Chapter 2
Pulsations

2.1 Overview of Oscillation Phenomena

For over more than four decades radio astronomers have been observing pulsating structures in the solar radio emission. "Pulsations" include a wide range of phenomena of quasi-periodic patterns or fine structures observed in the metric/decimetric/microwave frequency ranges. At the early stage they attracted the attention of solar radio astronomers by oscillating shapes of the time profiles of radio bursts. With the development of spectral observations it became clear that the pulsations occur almost simultaneously over a wide frequency range. They were described as series of fast drift bursts.

Slottje (1981) was the first who summarized the observational properties of the pulsations (see also Krüger (1979)). High resolution observations revealed that some pulsations consists of series of broad-band short-lived absorption pulses. Here, "absorption" does not mean the physical process. On the contrary, sometimes such pulsations were more likely the result of interruption of the emission process. Kuijpers (1975a) as well as Zaitsev and Stepanov (1975) and Benz and Kuijpers (1976) preferred, in view of their interpretation, the name "sudden reductions" of intensity.

All the available results and reports of observations show that pulsations appear at a wide range of the periods (from several minutes to sub-seconds) and emission frequencies, from meter (Rosenberg 1970; McLean and Sheridan 1973; Trottet et al. 1981), decimeter (Gotwols 1972; Bernold 1983), and to centimeter waves (Fu et al. 1990; Qin and Huang 1994), among others.

Aschwanden (1987, 2004a) presented an extensive review of all kinds of models for the pulsating events, and classified them into three groups: (1) MHD flux tube oscillations, which modulate the radio emissivity with a standing or propagating MHD wave (slow-mode magneto-acoustic oscillation, fast kink mode, fast sausage mode); (2) periodic self organizing systems of plasma instabilities (wave-particle, wave-wave interactions); and (3) modulation of acceleration (repetitive injection of particles into a loss-cone configuration). The third type may explain the shortest periods (<1 s), and it can include nonstationary magnetic reconnection.

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Pulsations are rarely observed in pure form. Usually, they are superimposed on other elements of the fine structure: spikes, fiber bursts, zebra patterns.

As such a complex example in Fig. 2.1 the subsecond pulsations in a prolonged type IV burst of 5 February 1986 are shown. The pulsations in emission alternate with sudden reductions with a nonrigourous period of 0.2–0.8 s and both are superimposed onto fiber bursts. The time profile in Fig. 2.1 shows a large modulation depth of the intensity I in the fast pulsations, $\Delta I/I \simeq 0.6$, and the dependence of $\Delta I/I$ on the period p reveals a maximum with the value of $p \simeq 0.5$ s.

The statistical analysis of the modulation depth executed in Chernov and Kurths (1990) with five other events with fast pulsations in the meter range showed a similar behaviour of these parameters. Therefore, in order to understand the nature of such fast pulsations, let us briefly examine the possibilities of different models.

2.2 Brief Characteristics of Pulsation Models

The plasma model of radio pulsations in the context of beam instability is based on nonlinear wave scattering into the nonresonant range of the wave spectrum, in which they are damped by collisions and are converted into electromagnetic radiation (Zaitsev et al. 1985; Aschwanden 1987). It should yield a strict period $p \simeq 2\,\pi/\nu_{ei}$ (ν_{ei} is the frequency of electron-ion collisions), but it can operate efficiently only for protons (Zaitsev et al. 1984).

Oscillations of loss-cone 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 ($\gamma \geq \gamma_{ei}$) for loss-cone instability are an increase in the modulation depth and a decrease in the intensity of the pulsations with an increase of their period. The strongest pulsations should have should have the shortest period (Zaitsev et al. 1985), which may be of millisecond value ($p \sim 1/\gamma$). But since the growth rate γ is proportional to the density of fast particles and the plasma frequency

$$\gamma \sim \frac{n_h}{n_c}\,\omega_{Pe},$$

a pronounced modulation may be expected only in the interior of the corona, such as in flare loops, in which $\omega_{Pe} \sim 10^{10}\ s^{-1}$ and $n_h/n_c \geq 10^{-5}$. Their most likely application has therefore been in terms of microwave millisecond (spike) oscillations (Zaitsev et al. 1985).

