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Analysis of depth of modulation in fast pulsations of solar radio emission

G. P. Chernov and J. Kurths

Institute of Terrestrial Magnetism, the Ionsophere, and Radio Propagation, USSR Academy of Sciences; Central Institute for Astrophysics, GDR Academy of Sciences

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The model of millisecond pulsations of radio emission due to the pulsating regime of the whistler spectrum is confirmed by a statistical analysis of the depth of modulation in five type IV bursts: distributions of the depth of modulation $\Delta I/I$ as a function of period p display linear growth with different slopes and a maximum at high modulations $\Delta I/I \approx 0.5$–0.6. This mechanism is also supported by the same $\Delta I/I(p)$ relation for spikes observed in the same events. If filaments with intermediate frequency drift and sudden reductions are superposed on the pulsations, the characteristic $\Delta I/I$ distributions display the diffuse "tails" that are explained naturally in the well-known models of the formation of this fine structure.

INTRODUCTION

In the course of type IV radio bursts in the meter and decimeter ranges, one observes a large variety of one-second pulsations,[1] which are usually explained on the basis of two models: magnetohydrodynamic (MHD) oscillations of the source and plasma oscillations of beam or conical instability.[2]

But in the meter range, along with one-second pulsations ($p \gtrsim 1$ sec), one often observes millisecond pulsations with a period $p < 1$ sec and a duration of $<<0.1$ sec, which cannot, for various reasons, be explained in the context of these models[3,4]: the MHD model does not satisfy the rapid pulsations in terms of period, and the plasma models do not satisfy it in terms of depth of modulation, which is the most critical characteristic of the pulsations.

In the present paper we use a statistical analysis of the depth of modulation of radio emission to test the model of millisecond pulsations in whistlers that was discussed in Ref. 5. It is well known that whistlers have been used earlier to interpret radio pulsations in both the meter[6,7] and the microwave[8] ranges. In Ref. 6, however, principal attention is devoted to the pulses amplification of the instability of plasma waves by distributions of energetic electrons in which there is a gap, formed by periodic packets of whistlers. But according to current concepts, the propagation of periodic packets of whistlers in magnetic traps should result in the formation of filaments with intermediate frequency drift.[9] Moreover, localization of the source of plasma waves only at the top of the trap, as is assumed in Ref. 7, does not fit observations of the broadband continuum.

The periodic precipitation of fast particles into the loss cone in the interaction with whistlers may lead to pulsations with considerably longer periods.[8,9] Finally, in Ref. 5 (which is the theoretical foundation for the present paper) it was shown that millisecond pulsations may be caused by a pulsating mode of the whistler spectrum formed in the scattering of whistlers from cool plasma and in decay processes with ion–acoustic waves.

First let us briefly consider other possible mechanisms for fast radio pulsations, i.e., oscillatory modes of beam or conical instability of plasma waves and MHD oscillations of the radio source. Here it is important to note that the analysis is carried out for the regime of weak turbulence or, more precisely, for the linear stage of instability. For plasma models of radio pulsations, such an assumption is justified primarily by the fact that at the altitudes of the meter range in the corona one usually assumes that the number of energetic particles is small compared with the background plasma ($n_1/n_0 \lesssim 10^{-6}$).

The MHD oscillations of a magnetic trap are also associated only with small changes in the magnetic field, $\Delta B << B$, since all other data on magnetic fields in the corona (optical observations of coronal lines, radio observations of time profiles of the polarization of type III bursts and the fine structure of type IV bursts, such as filaments with intermediate frequency drift) indicate the absence of rapid and strong field variations.

