1984SoPh...93..363Z

PULSATIONS OF TYPE IV RADIO BURSTS AS AN INDICATOR OF PROTONABILITY OF SOLAR FLARES

V. V. ZAITSEV
Applied Physics Institute, Gorky, U.S.S.R.

A. V. STEPANOV
SibIZMIR, Irkutsk, U.S.S.R.
and
G. P. CHERNOV
IZMIRAN, Troitsk, U.S.S.R.

(Received 12 December, 1983; in revised form 9 April, 1984)

Abstract. The analysis of observational data has shown that the duration of a pulse train in type IV radio bursts decreases with increasing hardness of the spectrum of high-energy protons and increases with decreasing proton fluxes from the Sun. It is shown that such a correlation corresponds to a magnetohydrodynamic (MHD) model of pulsations and is inexplicacable within the framework of a nonlinear periodical regime of plasma instabilities. The pulse train duration is determined by proton pitch-angle diffusion caused by Alfvén waves in coronal magnetic loops. A method of predicting solar proton hardness and proton fluxes using type IV radio burst pulsations is proposed.

1. Introduction

McLean *et al.* (1971) were the first to draw attention to a correlation between the pulsations of metre-wave type IV radio emission and the increase of solar cosmic ray fluxes. Of eight pulsating structures five were associated with solar energetic protons, as observed by satellites. McLean *et al.* (1971) drew the conclusion that the pulsations were a manifestation of a proton acceleration process operating during a solar flare. Kosugi (1982) has shown that the start of pulsations in the solar flare of 10 November, 1978 coincides with the origination of new microwave sources above sunspots. In this case the pulsations seem to be the manifestation of a second-step acceleration of particles in the corona. Attempts have been made previously to provide a theoretical explanation for the correlation between the ratio pulsations and the high-energy protons (Zaitsev and Stepanov, 1975a; Meerson *et al.*, 1978). However, experimental investigation of the association of protons with pulsations is not yet complete. Proton flares over a long period have not been considered, and no qualitative characteristics of such an association are yet available. In this paper an analysis of 57 type IV radio pulsation events is presented that provides a close correlation between pulsations and proton fluxes from the Sun and a dependence of the duration of pulse trains on proton flux and hardness of the proton spectrum.

Current methods for the quantitative diagnosis of proton flares using radio emission

Solar Physics **93** (1984) 363–377. 0038–0938/84/0932–0363$02.25.

are generally based on the relationship of the spectrum of the microwave emission generated by energetic electrons in the solar corona to proton characteristics in the vicinity of the Earth. Bakshi and Barron (1979), for example, found a correlation between the hardness of the proton spectrum and the width of the U-shaped peak flux density spectra of solar radio bursts. Chertok (1982) suggested the determination of the spectral index Γ of the integral power-law energy proton spectrum from the value of the ratio of maximum solar radio burst flux densities at frequencies of 9 and 15.4 GHz. This paper demonstrates that the origin and duration of pulsations are directly associated with the injection and trapping of energetic protons in a coronal magnetic trap the type IV radio pulsation source. This is the physical basis for the method we offer for predicting the solar proton flux characteristics using pulse train duration.

2. Observational Data Analysis

In order to investigate the correlation between radio pulsations and proton fluxes we have employed all the data available to us in the literature as well as type IV burst dynamic spectra between 45 and 230 MHz as taken at IZMIRAN. This categorization of pulsations involved essentially instantaneously emitted quasiperiodic modulations over a broad range of frequencies ($\gtrsim 50$ MHz). No account was taken of broad-band short-lived absorption pulses (sudden reductions), which have a quite different origin (Slottje, 1981). Determining a pulse period T and pulse train duration τ in some events is easy (see, e.g., McLean *et al.*, 1971; McLean and Sheridan, 1973). However, a number of phenomena showed a variability of pulsation period for the same series and recurrent series of pulsations of different duration. In such cases we chose a minimal duration τ of the series and a minimal pulse period T for typical values.

With all this in mind, we were successful in identifying 57 type IV bursts with pulsating structure. Data on proton fluxes were taken mainly from *Solar Geophysical Data* Bulletins and were checked using *Catalogs of Solar Particle Events* (Švestka and Simon, 1975; Logachev, 1983). Allowance was made for proton fluxes, recorded both by orbiting satellites (Explorer, Imp) and by heliocentric satellites (Pioneer). In 42 of the 57 events (74% of cases) > 10 MeV proton fluxes above 1 proton $\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$ were observed. In 7 low-energy cases 0.6 to 13 MeV protons were recorded, and in only 8 events were no protons detected. The last two groups of phenomena were primarily associated with weak solar flares in the eastern hemisphere. Note that the type IV radio bursts are identifiable with flares with rather high confidence. The identification of < 10 MeV protons with these flares will be considered as reliable in this paper when the delay time between the onset of the flare and the associated particle flux does not exceed two days. Thus, with due regard for low-energy events, the type IV radio burst pulsations are associated with proton events in 86% of the cases. Actually, with particle propagation effects taken into account, the correlation can be better.

To study the dependence of the pulsation period T and duration τ of a pulse train of a given period on the exponent of integral power-law proton spectrum and on > 10 MeV proton flux F we chose 23 events for which there were reliable data on fluxes of 10–30 MeV protons and on spectral index Γ. These events are summarized in Table I, which also lists the Hα flare parameter. In some cases Γ was determined using data on fluxes of > 10 MeV and > 30 MeV protons. The data on a flux of > 10 MeV protons, appearing in Table I in brackets, were extrapolated from values of high-energy particle fluxes, assuming $\Gamma =$ const. in the energy range under consideration.