Relaxation oscillations of beam instability on electrons must be maintained by a periodic source of fast electrons and must have a low quality factor (Q, 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 excited by protons in Cherenkov or bounce resonance. Their period is determined only by the size of the

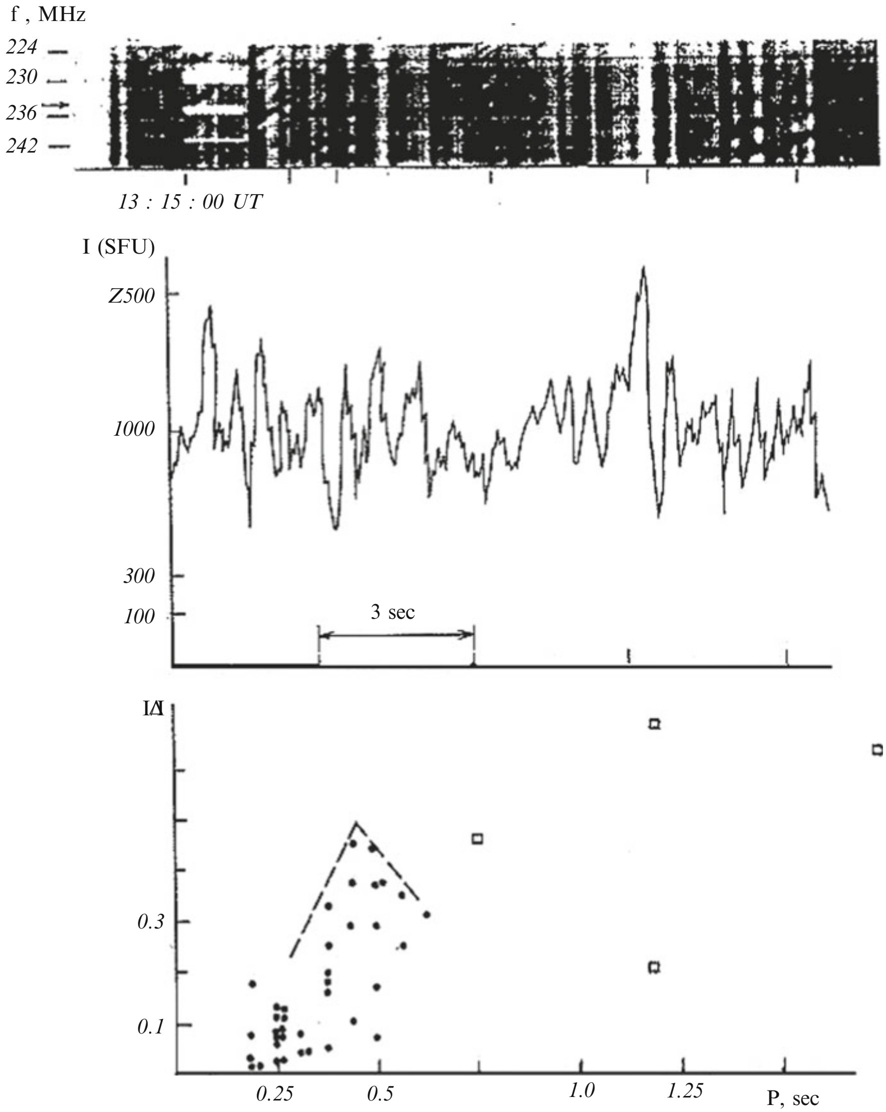

Fig. 2.1 Fast pulsations in emission and absorption superimposed onto fiber bursts in a prolonged type IV burst 5 February 1986. At the *top* is dynamic spectrum in the 224–245 MHz range (IZMIRAN); in the middle is the time profile of the radio emission flux (1 sfu $= 10^{-22}$ W m^{-2} Hz^{-1}) at 234 MHz (Potsdam) and in the *bottom* is the distribution of the modulation depth of the radio emission, $\Delta I/I = (I_{\max} - I_{\min})/(I_{\max} + I_{\min})$, as a function of the pulsation period p(s). *Dots* denote single pulsations, the *empty small squares* are complex long-period oscillations (Chernov and Kurths 1990)

trap and therefore it cannot be very short. Under 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, $V_A \cong (c/43)(f_{He}/f_{Pe})$ (f_{He} and f_{Pe} are the cyclotron and plasma frequencies of electrons), for a period $p = 0.05$ s we must assume the magnetic arch high in the corona with the improbably small dimensions, $R \approx 10^6$ cm and $l \approx 5 \cdot 10^8$ cm ($V_A \approx 3.5 \cdot 10^7$ cm for $f_{He}/f_{Pe} \approx 1/20$ and $V = 10^{10}$ cm s^{-1}).