BRIEF CHARACTERISTICS OF PULSATION MODELS

The plasma model of radio pulsations in the context of

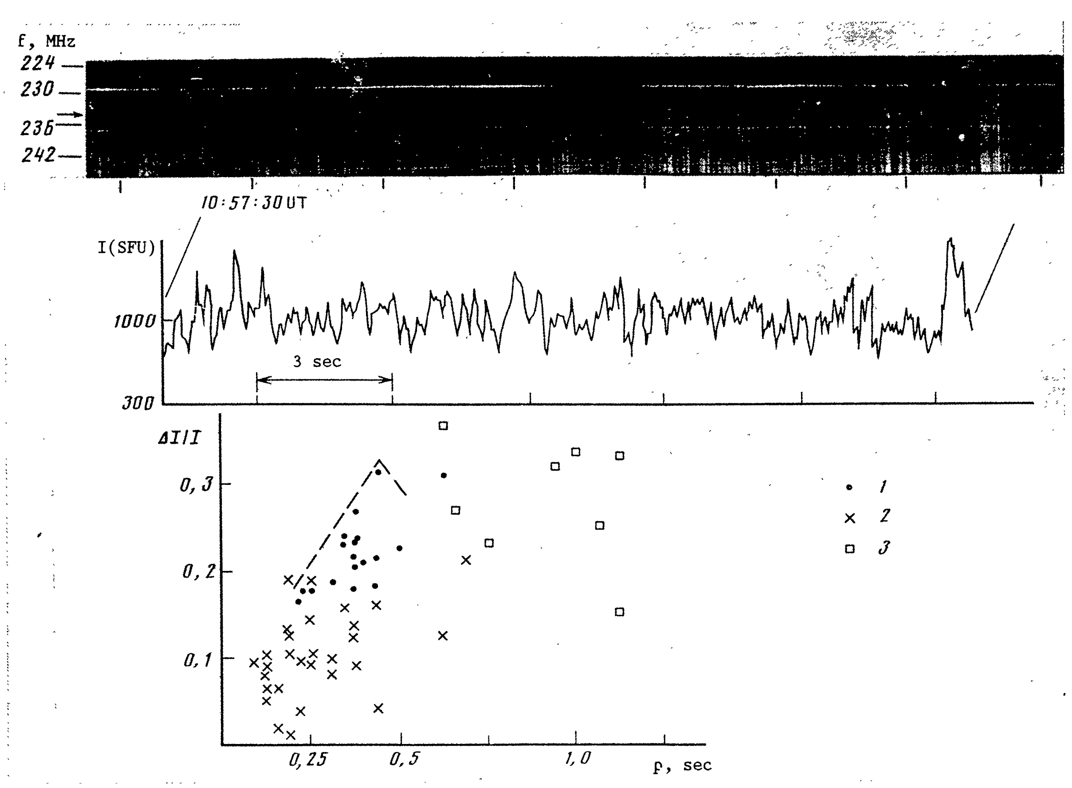

FIG. 1. Fast pulsations in a large type IV burst on 24 April 1985: at the top is the dynamic spectrum in the 224-245 MHz range (IZMIRAN), at the center is the time profile of the radio emission flux [1 SFU (solar flux unit) = 10^{22} W/m^2·Hz] at 234 MHz (Tremsdorf Observatory), and at the bottom is the distribution of the depth of modulation of the radio emission, $\Delta I/I = (I_{\max} - I_{\min})/(I_{\max} + I_{\min})$, as a function of the pulsation period p (sec). 1) Dots denote single pulsations; 2) single pulsations against the background of longer ones; 3) complex long-period oscillations.

beam instability is based on nonlinear wave scattering into the nonresonant range of the spectrum, in which they are damped in collisions and are converted into electromagnetic radiation.[2,3] It should yield a strict period $p \approx 2\pi/\nu_{ei}$ (ν_{ei} is the frequency of electron–ion collisions), but it can operate efficiently only for protons.[10]

Oscillations of conical instability are determined by quasilinear effects of damping of plasma waves on fast particles that are precipitating into the loss cone. The main properties of the plasma model of pulsations near the excitation threshold ($\gamma \gtrsim \gamma_{ei}$) for conical instability are an increase in the depth of modulation and a decrease in the intensity of the pulsations with an increase in their period. The strongest pulsations should have the shortest periods,[3] which may be millisecond periods $p \sim 1/\gamma$. But since the growth rate γ is proportional to the density of fast particles and the plasma frequency,

$$\frac{\Delta I}{I}=\frac{I_{\max}-I_{\min}}{I_{\max}+I_{\min}}.$$

pronounced modulation may be expected only in the interior of the corona, such as in flare loops, in which $\omega_{Pe} \approx 10^{10}$ sec^{-1} and $n_1/n_0 \gtrsim 10^{-5}$. Their most likely application has therefore been in terms of microwave millisecond (spike) oscillations.[3]

Relaxation oscillations of beam instability on electrons must be maintained by a periodic source of fast electrons and must have a low quality factor (a small number of pulsations per series).