The data analysis showed that the values of the pulsation period fall within the interval of 0.2 to 20 s and do not show any dependence on spectral index Γ or proton flux F. However, the pulse train duration τ shows a conspicuous correlation with energetic proton parameters. Figure 1 shows the variation of the spectral index Γ of protons with τ. It is apparent that in 11 events associated with flares in the Western Hemisphere, for which the influence of heliolongitude on the particle spectrum is minimal, Γ increases markedly (the spectrum is softened) with increasing pulse train duration. In Figure 1 these events are denoted by filled circles. For comparison, open circles in Figure 1 denote eight events in the eastern hemisphere, which, on the whole, show a softer spectrum and for which the above dependence $\Gamma(\tau)$ is violated. A spectral steepening of protons for the eastern part of the solar disk, possibly associated with propagation effects in the corona and interplanetary space, was pointed out by Van Hollebeke *et al.* (1975) and Chertok (1982).

Figure 2 shows a flux of > 10 MeV protons F versus τ for the events listed in Table I. The pulse train duration has a tendency to increase with decreasing particle flux F. Only events Nos. 2 and 14 violate this relationship. The eastern events (open circles) do not violate the relationship $F(\tau)$. Considering that an increase in τ leads to a steeper slope (softer spectrum) (Figure 1), we may conclude that the shortest pulse trains are associated with the release into the corona and interplanetary space of a large number of protons with a hard spectrum.

3. Pulsation Models

A variety of type IV radio burst pulsations are presently explained in terms of two types of models: (1) plasma models, in which the modulation of radio emission is related to periodic regimes of plasma instabilities, and (2) magnetohydrodynamic (MHD) models, in which the radio continuum is modulated by the source (magnetic tube) MHD oscillations.

3.1. PLASMA MODELS

Assume that a fraction of the particles accelerated in a flare and fairly rapidly injected into a coronal magnetic trap excite plasma waves because of beam or loss-cone instabilities. The conversion of plasma waves into electromagnetic waves produces the type IV radio emission (Stepanov, 1973; Kuijpers, 1974). Under certain conditions a periodic regime of plasma instabilities due to nonlinear induced scattering of plasma waves by the background plasma particles is possible (Trakhtengerts, 1968). The excited plasma waves are transferred rather quickly into a nonresonant region of the plasma wave spectrum, and the resonant particle distribution therefore varies only slightly

TABLE I

Radio pulsations and proton data

No.	Date	Start of type IV bursts (UT)	Radio pulsations			Hα flare		Proton data		References	
			Onset (UT)	τ (min)	T (s)	Onset (UT)	Position	flux F ($E > 10$ MeV) Pr/s cm^2 sr	10–30 MeV spectral index Γ	Dynamic spectrum	Proton spectral index
1	2	3	4	5	6	7	8	9	10	11	12
1	12 Sep. 1957	15:17	15:24	3	1–2	15:10	12 N 20 W	(6.3)		Maxwell *et al.* (1958)	
2	20 Jul. 1961	15:52	16:08	4	3–5	15:24	08 S 90 W	(390)	3.3	Tompson and Maxwell (1962)	**
3	25 Feb. 1969	09:52	09:55	1	0.3	09:00	13 N 37 W	88.4	0.7	Slottje (1981)	Chertok (1982)
4	27 Feb. 1969	14:03	14:33	1.4	0.5–1.8	13:48	13 N 65 W	28.1	1.1	Slottje (1981)	Bakshi and Barron (1979)
5	24 Nov. 1969	09:17	09:29	2	–	09:14	15 N 31 N	3.5	1.2	Slottje (1981)	Bakshi and Barron (1979)
6	27 Sep. 1969	04:03	04:12	2.5	2–3	04:03	09 N 02 E	1.1	2.6	McLean *et al.* (1971)	Bakshi and Barron (1979)
7	5 Nov. 1970	03:25	03:37	1.8	2.4	03:08	12 S 36 E	42.0	2.9	Kai and Takayanagi (1973)	**
8	14 May 1971	14:15	14:19	5.5	0.5–1	14:14	04 N 11 E	1.5		Slottje (1981)	
9	29 Jun. 1971	16:22	16:28	5.8	0.3	15:46	08 S 60 W	1.0		Slottje (1981)	
10	5 Mar. 1972	11:36	11:37	2	0.8	11:36	07 S 40 E	3.8		Slottje (1981)	
11	16 May 1972	03:08	03:14	3.3	4.28	03:07	16 S 15 W	(10)	2.7	McLean and Sheridan (1973)	**
12	29 May 1972	10:12	10:21	1	0.5–1	10:16	09 N 15 E	85.1	2.7	*	**
13	4 Aug. 1972	06:25	16:45	0.6	0.2; 20	06:21	09 N 08 E	2.3×10^4	1.3	*	Bakshi and Barron (1979)
14	7 Aug. 1972	15:03	15:23	2.5	0.3	14:49	14 N 37 W	810	2.18	Slottje (1981)	Bakshi and Barron (1979)
15	7 Sep. 1973	11:53	12:00	2	3–5	11:41	18 S 46 W	(20)	3.0	*	**
16	3 Jul. 1974	08:30	08:33	1.5	0.5–1	08:01	15 S 09 E	100	2.6	*	**

Table I (continued)