MHD oscillation modes propagating in dense traps may yield the typical variation of the 1 s periods and the modulation depth, including three phases: (i) a periodic phase associated with the arrival from the flare region of a low-frequency disturbance with a maximum group velocity; (ii) a quasiperiodic phase with increasing modulation due to the interaction of the first disturbance and subsequent higher-frequency disturbance which arrives at the same level in the corona with the minimum group velocity; (iii) and a decay phase (Roberts et al. 1984; Aschwanden 1987, 2004).

MHD pulsations are determined by weak oscillations of the magnetic field in a FMS wave, $\Delta B \ll B_0$(B_0 *is undisturbed field*), so they must shallow modulation $\Delta I/I \approx \Delta B/B_0$ (Rosenrauh and Stepanov 1986).

Zaitsev et al. (1984) shown that the duration of pulse train (with the period of several seconds) in type IV radio bursts decreases with increasing hardness of the spectrum of high-energy protons and increases with decreasing proton flux from the Sun (in the Earth's orbit). Such a correlation (shown in Fig. 2.2) corresponds to a MHD model of pulsations and inexplicable within the framework of a nonlinear periodical regime of plasma instabilities.

In this case the oscillation period is determined only by the parameters of the trap and is independent of the density and spectrum of trapped particles. The duration of a pulsating structure is determined by the trapping time of the energetic protons sustaining MHD oscillations of the source (FMS waves). As the result of diffusion by small-scale Alfvén waves, the characteristic time required for the protons to escape the trap decreases with increasing density and hardness of the protons, which is essentially in agreement with observational data (Zaitsev et al. 1984).

The physical coupling of the pulsations and the energetic protons is as follow. The electrons and protons produced during the flare are partially trapped in a

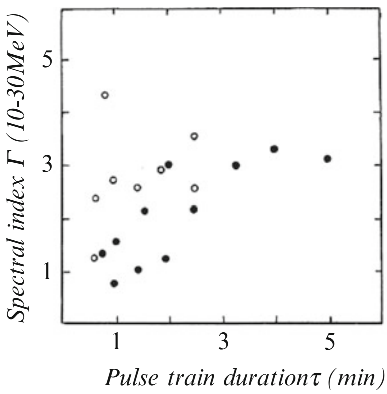

Fig. 2.2 The variation of integral spectral index (Γ) in the 10–30 MeV range versus pulse train duration (τ, min). The *filled circles* indicate 11 western flares, the *open circles* 8 eastern flares (Zaitsev et al. 1984)

coronal magnetic trap (loop) with an enhanced plasma density, the loop being a source of type IV radio emission as well as a resonator for the fast mode MHD wave. The energetic electrons are rather rapidly (over approximately a few seconds) released from the trap, after which their density within the trap is maintained at a comparatively low level, providing only the intensity required for type IV radio emission. The residence time of >10 MeV protons in the trap is substantially longer, and they excite and sustain MHD oscillations at the source, thus determining the duration of pulsating structures.

The protons trapped in the magnetic loop can, moreover, make a substantial contribution to the cosmic ray flux near the Earth as well. At times less the diffusion time, such protons drift with the speed $\upsilon_D \approx \upsilon^2/\omega_i R \approx 10^6 \mathrm{cm\,s^{-1}}$ (ω_i is the proton gyrofrequency, R is the radius of loop) toward the open magnetic field lines and escape into interplanetary space. Therefore, the pulsations of type IV radio emission are predictors of the appearance of protons in the vicinity of the Earth.