MHD models of pulsations are based on modulation of the plasma density in a magnetic trap, mainly by fast magnetosonic (FMS) waves exited by protons in Cherenkov or bounce resonance. Their period is determined only by the size of the trap, and therefore it cannot be very short. Under the conditions of bounce resonance, for example, $p = R/V_A = l/V$, where R and l are the radius and length of the trap, V is the velocity of the fast particles, and V_A is the Alfvén velocity, $V_A \simeq c/43 f_{He}/f_{Pe}$ (f_{He} and f_{Pe} are the cyclotron and plasma frequencies of electrons), for a period $p = 0.05$ sec we must assume that the magnetic arch is high in the corona and has the improbably small dimensions $R \approx 10^6$ cm and $l \simeq 5 \cdot 10^8$ cm ($V_A \approx 3.5 \cdot 10^7$ cm for $f_{He}/f_{Pe} \approx 1/20$ and $V = 10^{10}$ cm/sec).

MHC oscillation modes propagating in dense traps may yield the typical variation of the one-second periods and the depth of modulation, including three phases: a periodic phase associated with the arrival from the flare region of a low-frequency disturbance with the maximum group velocity; a quasiperiodic phase with increasing modulation, due to the interaction of the first disturbance and a subsequent higher-frequency disturbance which arrives at the same level in the corona with the minimum group velocity; and a decay phase.[11,12]

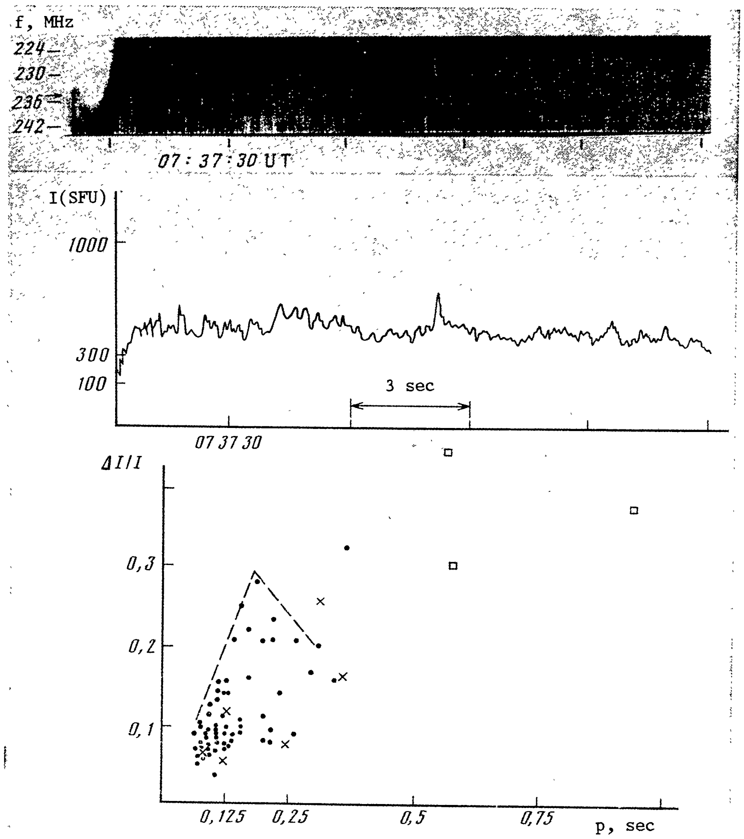

FIG. 2. Series of very brief spike bursts in the event on 4 February 1986. All notation is analogous to that in Fig. 1.

MHD pulsations are determined by weak oscillations of the magnetic field in a FMS wave, $\Delta B << B_0$ (B_0 is the undisturbed field), so they must have shallow modulation $\Delta I/I \approx \Delta B/B_0$ (Ref. 13).

A special class of pulsations consists of sudden reductions (SRs), which are often superposed onto one-second pulsations in emission and complicate the picture. They are caused by a cutoff of conical instability of plasma waves upon the injection of new particles into the loss cone.[14] They have the nature of deep troughs of radio intensity, so in an analysis of the depth of modulation they must be separated from pulsations in emission, although this is difficult to do on a dynamic spectrum, since SRs, like MHD pulsations, have a one-second scale.

Oscillations of conical instability of plasma waves at the boundary between weak and strong diffusion of fast electrons on whistlers, including the cutoff of instability during the injection of new particles into the loss cone,[15] or the model of torsional oscillations of a magnetic flux tube[16] may apply only to pulsations with a long period (>1 sec).

