ, falls into the range $\tau_s \leq \tau \leq \tau_l$, which does agree well with the observations.

5. Discussion

So we have considered three various models for the microwave millisecond pulsations and have checked them with the aid of the observational data in the November 17, 1991 event. We came to the conclusion that the observed pulsations are due to wave–wave nonlinear oscillations, rather than to wave–particle relaxational oscillations.

The model 4.2 of ECM nonlinear oscillations (in the X1-mode) may fit the observations under some extreme assumptions on the source parameters, while it properly explains the pulsations observed in the dMe star AD Leo (Bastian *et al.*, 1990). Model 4.3 of Langmuir wave nonlinear oscillations does not require any exceptional physical properties of the source. Thus it is reasonable to conclude that model 4.3 provides the best explanation for the pulsations in the November 17, 1991 event. The parameters of the radio source derived from the model for the event considered are as follows:

background plasma density:	$n \approx 2.5 \times 10^{10}$ cm^{-3} ;
kinetic electron temperature:	$T \approx 10^7$ K;
Langmuir turbulence level:	$w_l \approx 10^{-6}$;
brightness temperature:	$T_b \approx 8 \times 10^{11}$ K;
linear scale of the source:	$L \approx 500$ km.

Since the growth rate of the loss-cone instability is about $\gamma_l \approx 10^{-2}(n_1/n)\omega_p$, the number density of the fast trapped electrons is rather small, $n_1 \approx 10^{-6}n$. According to Equation (2) the number density of injected particles $n_2 > 0.2n_1 \approx 5 \times 10^3$ cm^{-3}. Thus, the analysis of this prominent event provides important information on the high-energy ($\approx$100 keV) electron injection into the magnetic trap. It was shown that then particle acceleration can proceed in relativley dense layers with $n > 2.5 \times 10^{10}$ cm^{-3}, in the low corona. It should be noted that according to Pan, Lin and Kane (1984) the 20–100 keV electrons could escape from an X-ray generating region ranging from the chromosphere to the corona. The characteristic time scale of the fragmented particle acceleration varies from $\tau_{\rm inj}^{\rm min} \approx 30$ ms to $\tau_{\rm inj} \approx 1$ s. The short pulses of the upward injected electrons reveal themselves as the single drifting absorption bursts: while the burst level is defined with the loss-cone instability, the sudden reduction is a direct consequence of the loss-cone filling with freshly injected electrons.

Nonlinear oscillations of Langmuir waves about of the reduced steady-state level (Figure 3) arise when the characteristic time of electron injection into the loss-cone becomes long enough, $\tau_{\rm inj} \approx 1$ s. Since the wave energy density in the steady state is $W_l^0 \sim \gamma_l \sim A(t)n_1(t)$, where $A(t)$ is the degree of anisotropy, the loss-cone filling with the injected electrons diminishes the $A(t)$ and the steady-state level W_l^0. By this the value of $n_1 \approx$ constant, because Equation (2) shows that it is sufficient to have $n_2 \ll n_1$ to quench the instability, and the particle trapping is not so important during the 1-s injection. Thus, the beam injected into the loss-cone both reduces the 'zero level' and synchronizes oscillations at different altitudes. In the suggested model it is assumed that the slow increasing of the average burst level is due mainly to the trapping and accumulating of the injected electrons in the loop (increase of n_1). The trapping efficiency may be as high as a few tens of percent of the injected particles (Roque and Gregory, 1972).

The comparison of the HXR and the microwave time profiles (Figure 1) shows that the microwave pulsations occur a few seconds earlier the first large peak in the HXR emission and a minute before the main HXR maximum. This indicates that the particles accelerated below the level $f_p \approx 1.43$ GHz contain a small fraction of the total electron energy of the flare and contribute little to the total HXR flux.

Thus, observations of microwave emission with high time resolution are quite sensitive to the weak-fragmented acceleration process. Anyway, the HXR observations with high time resolution are very valuable for flare plasma diagnostics.

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