Sudden reductions (SRs) represent a special class of pulsations which are often superimposed onto sub-second pulsations in emission and complicate the picture. They are caused by a quench of loss-cone instability of plasma waves upon the injection of new particles into the loss-cone (Zaitsev and Stepanov 1975; Benz and Kuijpers 1976). They have the nature of deep troughs of radio intensity, so in an analysis of the modulation depth 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 loss-cone instability of plasma waves at the boundary between weak and strong diffusion of fast electrons on whistlers, including the quench of instability during the injection of new particles into the loss-cone (Trottet et al. 1981) or the model of torsional oscillations of a magnetic flux tube (Tapping 1983) may apply only to pulsations with a long period ($\gg$1 s).

Thus, the known models of pulsations do not enable us to explain millisecond pulsations with deep modulation of radio emission. In this connection Chernov (1989) proposed the mechanism of coalescence of plasma waves with whistler waves in which the whistler spectrum is determined by the pulsating regime of their interaction with ion-sound waves.

Model with whistler waves. In the pulsed regime of energy transfer between whistlers (w) and ion-sound waves (s) the combining mechanism of radio emission (t) due to the coalescence of whistlers with plasma waves (l) $l + w \rightarrow t$ yields pulses of radio emission in a wide frequency range at times of maximum of whistler energy (W^w). As a result of decay processes, a flat spectrum of whistlers $\mathrm{W^w} =$ Const (with respect to frequency and angle) is established, so the absorption bands typical for fiber bursts and zebra pattern will be washed out, and we should observe brief wideband pulses with a period of ~0.01–1 s that depends on W^w.

The main process resulting fast pulsations is associated with the pulsating regime of coalescence and decay of s– waves with whistlers: $s + s' \leftrightarrow w$. From experiments it is well known that this process proceeds at both the sum and difference frequencies. The maximum increment of s-waves falls at frequencies close to the ion plasma frequency ω_{Pi}. In the solar corona at the altitudes of meter and decimeter ranges, the approximate equality $\omega_{Pi} \approx \omega_{Be}/4$ is satisfied, which favors the realization of conservation laws for processes $s + s' \leftrightarrow w$ at the difference frequency and the maximum increment (Chernov 1989). Such a condition is not satisfied in the Earth's magnetosphere.

A second necessary condition for satisfying the conservation laws for this pulsating process is isotropization of the wave vectors k^s and k^w, since the process proceeds for two oppositely directed vectors k^s and $k^{s'}$ and the vector k^w directed at an angle $\vartheta^w > 70°$ (Tsytovich 1977). In this case, the slowest process (determining the pulsation period) is scattering of whistlers on thermal electrons. For the usual whistler energy density (relative to thermal energy of the background plasma) $W^w/nT \approx 10^{-7}$, this scattering time is ~0.3–0.2 s.

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

The source of such pulsations may be located in a region of reconnection (of high coronal loops) with a vertical size ~ (2–5) 10^9 cm, for instance, between magnetic islands after a flare. Such a region must contain a neutral magnetic point of the X type with diverging shock fronts, between which the nonisothermicity develops ($T_e \gg T_i$) and ion-sound waves are excited. Even in an initially isothermal plasma in the reconnection region, the ion-sound waves are excited by Cherenkov mechanism with a large increment due to the electron drift relative to ions V_d in the current sheet. The ion-sound instability changes smoothly into Buneman instability for $V_d > V_{Te}$ (the thermal velocity of electrons), maintaining the nonisothermicity in the reconnection region (Kaplan and Tsytovich 1973). The heating occurs simultaneously over a wide altitude range between shock wave fronts. The conservation laws for the processes $s + s' \leftrightarrow w$ and $l + w \rightarrow t$ can be satisfied simultaneously over entire reconnection region only after the spectra of s- and w-waves become isotropic due to scattering.

All these nonlinear processes are accelerated with increase in W^s and W^w and if $p > \nu_{ei}^{-1}$, then the period will decrease with increasing of W^w (i.e., with increasing pulse intensity and modulation depth), regardless of the level W^l of the plasma waves (i.e., the continuum level). For high levels of W^w, when $p < \nu_{ei}^{-1}$, the pulse modulation depth $\Delta I/I$ will decrease sharply with decreasing period due to the coalescence of individual pulses, when the intermittence disappears. Therefore, the dependence of $\Delta I/I$ on period p should typically have a maximum at $p = \nu_{ei}^{-1}$.