The known models of pulsations thus do not enable us to explain millisecond pulsations in the meter range with deep modulation of radio emission. In this connection, *a model of millisecond pulsations in the context of the mechanism of merging of plasma waves with whistlers*, in which the whistler spectrum is determined by the pulsating regime of their interaction with ion–acoustic waves, has been considered in Ref. 5.

The main process resulting in fast pulsations is associated with the pulsating regime of merging and decay of ion–acoustic (s) waves with whistlers (w): $s + s' \rightleftarrows w$. From experiments it is well known that this process proceeds at both the sum and difference frequencies. The maximum increment of Cherenkov instability of s waves falls at frequencies close to the ion plasma frequency ω_{pl}. In the solar corona at the altitudes of the mater range, the approximate equality $\omega_{\mathrm{pl}} \approx \omega_{\mathrm{H}_e}/4$ is satisfied, which favors the observance of conservation laws for $s + s' \rightleftarrows w$ processes at the difference frequency and the maximum increment.[5] Such a condition is not satisfied in the earth's magnetosphere.

A second necessary condition for satisfying the conservation laws for the $s + s' \rightleftarrows w$ pulsating process will be isotropization of the wave vectors $\vec{k}^s$ and $\vec{k}^w$, since the process proceeds for two oppositely directed vectors $\vec{k}^s$ and $\vec{k}^{s'}$ and the vector $\vec{k}^w$ directed at an angle $\vartheta^w > 70°$ to the magnetic field.[17] Here the slowest process (determining the pulsation period) turns out to be scattering of whistlers from thermal electrons. For the usual whistler energy density $W^w/nT \approx 10^{-7}$, this scattering time is[5] ~0.3-0.2 sec.

The process $l + w \rightarrow t$ of merging of plasma waves with whistlers is very fast (about 10^{-3} sec), so the duration of one pulsation actually will not exceed the collisional damping time $\nu_{\mathrm{ei}}{}^{-1} \approx 10^{-2}$ sec.

The source of such pulsations may lie in a reconnection region with a vertical size ~(2-5)·10^9 cm (in the formation of magnetic islands in a vertical current sheet after

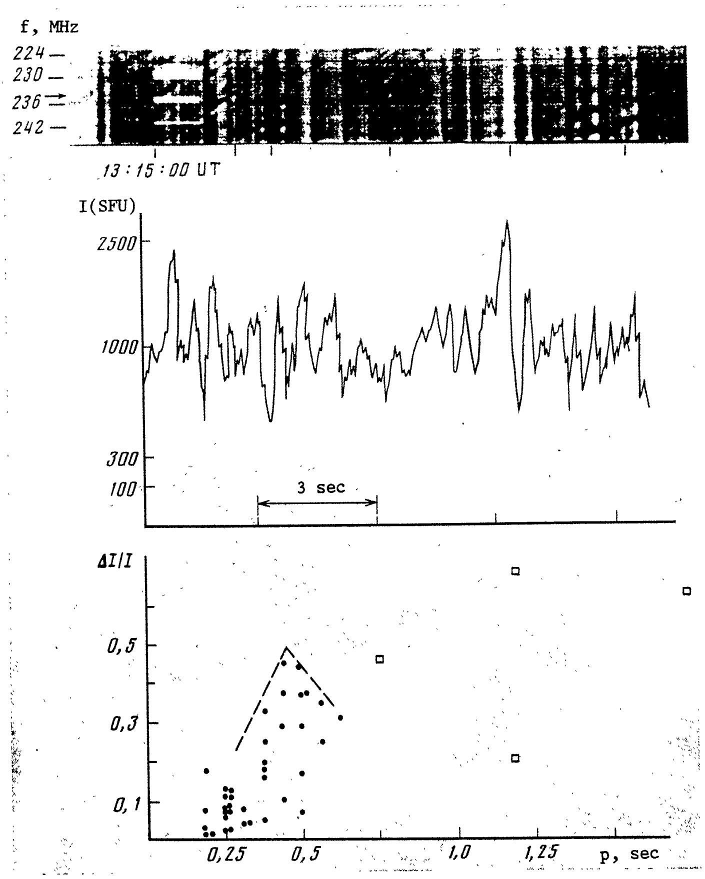

FIG. 3. Fast pulsations in emission and absorption (SRs) and filaments (fiber bursts) in a small type IV burst on 5 February 1986. Notation same as in Fig. 1.

a flare, for example[18]) and containing diverging shock fronts, between which nonisothermicity develops ($T_e >> T_i$) and ion–acoustic waves are excited (Ref. 17, Sec. 4.10, and Ref. 19, Sec. 1.4).