No.	Date	Start of type IV bursts (UT)	Radio pulsations			Hα flare		Proton data		References	
			Onset (UT)	τ (min)	*T* (s)	Onset (UT)	Position	flux *F* ($E > 10$ MeV) Pr/s cm^2 sr	10–30 MeV spectral index Γ	Dynamic spectrum	Proton spectral index
1	2	3	4	5	6	7	8	9	10	11	12
17	12 Sep. 1977	10:32	10:47	0.7; 6	0.5; 20	10:28	05 N 57 W	132	1.3	*	Pereyaslova *et al.* (1977)
18	22 Nov. 1977	10:02	10:02	1; 3	0.2; 5	09:45	23 N 40 W	350	1.6	*	**
19	31 May 1978	10:21	10:50	5	1.7	10:20	20 N 40 W	(11)	3.1	Trottet *et al.* (1981)	**
20	10 Nov. 1978	00:53	01:15	0.8	5–8	01:13	17 N 02 E	(10)	4.3	Kosugi (1982)	Kahler (1982)
21	3 Apr. 1980	07:14	07:19	1.5	1–2	06:39	28 N 16 W	310	2.1	*	**
22	12 Oct. 1981	06:25	06:25	0.6	1	06:15	22 S 35 E	(10^3)	2.4	*	**
23	16 May 1981	08:15	08:25	2.5	0.3	08:10	09 N 11 E	(90)	3.5	*	Avdyushin *et al.* (1982)

Notes:
* Dynamic spectrum as observed at IZMIRAN.
** The spectral index is calculated by the present authors using proton data from *Solar Geophysical Data*. The proton data bracketed in column 9 were extrapolated.

(stabilization). However, the waves in the nonresonant region are continually damped, due to Coulomb collisions, for example. Again, a fraction of the resonant particles excite plasma waves, which are scattered into a nonresonant region, damped, etc. Hence the characteristic relaxation time of unstable particle distributions under the action of the waves (Zaitsev, 1971; Zaitsev and Stepanov, 1975a),

$$\tau_N \approx 10^{-3} \frac{1}{\nu_{ei}} \frac{v^2}{v_e^2} \begin{cases} (m_i/m_e)^2 , & \text{protons} , \\ 1 , & \text{electrons} , \end{cases} \tag{1}$$

can be well above the time predicted by quasi-linear theory. Here ν_{ei} is Coulomb collision frequency, v is the typical velocity of energetic particles, v_e is the thermal speed of background plasma electrons, and m_e and m_i are the mass of electrons and protons, respectively. The retarded relaxation is accompanied by plasma wave energy density oscillations, whose period in the case of weak modulation is

$$T_N \approx 2\pi(\gamma \nu_{ei})^{-1/2} , \tag{2}$$

where the growth rate of plasma wave instability is

$$\gamma = \eta \frac{n}{n_0} \omega_p \begin{cases} m_e/m_i , & \text{protons} , \\ 1 , & \text{electrons} , \end{cases} \tag{3}$$

where η is the anisotropy measure ($\eta \approx 1$ for beam instability; $\eta \approx 10^{-1} - 10^{-3}$ for loss-cone instability), n and n_0 are the densities of energetic particles and background plasma ($n \ll n_0$), and ω_p is the plasma frequency of electrons.

In the solar corona the condition for the existence of nonlinear oscillations $\tau_N \gg T_N$ is satisfied for protons but not for electrons. Therefore, stabilized beams of protons moving along the coronal trap axis were invoked to explain 'rain-type' bursts (type IV radio emission pulsations) (Zaitsev, 1971). The pulsating regime of a loss-cone instability is also possible for electrons. However, this requires the continuous injection of energetic particles into the trap (Zaitsev and Stepanov, 1975a).

Assume that the energetic protons escaping into interplanetary space along open magnetic field lines and protons trapped in coronal magnetic loops pertain to the same population. It is known that for flares originating in the region 20–80° W the influence of the corona and interplanetary space on the proton spectrum in the energy range from 20 to 80 MeV is negligible during the rise to maximum particle intensity (Van Hollebeke *et al.*, 1975). On the other hand, the most conspicuous dependences, $\Gamma(\tau)$ and $F(\tau)$ (cf. Table I and Figures 1 and 2), refer to > 10 MeV protons, coming only from western flares (15–90° W). Therefore, as a first approximation we may infer that the characteristics of protons observed at 1 AU for the western events under consideration coincide with those in coronal traps. From Formula (1) it follows that τ_N, which determines the pulse train duration, is proportional to the particle energy. An increase in particle energy for the integral power-law spectrum $N(E) \sim E^{-\Gamma}$ implies a decrease in Γ (hardening of the spectrum). However, Figure 1 shows that for western flares the dependence $\Gamma(\tau)$ is the reverse: τ increases with increasing Γ. Moreover, from (2) and (3) it follows that the

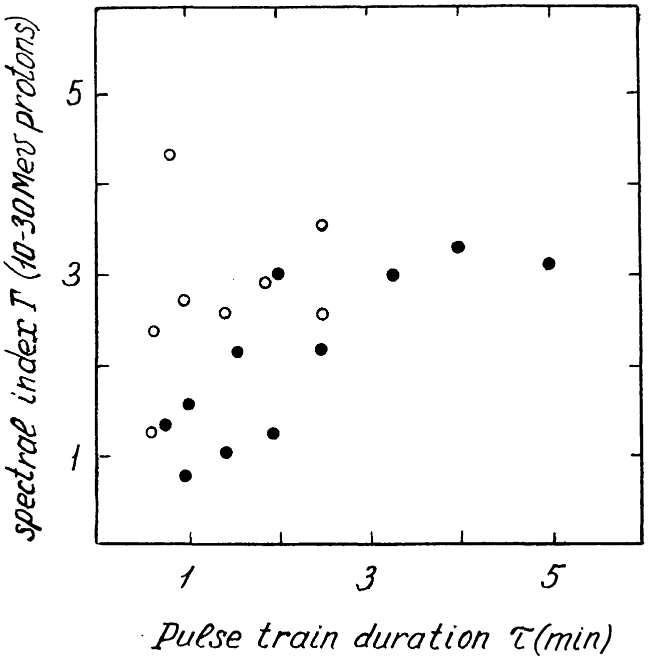

Fig. 1. The variation of the integral spectral index (Γ) in the 10–30 MeV range versus pulse train duration (τ). The filled circles indicate 11 western flares, the open circles 8 eastern flares.

