ON THE MODULATION OF PLASMA EMISSION FROM CORONAL MAGNETIC ARCHES

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ABSTRACT. Pulsations of plasma emission of type IV radio bursts and microwave emission of magnetic loops as a result of MHD oscillations of related sources, are considered. A relation between the amplitude of magnetic field oscillations and second harmonic plasma emission is found making it possible to estimate the energy density of flare-produced protons and their geo-efficiency.

О МОДУЛЯЦИИ ПЛАЗМЕННОГО РАДИОИЗЛУЧЕНИЯ КОРОНАЛЬНЫХ АРОК: Рассмотрены пульсации плазменного радиоизлучения IУ типа и микроволнового излучения вспышечных петель, обусловленные МГД-колебаниями источника. Найдена связь амплитуды магнитного поля с глубиной модуляции радиоизлучения, возникающего при конверсии ленгмюровских волн в электромагнитные. Получены соотношения, позволяющие по глубине модуляции радиоизлучения корональных арок оценивать плотность ускоренных во вспышке протонов и судить о геоэффективности вспышек.

O MODULÁCII PLAZMOVÉHO RÁDIOVÉHO ŽIARENIA, VZNIKAJÚCEHO V KORONÁLNYCH SLUČKÁCH: V práci sú skúmané pulzácie plazmového rádiového žiarenia IV. typu a mikrovlnného žiarenia z erupčných slučiek, ktoré vznikajú MHD osciláciami zdroja. Zo vzťahu zisteného medzi amplitúdou oscilácie magnetického poľa a emisiou vyžarovanou na druhej harmonickej frekvencii je možné určiť hustotu protónov urýchlených v erupcii a geoefektívnosť erupcie.

Periodic modulation is a typical feature of the radio emission from coronal magnetic arches. Microwave emission pulsations with a period of order of one second or less often occur during the impulsive phase of the flare (1). Pulsations with a period of several seconds are common patterns of fine structure of type IV radio bursts.

The origin of emission fluctuations is now being associated with radial oscillations of the emission source - a flux tube with a plasma density much higher than that of its surroundings (2, 3). These MHD-oscillations of the flaring loop may be excited due to a fast energy release that results in an flaring loop may be excited due to a fast energy release that results in an expansion of the flux tube (4). Radial oscillations of type IV burst sources - large ($\sim 10^{10}$ cm) coronal magnetic arches - can be excited by $\gtrsim 10$ MeV proton which are accelerated during the impulsive phase (3). The eigenperiod of the fundamental mode of these fast magnetosonic (FMS) waves $T_p \sim L_\perp/C_A$ agrees with observations when the characteristic transverse size of the flux tube is $L_\perp \sim 10^3$ km ($C_A \sim 10^3$ km s^{-1} - local Alfven velocity).

Rosenberg (2) treated the relations between FMS oscillations of a magnetic arch and modulations of synchrotron emission. However, the major role of plasma emission, rather than the synchrotron emission, for type IV metric and decimetric bursts is now generally accepted (5, 6).

In the present paper, the plasma emission pulsations due to FMS oscillations of related sources, i.e. the response of second harmonic of plasma frequency emission to the variations in the magnitude of the magnetic field, is considered. The results have importanst implications and make it possible to estimate the energy density of flare-produced protons and their geo-efficiency.

Within the frames of a plasma emission model it is assumed that radio emission arises as a result of Langmuir wave excitation and their subsequent nonlinear conversion into electromagnetic modes Langmuir waves in coronal arches are supposed to be excited by suprathermal electrons with energy E 100 keV. These electrons are confined in a magnetic trap and their distribution in velocity space may be anisotropic (of the "loss-cone" type). The intense microwave emission of flaring loops can also be explained by invoking a plasma emission model (7). The electron Langmuir frequency ω_p in the plasma of coronal arches is much greater compared with gyrofrequency, $\omega_p \gg \omega_B$; this inequality may be valid for flaring loops as well. The most important processes of nonlinear conversion under coronal arch conditions are those of coalescence and decay $l + l' \rightleftarrows t\,(2\omega_p)$. Spectral intensity for the second harmonic I_ω along the ray paths can be found from the transfer equation.

$$N_\omega^2 \frac{d}{ds}\left(\frac{I_\omega}{N_\omega^2}\right) = \alpha_\omega - (\mu_\omega^c + \mu_\omega^N)\, I_\omega \,. \tag{1}$$

Here α_ω is the emissivity of transverse waves with frequency $\omega = 2\omega_p$ due to coalescence of Langmuir waves, μ_α^c and μ_ω^N are the absorption factors associated with the Coulomb scattering and decay process $t\,(2\omega_p) \rightarrow l + l'$ respectively, and N_ω is the refraction index. Absorption factor μ_ω^N linearly depends on Langmuir wave energy density W, $\mu_\omega^N \propto W$, while $\alpha_\omega \propto W^2$.