In this mechanism of pulsations in whistlers, the modulation depth may be considerably higher than in other models, and its dependence on the period is characterized by a nearly linear increase with increasing period (with different slopes, determined by the energy level of whistlers and ion–acoustic waves and by the degree to which T_e exceeds T_i) up to some maximum value at a period $p \propto \nu_{ei}^{-1}$.

These differences from other models enable one to identify the mechanism of the pulsations from their measured parameters. The most important factor that displays the efficiency of the whistler mechanism is the depth of modulation.

STATISTICAL ANALYSIS OF THE DEPTH OF MODULATION OF PULSATIONS

To analyze the pulsations we used simultaneous observations of dynamic spectra that were carried out at the Institute of Terrestrial Magnetism, the Ionosphere, and Radio Propagation, USSR Academy of Sciences (IZMIRAN), in the 200-250 MHz range with ~0.02 sec time resolution, and of the flux density of radio emission at 234 MHz with a high time resolution ~0.016 sec at Tremsdorf Observatory (GDR). Such a comparison enables us, on the one hand, to reliably identify coinciding events of solar origin, and on the other, to make exact measurements of the depth of modulation of the pulsations (Figs. 1-4).

The observations included both large and small type IV bursts. The main parameters of the pulsations observed in the five bursts are collected in Table I. Each series of pulsations in these events lasted several minutes, as a rule, and only the time intervals used for measurements of the depth of modulation are given in the table. The "spectrum type" column shows that, along with pulsations (P), the spectrum contains filaments with intermediate frequency drift or fiber bursts (F), spikes (Sp), and sudden reductions (SR). Pulsations are rarely observed in pure form, in general. Besides these structures, the zebra structure sometimes appears in the pulsating mode.

According to Ref. 5, spikes in type IV bursts may be directly related to millisecond pulsations: a disruption of strict periodicity and a random localization of the radio source in altitude result in the degeneration of pulsations into spikes. The dependence of the depth of modulation on the period should therefor be similar for spikes and millisecond pulsations, and it was important to test this.

In Table I we give the range of periods for a given series of pulsations and the period for the maximum depth

TABLE I. Parameters of Fast Pulsations in Five Type IV Bursts

Date	Time, UT	Spectrum type	Period		Depth of modulation $\Delta I/I$	Shape of distribution	
			total interval	at maximum of $\Delta I/I$		slope before maximum	"tail" after maximum
24.IV.1985	10:57:27 – 10:57:46	*P*	0,6	0,4	0,30	Medium	Diffuse
	11:21:35 – 11:21:43	*P*	0,5	0,4	0,25		Short
4.II.1986	07:35:00 – 07:36:30	*P*, Sp	1,3	0,5	0,40	Flat, diffuse	Long
	07:37:26 – 07:38:12	Sp	0,35	0,2	0,25	Steep, diffuse	Short
26.IV.1984	09:03:19 – 09:03:32	*P*	0,7	0,3	0,2	Flat, diffuse	Short
13.VII.1982	11:05:40 – 11:06:50	*P*, SR, F	1,0	0,4	0,5	Steep	Short, diffuse
	11:07:00 – 11:08:21	*P*, F	1,0	0,35	0,30	Steep	Very short
5.II.1986	13:14:30 – 13:15:10	*P*, F, SR	0,8	0,4	0,60	Medium, diffuse	Long
	13:16:29 – 13:16:42	*P*, F, SR	0,5	0,5	0,45	Flat	Long
	13:06:00 – 13:06:25	F, SR	1,0	0,4	0,50	Level, diffuse	No tail

of modulation. At each of the successive maxima and minima of the time profiles of pulsations, we measured the radio fluxes ($I_{\max}$ and $I_{\min}$) and calculated the depth of modulation:

$$\gamma \propto \frac{n_1}{n_0} \omega_{p_e},$$

Some of the analyzed series of pulsations are shown in Figs. 1-4, in which the resulting distributions $\Delta I/I(p)$ are given below the spectra and profiles of the pulsations being compared. It is seen from the figures that the profiles of the pulsations reflect the superposition of pulsations with different periods, so it was useful to separate the profiles into three categories: simple single pulsations (designated by dots (·) in the figures); the same simple pulsations, but against the background of longer ones (×), their depth of modulation being measured with respect to this new background; complex profiles, i.e., long background pulsations which carry simple pulsations (□). The complex profiles thus reflect the superposition of millisecond pulsations onto other periodic structures, particularly filaments and SRs.