Figure 2.3 shows the modulation depth as a function of period calculated for several values of W^w, temperature $T_e = 10^6$ and $3 \cdot 10^6$, $f_{Pe}/f_{Be} = 30$ and two values of the parameter r – the ration of rates of rise of the radio emission in two processes, $l + w \rightarrow t$ and $l + i \rightarrow t$. The approximate domains of the pulse parameters in the models of MHD oscillations, plasma oscillations of loss-cone instability (Pl) and sudden reductions (SR) are also shown qualitatively. The presence of a maximum in the dependence of $\Delta I/I$ on p at the value $p = \nu_{ei}^{-1}$ is the main indicator for the model with whistlers. The number of electron-ion collisions decreases with increasing T_e approximately as ~$T_e^{-3/2}$, so a shift in the

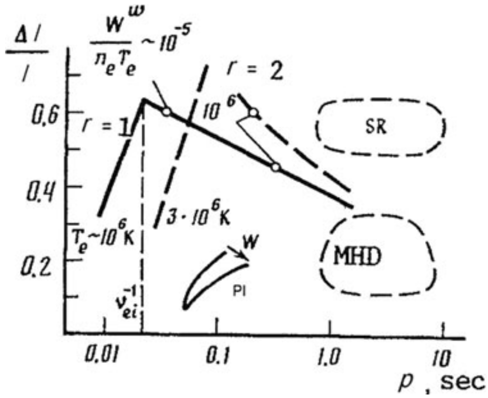

Fig. 2.3 Calculation of the modulation depth $\Delta I/I$ of radio emission as a function of the pulse period p in the model based on whistlers whose level is maintained by ion-sound turbulence (Chernov 1989)

maximum with time provides information about the variation of T_e in the source. The amplitude of the pulses increases sharply with increasing r. Then strong pulses should be observed even against a weak continuum emission. The sharp maximum may be smoothed out if W^w does not exceed $10^{-6}\ n_eT_e$. If a fiber burst is superposed on the pulses, then the modulation depth should increase due to the contribution of low-frequency absorption.

The nonlinear oscillatory regime of loss-cone instability discussed in Zaitsev et al. (1985) for microwave pulses, can also yield pulses in the meter-wave range. The period of such plasma oscillations, $p \approx 2\pi/\nu_{ei}$, increases with increasing modulation depth and intensity.

Pulses in the model of MHD oscillations of coronal traps with FMS waves in bounce resonance have relatively long period ($\gtrsim$1 s), determined only by the size of magnetic trap, and a small modulation depth, proportional to the magnetic field oscillation in the FMS wave, $\Delta I/I \approx \Delta B/B$, ($\Delta B \ll B$).

Thus, in this mechanism of pulsations with 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-sound waves and by the degree to which T_e exceeds T_i) up to some maximum value at a period $p\ p \propto \nu_{ei}^{-1}$.

In Fig. 2.1 fiber bursts and SRs are superimposed onto pulsations, and since they have absorption features, the modulation depth would be increased, which we do observe and a “tail” distribution is associated with these additional structure. Here, we see clear characteristic shape in the distribution with a maximum at $p \approx 0.45$ s, which indicates the value of $T_e \approx (7\text{–}8) \cdot 10^6$ K.

The statistical analysis carried out by Chernov and Kurths (1990) revealed a similar dependence $\Delta I/I(p)$ in numerous series of the fast pulsations observed in five other radio bursts. One of the most interesting events was a small type IV bursts on 13 July 1982 shown in Fig. 2.4. Following a strong group of type III bursts clearly defined pulsations in emission simultaneously with SR and fibers bursts in absorption were observed for about 10 min. The $\Delta I/I(p)$ distribution for six selected fragments display a similar form with maxima at p $\approx$ 0.4–0.5 s. The