Assuming the plasma density to be smoothly decreasing across the arch, one finds that the thickness of the emitting layer, L_N, (i.e. a layer where α_ω and μ_ω^N are nonzero) is much less compared with the characteristic transverse size of the arch: $L_N \sim (T/E)L_\perp$. Here T is the temperature of background plasma, and E denotes the energy of suprathermal particles. Assuming further the Langmuir wave spectrum to be isotropic and sufficiently broad in wave vector space $\Delta k \sim k \sim \omega_p \sqrt{m/E}$, and ignoring μ_ω^c inside the layer for it is small compared with μ_ω^N , one obtains the solutions of eq. (1) for the cases of an optically thin ($\tau_N \sim \mu_\omega^N L_N << 1$)

$$I_{\omega/s\to\infty} = \frac{(2\pi)^2}{30}\frac{\omega}{\omega_p}\frac{\omega^3}{K^3C^3}\frac{T}{mc^2}\left(\frac{W}{nT}\right)^2 N\omega\,(s=0)\ nTL\ \ e^{-\tau_c}\ ;\ \tau_N << 1 \quad (2)$$

and an optically thick source (9)

$$I_{\omega/s\to\infty} = \frac{\omega^2}{K^2C^2}\left(\frac{W}{n\,T}\right)\frac{n\,T}{K}\,e^{-\tau_c}\ ;\quad \tau_N >> 1. \quad (3)$$

In eqs. (2) and (3) is the background plasma density, and $\tau_c = \int_0^{L_L} \mu_\omega^c\,ds$ represents the optical depth related to the absorption due to the collision process. For pulsating type IV burst sources, $\tau_c \sim 10^{-2}$, whereas in flaring loops τ_c may be of order unity.

The optical depth due to the decay process τ_N depends on the energy density of Langmuir waves, and, in general, $\tau_N << 1$. However, in some powerful events of microwave band $\tau_N \gtrsim 1$.

It can be seen from eqs. (2) and (3) that the modulation of emission intensity due to FMS oscillations of the source is caused by variations in plasma density and temperature, source sizes and energy density of Langmuir waves. The latter can be determined from the kinetic equation for Langmuir waves. In this equation we take into consideration that the characteristic time of processes governing the wave spectra dynamics is much less than the FMS period, so we reduce the kinetic equation to an equilibrium condition between spontaneous or induced Cerenkov excitation of waves by suprathermal electrons with density n_1 , and induced wave pitch-angle scattering of the thermal ions into the absorption region.

In large coronal arches ($n \sim 10^8$ cm^{-3}; $n_1 \sim 10^{-6} n$; $T \sim 100$ eV) the distribution of fast electrons in velocity space is anisotropic (of the "loss-cone" type) and, there-fore, is unstable. In this case spontaneous emission of Langmuir waves is negligible. Magnetic moment $mV_\perp^2/2B$ of these collisionless particles in a slowly-varying magnetic field is conserved and the distribution function varies as

$$f(V_\parallel;\ V_\perp;\ t) = f(V_\parallel;\ V_\perp/\alpha(t));\quad \alpha^2 = B(t)/B(0). \quad (4)$$

Here B(t) defines magnetic induction as a function of time. Variations in the magnitude of the magnetic field result in those of the loss cone and, hence, in oscillations of the instability growth rate. A maximum of the instability growth rate usually corresponds to the waves propagating strictly across the magnetic field. Keeping in mind that the magnetic field is "frozen-in" to the plasma, $n(t) = n(0)\alpha^2(t)$, one can find that the relative energy density of Langmuir waves W/nT does not change:

$$\frac{W}{n\,T} \backsim \frac{n_1}{n} = \text{const} \quad (5)$$

The plasma temperature in a flux tube varies according to adiabatic law: $T(t) \backsim \alpha^{4/3}$. Assuming for the sake of simplicity, that the magnetic field oscillations are small, $\delta B/B << 1$, we obtain from (2) the following relation for type IV emission modulations (9):

$$\frac{\delta I_\omega}{I_\omega} = \frac{7}{6}\frac{\delta B}{B} . \qquad (6)$$