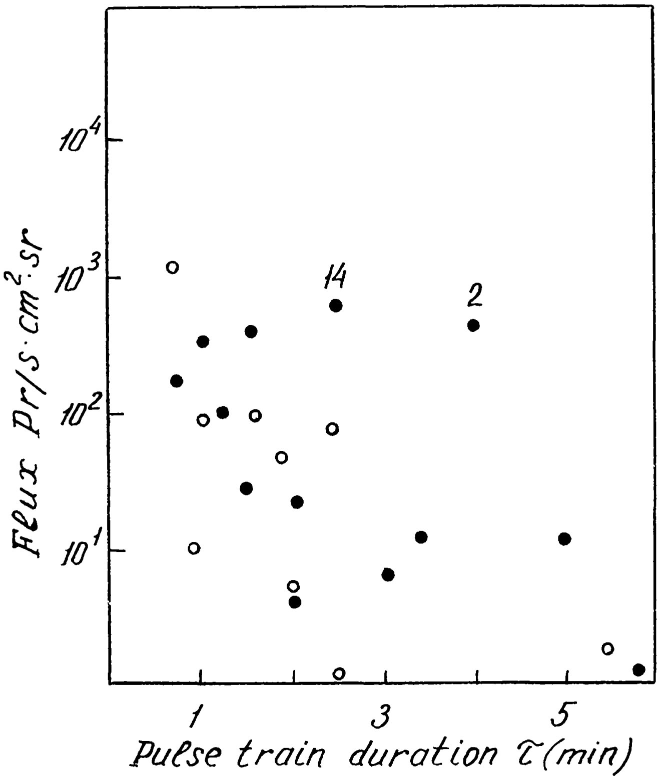

Fig. 2. The variation of the > 10 MeV proton flux (F) versus pulse train duration (τ) for the 23 events listed in Table I. Filled circles denote western flares, open circles eastern flares. Two points, No. 2 and 14 in Table I, denote large events. Their incompatibility with the other points may be due to some difficulties in processing the complex events with multiple series of pulses usually present.

period of nonlinear oscillations for the beam instability is related to the density of energetic particles through the relationship $T_N \sim n^{-1/2}$. In the case of loss-cone instability, wave absorption proceeds due to high-energy particles, i.e., $T_N \sim n^{-1}$. Data analysis, however, has revealed no dependence of the pulsation period on energetic proton parameters. This implies that the nonlinear plasma mechanism of pulsations does not explain experimental data even qualitatively.

As a result of the injection of electron beams into a coronal magnetic trap a periodic regime of plasma instabilities of the relaxation oscillation type is also possible; this is associated with the inertia of the 'electron-plasma wave' system and is described in terms of quasilinear theory (Bardakov and Stepanov, 1979). Under solar coronal conditions the quality of such oscillations is low – $Q \lesssim 5$, whereas of the events of our study $Q \gtrsim 10^1$–10^2. Hence, plasma models of pulsations do not explain the relationships we have derived and presented in Figures 1 and 2 and Table I.

3.2. MHD MODEL OF SOLAR RADIO PULSATIONS

Investigations of the soft X-ray solar emission during the Skylab mission (see, e.g., Švestka *et al.*, 1977; McGuire *et al.*, 1977) revealed the existence of rather large (up to 1 $R_\odot$) coronal loops (magnetic flux tubes), in which plasma density can exceed that of the surrounding corona (Priest, 1978). The plasma density in coronal loops may even increase as the result of flare ejection from chromosphere. Magnetic loops with increased plasma density are the resonators for the fast mode of MHD waves. At the time of a flare the energetic particles responsible for the type IV radio emission are captured by the loops. To explain the pulsations, Rosenberg (1970) suggested that fast magnetosonic oscillations of a magnetic tube (loop) modulate the synchrotron radiation of the relativistic electrons. The period of fast mode oscillations of the loop with a radius much smaller than the length ($R \ll L$) on the order of magnitude is

$$T \approx R(C_A^2 + C_s^2)^{-1/2}, \tag{4}$$

and at $(C_A^2 + C_s^2)^{1/2} \approx 10^8$ cm s^{-1}, $R \approx 10^8$–10^9 cm varies from 1 to 10 s. Here $C_A = B_0(4\pi n_0 m_i)^{-1/2}$ is the Alfvén velocity, and $C_s = (10T_0/3m_i)^{1/2}$ is the sound velocity. The plasma mechanism of type IV radio emission is the one generally accepted to date (Stepanov, 1973; Kuijpers, 1974). Fast magnetosonic oscillations also modify the mirror ratio of the loop and energetic component density; therefore, the type IV radio emission caused by plasma wave loss-cone instabilities will also be modulated.