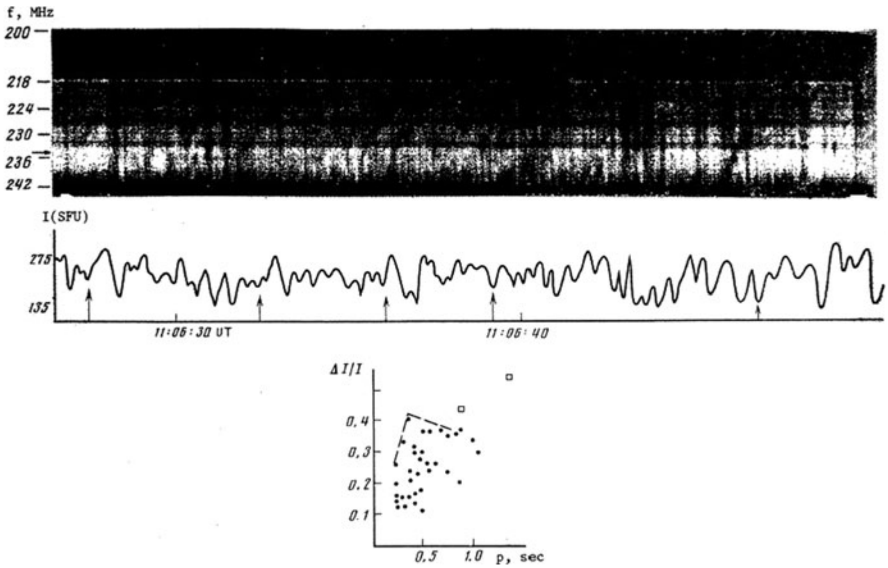

Fig. 2.4 Pulsation in emission and absorption and fiber bursts in absorption in brief type IV bursts on 13 July 1982. All the notations are analogous to that in Fig. 2.1 (Chernov and Kurths 1990)

slope of this distribution becomes stepper with time and a small decrease is noted in the modulation depth, which indicate (in accordance with the model of pulsations with whistlers) a gradual equalization of temperatures and a decrease in the whistler energy in the source. This event can be related with a magnetic reconnection high in the corona, since the start of the corresponding microwave burst was delayed by about 1 min relative to the meter bursts. The type III bursts (that immediately preceded the pulsations) were probably produced by fast electrons accelerated in a pulsed mode in the current sheet.

The mechanism of millisecond pulsations with 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.

2.3 Microwave Pulsations

2.3.1 New Observations

The microwave emission region is very close to the flaring region, therefore their periodic pulsations must carry important information about the physical conditions in flaring energy-releasing regions (Fu et al. 1990; Qin and Huang 1994). There is a series of new good observational data in the frequency range of 2.60–3.80 GHz taken with a Solar Broadband Radio Spectrometers (SBRS, Huairou, NAOC)

(Fu et al. 2004; Tan et al. 2007). The frequency resolution of SBRS is 10 MHz, and the cadence is 8 ms in the frequency range 2.6–3.8 GHz. This provides us with a good opportunity to study the temporal behavior of the microwave quasi-periodic pulsations.

Figure 2.5 shows three typical examples of the pulsating phenomena (in right polarization) in big event on 13 December 2006 observed equally with other kinds of fine structures: fiber bursts, zebra patterns, spikes (in emission and absorption).

Tan et al. (2007) carried out the statistical analysis of pulsations in this event. There are more than 40 cases of pulsations with periods of <1.0 s. They were observed at rising phase of the flare as well as at peak and post maximum phases. The mean pulsation duration was about 10–13.0 s. About 75% of pulsations events (31 in 41) had the period of $p < 100$ ms.

2.3.2 Theoretical Models

It is still an open question as to which pulsating mechanisms are relevant for the interpretation of the observing features, and how the proposed model works in detail, especially for the very short period pulsations.

Models known earlier usually dealt with the considerably larger periods of microwave pulsations. There is much evidence showing the existence of the electric current system in the flaring region. The disturbances of the current system produced by some beams of fast electrons propagating in the magnetic tube will lead to dynamic processes, which in turn will stimulate radiation of the system in X-rays and microwaves, which appeared in additional to the beam-generated radio bursts. By this process, a pulsating regime can be triggered with the global sausage mode (Nakariakov 2007); its period is in the range from several seconds to several tens of seconds.