Under flaring loop conditions ($n \sim 10^{12}$ cm^{-3}; $n_1 \sim (10^{-4} - 10^{-6})n$; and $T \sim 1$ keV) the characteristic time of waveparticle interaction is much less than the mean time required for a particle to traverse the loop length, when the Langmuir wave energy exceeds $W/nT \sim 10^{-8}$. In this case the velocity distribution is almost isotropic and the spontaneous, rather than induced, wave excitation appears to be of major importance. The balance of spontaneous excitation and induced scattering of thermal ions provides the following relation between W and the magnetic field: $W/nT \backsim \alpha^{-1/6}$. One then obtains from (3) and (2) /9/:

$$\frac{\delta I_\omega}{I_\omega} = \left[\frac{1}{12} - \frac{2}{3}\tau_c\right]\frac{\delta B}{B}\,; \quad \tau_c\frac{\delta B}{B} << 1; \quad \tau_N > 1 \qquad (7)$$

$$\frac{\delta I_\omega}{I_\omega} = -\left[\frac{1}{2} + \frac{2}{3}\tau_c\right]\frac{\delta B}{B}\,; \quad \tau_c\frac{B}{B} << 1; \quad \tau_N < 1. \qquad (8)$$

Note that, as follows from the above formulae, the second harmonic intensity modulations may either coincide in phase or to be in opposite phase with FMS oscillations.

Zaitsev et al. /10/ showed that 86 % of the type IV radio emission pulsations are accompanied by the appearance of protons in interplanetary space, and the shorter trains of pulsations precede escaping of a large number of protons with a hard spectrum. An important parameter that is useful for estimating the proton energy density, is represented by the modulation amplitude of radio flux. Thus, on 14 January 1971 the radio flux modulation was 5 to 10 % /11/ and the energy of FMS-waves, inferred from formula (6), constitutes only a minor ($\sim 10^{-2}$) fraction of the energy of an unperturbed magnetic field. The energy density of fast protons which were responsible for existing the FMS-waves, was, thus, at least 10^{-2} of the magnetic arch energy density. No protons were observed to escape. In the 14 May 1971 flare /12/ the modulation amplitude was ≈ 20 % and the ≥ 10 MeV proton flux was 1.5 (s.cm^2.sr)$^{-1}$. A deeper, ≈ 50 %-modulation of the 31 May 1978 burst /13/ was accompanied by more intense (> 10 (s.cm^2.sr)$^{-1}$) proton fluxes. Hence, there is a tendency for the protons to increase in numbers with increasing amplitude of the type IV radio emission pulsations.

Assuming, as was done in /4/, that the plasma thermal energy during the flare energy release goes into expanding the magnetic flaring loop, and using formulae (7) and (8) it is possible from the depth of microwave emission pulsations to estimate the parameter $\beta = 8\pi P/B^2$ in the region of primary energy release (P being the gas kinetic pressure of plasma). If the value of β exceeds the threshold of development of a flute instability, $\beta > 0.3$, it might then be expected that flare-accelerated particles would be escaping into interplanetary space and shock waves would be generated /14/.

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DISCUSSION

H. Aurass
You have shown 3 examples of the application of your method of diagnosis. In which frequency range the used radiofluctuations have been observed ?

Yu. M. Rozenraukh
We have simultaneous observations of radio emission and protons in interplanetary space only for decimetric and metric band.

M. A. Mogilevsky
Какие значения δB и B в высоких и низких корональных арках ?

Yu. M. Rozenraukh
Мы считали, что магнитное поле в арках таково, чтобы выполнялись условия $\omega_p \gg \omega_B$ т.е. в высоких арках $B \sim 10$ Гс, а во впышечных петлях $B \sim 10^2$ Гс. В разных событиях $\delta B/B$ может быть от единиц до десятков процентов.