In accordance with the intervals of values of $\Delta I/I$ in Table I, the dashed lines in the figures outline the domain of the $\Delta I/I(p)$ distribution in the form of the upper envelope of maximum values. In Fig. 1, for one of the series of pulsations in a large type IV burst on 24 April 1985, the shape of such an envelope with a maximum at $p \approx 0.4$-0.5 sec is similar to that expected in the model of pulsations in whistlers (Fig. 2 in Ref. 5). The duration of the individual pulsations in Fig. 1 lies at the limit of the resolving power of the spectrograph, ~0.02 sec.

We obtained a similar $\Delta I/I(p)$ distribution with a characteristic maximum at $p \approx 0.2$ sec for a series of spikes observed almost immediately after millisecond pulsations in a small type IV burst on 4 February 1986 (Fig. 2). But the slope of the envelope of the spike distribution is steeper than for pulsations. The slope should depend more on the whistler power, and the position of the maximum should depend more on the temperature ratio T_e/T_i. According to Fig. 2 in Ref. 5, assuming a constant ratio of the rates of rise of radio emission in the processes of merging of plasma waves with whistlers and of scattering from ions ($r \approx 1$), we may roughly estimate that $T_e \approx (7$-$8)\cdot 10^6$ K in the source of the pulsations on 24 April 1985, and $T_e \approx 3\cdot 10^6$ K (for $T_i = 10^6$ K) in the spike source on 4 February 1986. The distribution of millisecond pulsations in this event, like that in Fig. 1, corresponds to a temperature $T_e \approx (7$-$8)\cdot 10^6$ K. We may therefore assume that such different nonisothermicity in the source of pulsations and spikes is inherent to all events.

The behavior of the slope of the $\Delta I/I(p)$ distribution and of the diffuse "tail" of this distribution is characterized qualitatively in the last columns in Table I. The slope is estimated with only three positions: medium (~50-60°), steeper, and flatter and the diffuse "tail" of the distribution is estimated with two sizes of the period, short and long (allowing for the spread in the depth of modulation).

The long type IV burst on 5 February 1986 was rich in fine structure. In Fig. 3 we give information about only a small segment of one-second pulsations with filaments and SRs superposed onto them. Since the filaments and SRs have absorption features, the depth of modulation would be increased, which we do observe, and the "tail" distribution is associated with these additional structures. Here we have an even clearer characteristic shape in the distribution with a maximum at $p \approx 0.45$, which indicates $T_e \approx (7$-