As the pulsations may indicate the existence of the longitudinal electric current in the solar plasma loops, Zaitsev et al. (1998) provided another model of an LRC circuit analog of current-carrying magnetic loop to diagnose the electric current in the solar plasma loops.

Kliem et al. (2000) proposed another model in which the radio pulsations are caused by quasi-periodic particle acceleration episodes that result from a highly dynamic regime of magnetic reconnection in an extended large scale current sheet above the soft X-ray flare loop. They think that radio pulsation is a signature of dynamic magnetic reconnection, and that the reconnection is dominated by repeated formation and subsequent coalescence of magnetic islands, known as secondary tearing modes. With this model, Kliem et al. may explain the pulsations with periods of 0.5–5 s.

However, up to now we have not had a good model for accurately interpreting fast pulsating events with a very short period (VSP) of several tens of milliseconds at a frequency of microwaves.

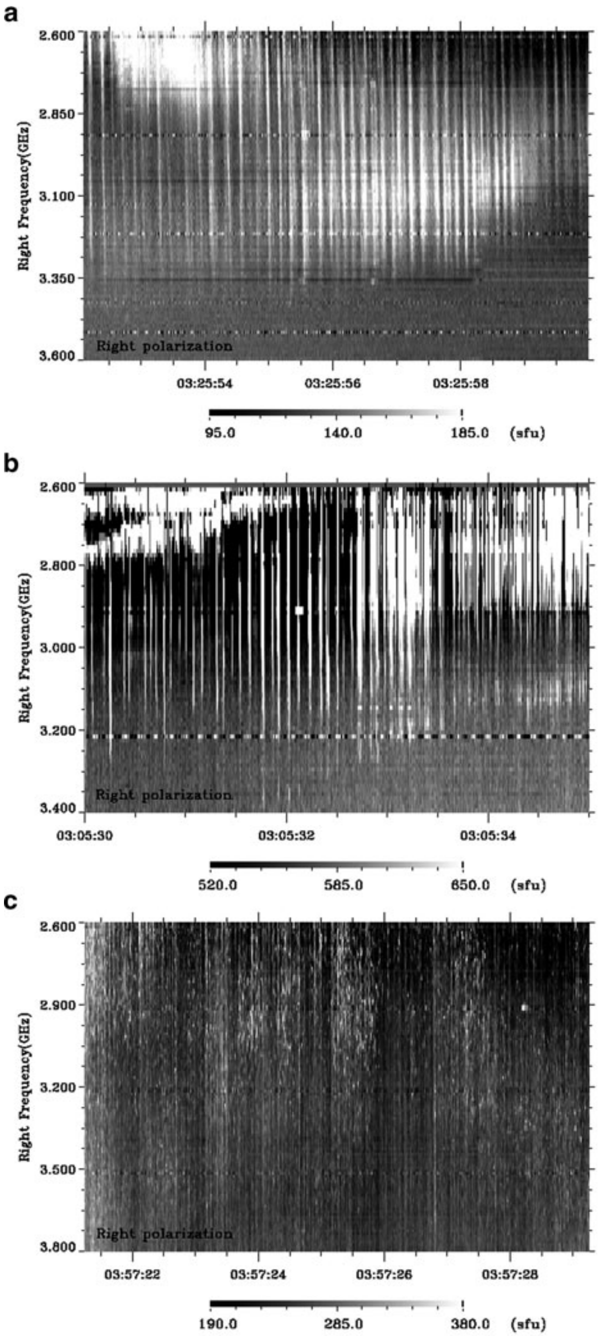

Fig. 2.5 The pulsations structures in the long-lasting event on 13 December 2006. The *panel* (**a**) shows an fragment that occurred during 03:25:52.0–03:25:59.0 UT, after the peak of the flare. The *panel* (**b**) shows an fragment that occurred during 03:05:30.0–03:05:32.7 UT, just after the peak of the flare. The panel (**c**) shows *snowflake-like spikes* distributed along the *vertical lines* of the microwave pulsations during 03:57:21–03:57:29 UT, quite a bit after the peak of the flare (SBRS/Huairou) (Adapted from Tan et al. 2007)