Fast-mode oscillations of the tube undergo emissive damping, the decrement being of the order of the ratio of the plasma density outside of the tube to that inside the tube (Zaitsev and Stepanov, 1975b):

$$\nu/\omega \approx n_{\text{ext}}/n_0 \approx 10^{-1}\text{–}10^{-2}. \tag{5}$$

The emissive damping can be compensated for, e.g., by the bounce-resonant instability of the fast mode of MHD waves arising upon injection into the trap of a fairly large number of energetic particles (Meerson *et al.*, 1978).

When the distribution function of energetic protons, f, is isotropic*, i.e., it depends only on the energy $\varepsilon = m_i v^2/2$,

$$f \sim \varepsilon^j \exp[-\varepsilon(j + \tfrac{3}{2})/T_h], \qquad j > 0, \tag{6}$$

the growth rate of the fast mode has a maximum under a bounce-resonance condition $\omega \simeq \Omega_b$, $\Omega_b^2 = 2T_h/m_i L^2(j + \frac{3}{2})$ and at $k_z L \simeq 3$. Thus the main mode of the flux tube is excited most effectively. The growth rate of bounce instability is (Meerson *et al.*, 1978)

$$\gamma_b/\omega \simeq \beta_h \begin{cases} 0.1, & j \simeq 2, \\ 1.0, & j \gtrsim 3, \end{cases} \tag{7}$$

where $\beta_h = 8\pi n T_h/B_0^2$. Note that the result (7) depends only slightly on the specific form of distribution function f. It is essential only that this function have a sufficiently abrupt fall in the low-energy region of the spectrum. The reasons for the lack of 'soft' particles in the coronal magnetic trap were discussed by Meerson *et al.* (1978). Excitation of global fast-mode oscillations of the loop is also possible through Čerenkov resonance. The growth rate of Čerenkov instability is $\gamma/\omega \approx \beta_h$ (Akhiezer *et al.*, 1974). However, the excitation of oscillations requires the existence of a proton beam along the magnetic trap axis, which is less probable than the appearance in the trap of isotropically distributed protons with an energy peak (6). From (5) and (7) it follows that the main fast mode of the flux tube is excited at $\beta_h > \beta_* \approx 0.1$. This condition is easily satisfied during a flare. Indeed, at $B_0 = 5$ G the value $\beta_h \approx 0.1$ when proton density n (30 MeV) $\approx 10^3$ cm^{-3} (where $n/n_0 \approx 10^{-4}$–10^{-6}). The energy of such protons in a magnetic flux tube of a volume of 10^{28} cm^3 is of the order of 10^{27} erg. Such energies are easily attainable: In particular, for the flare of 7 August, 1972, listed in Table I (No. 14), 0.1–240 MeV protons contain about 2×10^{31} erg, which constitutes several percent of the total flare energy (Morozova *et al.*, 1977). Note that the instability threshold $\beta_* \approx 0.1$ can decrease at $R^2/L^2 \geq n_{\text{ext}}/n_0$ when the wave undergoes total internal reflection (Meerson *et al.*, 1978). Estimates show that in this case the damping of the fast mode of MHD waves is determined by ion viscosity which for $T > 1$ s is smaller than the emissive damping (5).

Whereas pulsation models based on pulsating regimes of plasma instabilities provide quite a definite dependence of the pulsation period on the energetic particle density $T_N \sim n^{-1/2}$ or $\sim n^{-1}$, in the MHD model the pulsation period (4) is independent of energetic particle parameters and is determined only by the loop geometry and 'cold' plasma parameters. Also, for the minimal period $T_{\text{min}} = 0.2$ s, included in Table I, at $(C_\text{A}^2 + C_s^2)^{1/2} \approx C_\text{A} \approx 10^8$ cm s^{-1} (a typical value in the corona) the loop must be sufficiently thin: $R \approx 10^7$ cm. The bounce-resonance condition $\omega \simeq \Omega_b$ implies that $R/C_\text{A} \approx L/v$, where v is a typical velocity of energetic protons. From this it follows that at $v \approx 10^{10}$ cm s^{-1} the length of a pulsation source with a period $T_{\text{min}} = 0.2$ s should

---

* We have neglected here a loss-cone anisotropy because of the large mirror ratio of the loop.

not exceed the value of $L \approx 10^9$ cm. This means that either most of the energetic particles have high mirror points or that there exist additional 'mirrors' in the vicinity of the top of the loop. A limitation on the source size, $L \lesssim 10^9$ cm, also follows from the very existence of pulsations with a period of about 0.1 s, because at $L > 10^9$ cm such pulsations undergo 'erosion' because of the finiteness of the speed of light. The MHD model of pulsations, therefore, explains the observed periods of pulsations and the absence of any dependence of the period on the proton spectral index Γ and on proton flux F.

Let us now examine how the MHD model can be used to understand the dependences of Γ and F on pulse train duration τ (Figures 1 and 2). If the pressure of plasma and energetic particles is comparable with the magnetic field pressure $\beta \approx 1$, the particle-trapping magnetic configuration breaks down and the particles, together with a cold plasma, are released from it for a period of about $R/C_A \approx 1-10$ s. We have shown previously that MHD oscillations of the magnetic tube are supported at a lower pressure, $\beta_h \approx 0.1$. With decreasing β_h magnetic tube oscillations are rapidly damped, and the pulse train duration in terms of the MHD model is therefore actually determined by the proton trapping time in a coronal magnetic loop. The maximum trapping time of protons is determined by Coulomb collisions, and it lasts for many hours or even days, depending on the proton energy (Newkirk, 1974). The proton drift in a non-homogeneous and curved magnetic field of the loop gives roughly the same time of trapping. The most 'hazardous' condition for cosmic ray storage in the solar corona is Alfvén wave cyclotron instability, which is caused by an anisotropy of energetic protons (Wentzel, 1976). The cyclotron-resonance condition $\omega_A - k_z^A v_z \pm \omega_i = 0$ determines the frequency of excited Alfvén waves $\omega_A \simeq \omega_i C_A/v \approx 10^{-2} \omega_i$ and the longitudinal wave number $k_z^A L \simeq \omega_i L/v \approx 10^4-10^5$, where ω_i is the proton gyrofrequency. The instability growth rate is maximal for waves propagating along the magnetic field (Kennel and Petchek, 1966),