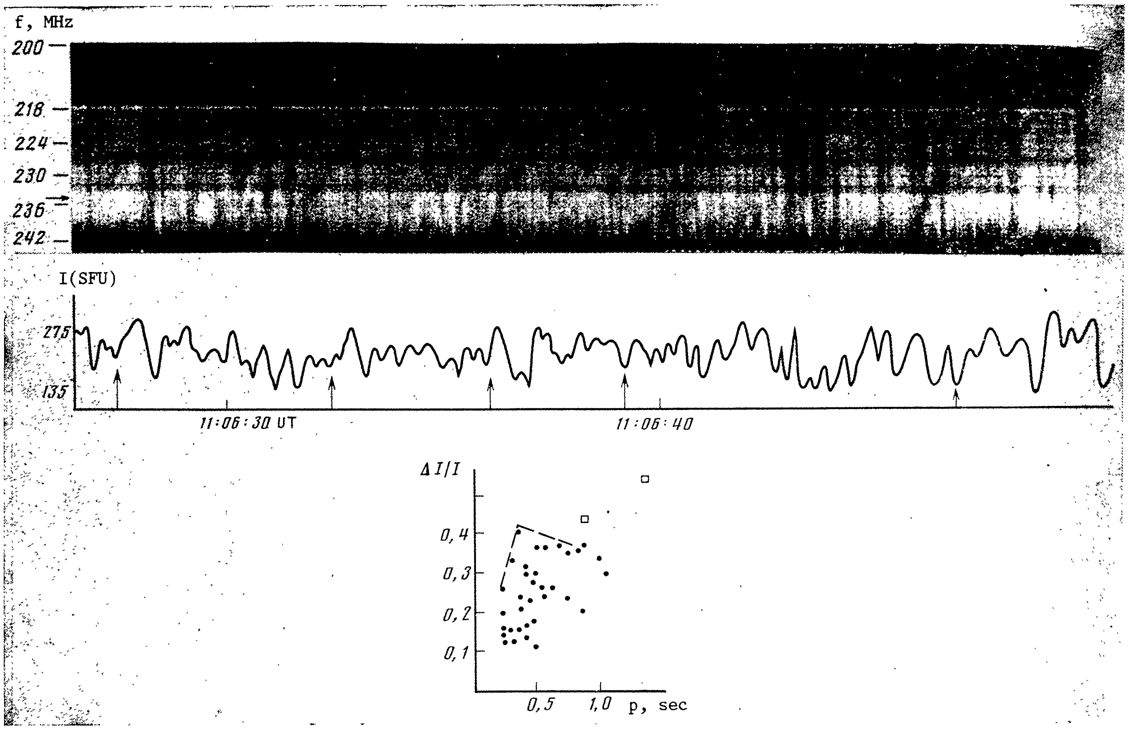

FIG. 4. Pulsations in emission and absorption and filaments in absorption in a brief type IV burst on 13 July 1982. All the notation is analogous to that in Fig. 1.

8)·10^6 K under the same assumptions. According to Ref. 5, the moderate depth of modulation in these events indicates a low level of whistler power in the sources of the pulsations and spikes, $W^w/n_eT_e \approx 10^{-6}$. the section of the spectrum containing single filaments has more depth of modulation, but it does not display the slope of the $\Delta I/I(p)$ distribution that corresponds to the model of the formation of filaments without ion–acoustic waves.

One of the most interesting events containing pulsations was a small type IV burst on 13 July 1982 (Fig. 4), associated with a weak flare (SN) in a small active region. Following a strong group of type III bursts, clearly defined pulsations in emission simultaneously with SRs and filaments in absorption were observed for about 10 min. The $\Delta I/I(p)$ distributions for six selected sections display a similar form with maxima at $p \approx 0.4$-0.5 sec. The slope of the $\Delta I/I(p)$ distribution becomes stepper with time and a small decrease is noted in the depth of modulation, which indicate (in accordance with the model of pulsations in whistlers) a gradual equalization of temperatures and a decrease in the whistler power in the source. All of this event can be described successfully in the model of pulsations in a reconnection region, which probably occurred fairly rapidly here. The type III bursts that immediately preceded the pulsations were produced by means of escaping electrons accelerated in a pulsed mode in the current sheet. This reconnection actually must have occurred high in the corona, since the start of the corresponding microwave burst was delayed by about 1 min relative to the meter burst (at 200 MHz).

CONCLUSION

Our analysis of the depth of modulation of fast pulsations of type IV radio bursts in the meter range shows agreement with the model of pulsations on whistlers in a pulsating mode of the latter with ion–acoustic waves in a source like a region of magnetic reconnection high in the corona. The depth of modulation $\Delta I/I$ of the pulsations increases almost linearly with period up to some maximum value $p \approx \nu_{ei}^{-1}$, which makes possible an approximate estimate of the electron temperature in the source. Agreement with observations is reached for a ratio $T_e/T_i \approx 7$ for fast pulsations and $T_e/T_i \approx 3$ for spikes and for a relative whistler energy density $W^w/nT_e \approx 10^{-6}$-10^{-7}. The time variation of the maximum value of $\Delta I/I(p)$ enables one to judge the variation of T_e/T_i and W^w in the course of an event.

The mechanism of millisecond pulsations in whistlers is attractive in that it does not require a pulsing source of fast particles or a pulsing disturbance that propagates from the flare region.

Here we do not discuss other spectral characteristics of the pulsations, particularly frequency drift, since it is usually not displayed in our millisecond pulsations. The latter corresponds to the model of pulsations in a reconnection region, in which the whistler pulsing mode is turned on when a nonisothermicity $T_e >> T_i$ is reach simultaneously over a wide altitude range, encompassed by shock fronts in the reconnection region, for example.

Despite the fact that for the shortest periods we observe a linear dependence of $\Delta I/I$ on p, which is also typical of the oscillatory mode of conical instability,[3] sharp differ-