Tan et al. (2007) proposed a new model of the tearing-mode oscillation in current-carrying flare loops to explain the very short pulsation period. The flaring region must consist of many current-carrying compact loops. 2. In each current-carrying flare loop, the resistive tearing mode instability will trigger the formation of a series of multiscale magnetic islands (with different poloidal number m). The positions of X-points is between two magnetic islands. Electron accelerations occur in the regions near each X-points, and the energetic electrons are distributed mainly along the X-lines of the magnetic configuration in the current-carrying flare loops. Such an electron acceleration process is a bit similar to the stochastic particle acceleration model. The resistive tearing-mode oscillation will modulate the plasma emission, turning the emission spectrogram into pulsating structures. The evolution of the tearing-mode instability dominates the duration of the pulsating events, and the period of the tearing-mode oscillation governs the period of the pulsating events.

The period of the oscillations mainly depends on several factors:

1. For the total electric current (I), $p \propto 1/\mathrm{I}$.
2. For the geometrical parameters of the loop, a and R_0, the loop section radius a is especially sensitive to the period of the pulsations, $p \propto a^2$.
3. For the plasma density ρ, $p \propto \sqrt{\rho}$; here, $\rho \approx Nm_i$.

The calculated values of period are shown in Fig. 2.6.

From Fig. 2.6 we find that the shorter the period of the oscillation, the greater the poloidal number m.

So, the main conclusion is that the pulsations of the microwave emission are the result of the modulation of the resistive tearing mode oscillation in the current-carrying flare loops.

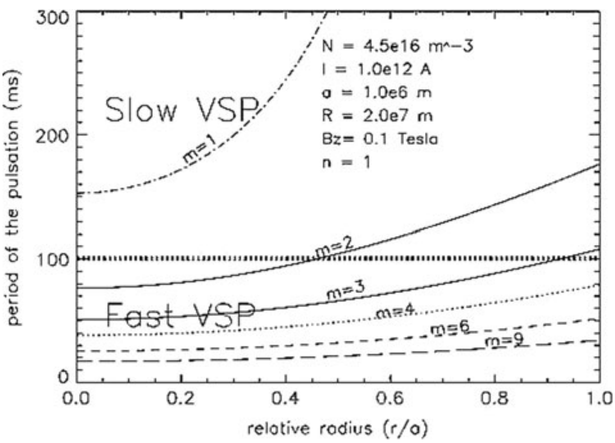

Fig. 2.6 Pulsation period due to the tearing-mode oscillation with different poloidal mode numbers in the flare loops. The fast VSP is located below the *broad dashed line* at 100 ms, where the poloidal number is $m > 2$, and the slow VSP is located above the *broad dashed line*, where $m < 2$ (Courtesy of Tan et al. 2007)

Tan (2008) defined a set of observable parameters of short pulsations and then discussed the possible relations among these observed parameters and their physical implications for the dynamical processes of solar eruptive events, and applied them to interpret the nature of the pulsations.

2.4 Summary

Pulsations in the solar radio emission have been observed during more than four solar cycles. Many theoretical models were developed several decades earlier and described in numerous reviews and several books. However, new spectral observations have shown that all known models do not explain the large modulation depth, and the most developed MHD model cannot explain fast (millisecond) pulsations both in the meter and in microwave ranges. Here, we described, possibly, the unique model of pulsations with the whistlers, which explains the large modulation depth in the fast pulsations (§ 2). It is presented for the meter and decimeter ranges, although, possibly, with the larger probability it can explain millisecond pulsations in the microwave range. However, more contemporary recent developments connect millisecond pulsations in the microwave range with the resistive tearing-mode oscillations in the current-carrying flare loops (§ 3.2). In any case, the plasma model does not correspond to radio-pulsations, first of all in the modulation depth of pulsations, possibly, because of a large extent of the source of pulsations in height in the corona, when nonlinear oscillations from different parts of the source become dephased, and pulsations wash off. So, if we obtain microwave spectrograms with high cadence and a high frequency resolution, in addition to radioheliographs with high resolution in space instantaneously, then we can distinguish the detailed electromagnetic structure of the flaring region, and this will help us to understand the physical mechanism of the eruptive processes.

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