$$\gamma_A/\omega_A \approx 0.4 \eta \beta_h \, , \qquad \eta > \omega_A/\omega_i \, , \tag{8}$$

and decreases rapidly at $k_\perp^A/k_z^A > (\omega_A/\omega_i)^{1/2}$, where $k_\perp^A$ is the transversal wave number. For the temperature anisotropy of energetic protons ($T_\perp > T_\parallel$) the measure of anisotropy $\eta = T_\perp/T_\parallel - 1$. If the anisotropy is associated with the loss-cone, then $\eta \simeq \frac{3}{2}(\sigma - 1)$, where σ is the mirror ratio of the loop.

The interaction of Alfvén waves with energetic protons leads to pitch-angle diffusion of the protons into the loss-cone of the trap and to their precipitation into the collision-dominated chromosphere. A rigorous theory of diffusion must take into account the non-homogeneity of the magnetic field and plasma and the non-homogeneity of the energetic particle distribution. Here we will restrict our attention to the simplest estimations (see, e.g., Meerson and Rogachevskii, 1983). The pitch-angle diffusion coefficient in a homogeneous plasma can be written thus (Kennel and Petschek, 1966):

$$D \approx \frac{B_A^2}{B_0^2} \, \frac{\omega_i^2}{v_z \Delta k} \, , \tag{9}$$

where B_A is the Alfvén wave amplitude and $\Delta k \approx \omega_i/v$ is the characteristic wave spectrum width. With a sufficiently low level of Alfvén wave turbulence, $B_\mathrm{A}^2/B_0^2 \ll 1$, the value of B_A^2 can be deduced from the linear theory,

$$B_\mathrm{A}^2 = B_{\mathrm{A}f}^2 \exp A\,, \tag{10}$$

where $B_{\mathrm{A}f}^2$ is the level of thermal Alfvén noise and $A = 2\gamma l/C_\mathrm{A}$ is the amplification coefficient on length l.

With cold Alfvén wave dispersion due to the finiteness of the ratio $\omega_\mathrm{A}/\omega_i \ll 1$ taken into account, the magnetic flux tube with an increased plasma density (duct) represents a waveguide for Alfvén waves when the parameter $\xi = \omega_\mathrm{A}^2 R/\omega_i C_\mathrm{A} > 1$ (Mazur and Stepanov, 1984). For pulsating type IV burst sources the condition $\xi > 1$ is satisfied over a significant part of the loop, with the exception of regions near the feet of the loop. Therefore an Alfvén wave train keeps a quasi-longitudinal character of propagation $k_\perp^4/k_z^4 < (\omega_\mathrm{A}/\omega_i)^{1/2}$, which leads to an effective amplification of the wave train along virtually the whole loop* ($l \approx L$). With this taken into account, the amplification coefficient can be represented as $A \approx \omega_i \mu \beta_h L/v$, while the thermal noise level in the region of quasi-longitudinal propagation is

$$B_{\mathrm{A}f}^2 \approx \frac{\omega_\mathrm{A}}{\omega_i}\,T_h k_\mathrm{A}^3\,, \qquad k_\mathrm{A} \approx \omega_i/v\,, \tag{11}$$

where T_h is the 'temperature' of the energetic component. Upon substitution of (10) and (11) into (9) we find the characteristic time of diffusion $\tau_D \approx D^{-1}$, which defines the pulse train duration

$$\tau_D \approx \frac{\omega_i}{\omega_\mathrm{A}}\,\frac{B_0^2}{T_h k_\mathrm{A}^3}\,\exp(-\eta\beta_h\omega_i L/v)\,. \tag{12}$$

At $B_0 \approx 3$ G, $T_h \approx 30$ MeV, $C_\mathrm{A} \approx 10^8$ cm s^{-1}, and $L \approx 10^{10}$ cm from the condition $\tau_D \approx \tau \approx 2 \times 10^2$ s for a minimum possible anisotropy $\eta \approx \omega_\mathrm{A}/\omega_i \approx C_\mathrm{A}/v$, with the aid of (12) we get $\beta_h = 4\pi n m_i v^2/B_0^2 \approx 0.1$. The amplification value then is $A \approx 40$ and $B_\mathrm{A}^2/B_0^2 \approx 4 \times 10^{-7} \ll 1$. Moreover, an estimation has shown that under such conditions the contribution of energetic protons to the real part of Alfvén wave frequency ($\approx \beta_h\,\omega_\mathrm{A}^2/\omega_i$) remains much less than that of cold dispersion ($\approx \omega_\mathrm{A}^2/\omega_i$). Our approach, then, is valid.

It is apparent from (12) that the pulse train duration is decreased with increasing hardness of protons (or with decreasing Γ) and with increasing proton flux F. This is in qualitative agreement with the relationships in Figures 1 and 2. The non-exponential character of the dependences $\Gamma(\tau)$ and $F(\tau)$ in Figures 1 and 2 can be accounted for by the simplified assumptions that we have made in deriving (12).

---

* If no cold dispersion effect were taken into account, the Alfvén waves propagating in coronal magnetic loops would be subjected to refraction (Wentzel, 1976; Meerson and Rogachevskii, 1983). In such a case the amplification length would become much shorter: $l \approx (\omega_\mathrm{A}/\omega_i)^{1/2} L$.

That the pressure of energetic electrons in a flare is so high that in the starting phase of pulsations they make a substantial contribution to the excitation of fast-mode MHD wave oscillations must be considered. But the electrons excite plasma waves and whistlers most effectively, thus leading to an intensive diffusion of electrons into the loss-cone. With strong diffusion on whistlers, for example, when the loss-cone is almost filled, 'turbulent mirrors' arise at the feet of the loop and slow donw the release of electrons from the trap. In such a case the maximum lifetime of electrons within the trap is (Bespalov and Trakhtengerts, 1980)

$$\tau_e \approx \frac{4\pi n_0 m_e v^2}{B_0^2} \frac{L}{v} \approx 10\ \mathrm{s}\,. \tag{13}$$

In (13) we have assumed that $n_0 = 10^8\ \mathrm{cm}^{-3}$, $B_0 = 3$ G, $L = 10^{10}$ cm, and $v = 10^{10}\ \mathrm{cm\ s}^{-1}$. Compared to protons, electrons seem to escape from the trap much more rapidly. Their pressure drops abruptly, and the type IV radio emission is thereafter maintained due either to the slowing-down of electron diffusion on the waves or by a weak particle source. The energetic protons leave more slowly, 'supporting' global MHD oscillations of the loop over the course of several minutes. A fairly strong injection of electrons into the coronal magnetic traps is evidenced by the 'zebra' pattern frequently observed along with the pulsations (Slottje, 1981). The 'zebra' pattern may be caused, e.g., by the excitation of Bernstein modes, which requires a high density of energetic electrons: $n/n_0 \gtrsim 10^{-4}$ (Zheleznyakov and Zlotnik, 1975), whereas the excitation threshold of IV type radio emission associated with the development of loss-cone instability near the upper hybrid frequency is significantly lower: $n/n_0 \gtrsim 10^{-7}$.

4. Discussion

The foregoing analysis of the correlation between the pulsations of type IV radio bursts and the appearance of solar energetic protons at distances of 1 AU has led us to conclude that

(1) At least 86% of the 57 type IV radio bursts with pulsations used in our analysis were accompanied by the appearance in interplanetary space of proton fluxes of solar origin with different energies. In 14% of the cases where no protons had been recorded the relevant flares were situated in the eastern hemisphere, and the absence of particles may be associated with proton propagation effects in the corona and interplanetary space.

(2) The pulse train duration τ increases with increasing spectral index Γ of the integral power-law spectrum. This relationship is most pronounced for western flares when the influence of propagation effects on the proton spectrum is minimal.

(3) The pulse train duration τ decreases with increasing flux of > 10 MeV protons.

(4) The pulsation period T does not depend on flux or proton spectral index.

The properties of pulsations just mentioned can be helpful in the diagnostics of proton events. It may be asserted that the shortest pulsation series are associated with the release into interplanetary space of a large number of protons with a hard spectrum. The use in future analyses of larger numbers of events will provide better defined dependences $\Gamma(\tau)$ and $F(\tau)$ than those in Figures 1 and 2 and will make it possible to develop a method of quantitative diagnostics of spectrum hardness and proton fluxes using pulse train duration.

The observed peculiarities of the association of the pulsations with solar protons permit the determination of the most probable reason for the appearance of pulsations. The pulsating regimes of plasma instabilities provide values of the period that depend on the density of energetic particles and values of pulse train duration that increase with increasing proton hardness and flux magnitude. These two consequences contradict observational data (Items 2, 3, and 4). Therefore, the analysis of the above-mentioned events leads us to conclude that the broad-band pulsation of type IV radio bursts is not associated with pulsating regimes of plasma instabilities. Apparently, this is because the pulsating plasma emission of a type IV burst source, sufficiently extended in height ($L \gtrsim 10^{10}$ cm), is different in phase. In more compact sources, for example, the sources of type III bursts in the initial stage (Zaitsev, 1974) and microwave emission sources (Slottje, 1978), the pulsations are probably associated with a plasma mechanism. It must be remembered that narrow-band pulsations of type IV radio emission (a compact source), which may also be unrelated to protons, are also caused by the oscillating regime of plasma instabilities. However, no appropriate analysis of experimental data has been made so far.

On the other hand, the properties of the pulsations examined thus far correspond best to the MHD model. 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. 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 (Figures 1 and 2).

The physical coupling of the pulsations of IV type radio emission and energetic protons is, we believe, as follows. The electrons and protons produced during a flare are partially trapped in a 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 waves. 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 of type IV bursts. 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 $t < \tau_D$ such protons drift with the speed $v_D \approx v^2/\omega_i R \approx 10^6$ cm s^{-1} toward the open magnetic field lines and escape into interplanetary space. The number of protons escaping per second from the closed magnetic configuration is $N \approx nv_D 2\pi RL$ at $n \approx 10^3$ cm^{-3}, $R \approx 10^9$ cm, $L \approx 10^{10}$ cm, and $v_D \approx 10^6$ cm s^{-1}, i.e., $N \approx 10^{29}$ s^{-1}. This value is sufficient to explain the observed density of solar cosmic rays at 1 AU ($n_{\mathrm{cr}} \approx 10^{-9}$–$10^{-10}$ cm^{-3}).

The pulsations of type IV radio emission, therefore, are predictors of the appearance of protons in the vicinity of the Earth. The association of the pulse train duration with the characteristics of protons can provide the basis for a method of predicting the proton properties in interplanetary space, thereby extending the capabilities of the diagnostics of proton events.

Acknowledgements

We express our appreciation to Dr U. G. Matyukhin, Dr B. I. Meerson, Dr V. V. Fomichev, and Dr I. M. Chertok for helpful discussions. Thanks are also due to Mr V. G. Mikhalkovsky for assistance in preparing the English version of the manuscript and for typing the text.

References

Akhiezer, A. I., Akhiezer, I. A., Polovin, R. V., Sitenko, A. G., and Stepanov, K. N.: 1974, *Plasma Electrodynamics*, Nauka, Moscow.

Avdyushin, S. I., Nazarova, M. N., Pereyaslova, N. K., and Petrenko, I. E.: 1982, *Izv. Akad. Nauk SSSR, ser. fiz.* **46**, 1754.

Bakshi, P. and Barron, W.: 1979, *J. Geophys. Res.* **84**, 131.

Bardakov, V. M. and Stepanov, A. V.: 1979, *Pisma v Astrofiz. Zh.* **5**, 460.

Bespalov, P. A. and Trakhtengerts, V. Yu.: 1980, *Voprosy teorii plazmy*, Vol. 10, Atomizdat, Moscow.

Chertok, I. M.: 1982, *Geomagnetizm i aeronomiya* **22**, 182.

Kahler, S. W.: 1982, *Astrophys. J.* **261**, 710.

Kai, K. and Takayanagi, A.: 1973, *Solar Phys.* **29**, 461.

Kennel, C. F. and Petschek, H. E.: 1966, *J. Geophys. Res.* **71**, 1.

Kosugi, T.: 1982, *Solar Phys.* **75**, 293.

Kuijpers, J.: 1974, *Solar Phys.* **36**, 157.

Logachev, Yu. I. (ed.): 1983, *Catalog of Solar Proton Events 1970–1979*, IZMIRAN, Moscow.

Maxwell, A., Swarup, C., and Thompson, A. R.: 1958, *Proc. IRE* **1**, 142.

Mazur, V. A. and Stepanov, A. V.: 1984, *Astron. Astrophys.* (in press).

McGuire, J. P., Tandberg-Hanssen, E., Krall, K. R., Wu, S. T., Smith, J. B., and Speich, D. H.: 1977, *Solar Phys.* **52**, 91.

McLean, D. J., Sheridan, K. V., and Stewart, R. T.: 1971, *Nature* **234**, 140.

McLean, D. J. and Sheridan, K. V.: 1973, *Solar Phys.* **32**, 485.

Meerson, B. I. and Rogachevskii, I. V.: 1983, *Solar Phys.* **87**, 337.

Meerson, B. I., Sasorov, P. V., and Stepanov, A. V.: 1978, *Solar Phys.* **58**, 163.

Morozova, E. I., Likin, O. B., and Pisarenko, N. F.: 1977, *Geomagnetizm i aeronomiya* **17**, 811.

Newkirk, G.: 1974, in G. Newkirk (ed.), 'Coronal Disturbances', *IAU Symp.* **57**, 473.

Pereyaslova, N. K., Nazarova, M. N., and Petrenko, I. E.: 1980, *Geomagnetizm i aeronomiya* **20**, 977.

Priest, E. R.: 1978, *Solar Phys.* **58**, 57.

Rosenberg, H.: 1970, *Astron. Astrophys.* **9**, 159.

Rosenberg, H.: 1971, in R. Howard (ed.), 'Solar Magnetic Fields', *IAU Symp.* **43**, 652.

Slottje, C.: 1978, *Nature* **275**, 520.

Slottje, C.: 1981, *Atlas of Fine Structure of Dynamic Spectra of Solar Type IV-dm and Some Type II Radio Bursts*, Dwingeloo.

Stepanov, A. V.: 1973, *Astron. Zh.* **50**, 1243.

Švestka, Z. and Simon, P. (ed.): 1974, *Catalog of Solar Particle Events, 1955–1969*, D. Reidel Publ. Co., Dordrecht, Holland.
Švestka, Z., Krieger, A. S., Chase, R. C., and Howard, R.: 1977, *Solar Phys.* **52**, 69.
Thompson, A. R. and Maxwell, A.: 1962, *Astrophys. J.* **136**, 546.
Trakhtengerts, V. Yu.: 1966, *Geomagnetizm i aeronomiya* **8**, 96.
Trottet, G., Kerdraon, A., Benz, A. O., and Treuman, R.: 1981, *Astron. Astrophys.* **93**, 121.
Van Hollebeke, M. A. I., Ma Sung, L. S., and McDonald, F. B.: 1975, *Solar Phys.* **41**, 189.
Wentzel, D. G.: 1976, *Astrophys. J.* **208**, 595.
Zaitsev, V. V.: 1971, *Solar Phys.* **20**, 95.
Zaitsev, V. V.: 1974, *Izv. VUZov, Radiofizika* **17**, 1438.
Zaitsev, V. V. and Stepanov, A. V.: 1975a, *Issled. po geomagn., aeron. i fiz. Solntsa* **37**, 11.
Zaitsev, V. V. and Stepanov, A. V.: 1975b, *Issled. po geomagn., aeron. i fiz. Solntsa* **37**, 3.
Zheleznyakov, V. V. and Zlotnik, E. Ya.: 1975, *Solar Phys.* **43**, 431.