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SOLAR ENERGETIC PARTICLE EVENTS FROM SOLAR FLARES WITH WEAK IMPULSIVE PHASES OF MICROWAVE EMISSION

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Abstract. In some solar energetic particle events relatively intense proton fluxes are accompanied by disproportionately weak intensity of μ-burst. A possible reason for such a situation is discussed in this paper. We use the idea that the dynamics of particles in flare loops strongly influences the efficiency of their escape into interplanetary space. It is proposed that in events with weak impulsive phase flare loops are large sized and stretched high into the corona, the magnetic field is weak, and the level of excited turbulence is rather low. All this leads to the weak diffusion of protons into the loss cone, a large lifetime of a particle in the loop ($\approx 10^3$ s) and, hence, to the relatively high efficiency of their escape into interplanetary space.

1. Introduction

One of the arguments for two-step acceleration in solar flares (Wild, Smerd, and Weiss, 1963; Bai, 1986; Cane, McGuire, and von Rosenvinge, 1986) is that some solar energetic particle (SEP) events with a sufficiently high proton flux are observed after flares with weak impulsive phases (WIP) (Cliver, Kahler, and McIntosh, 1983; Cliver *et al.*, 1983, 1989; Kahler *et al.*, 1986). WIP-flares, in particular, are characterized by low-intensity microwave (μ-) bursts. So WIP-flares do not satisfy the criteria of proton flares which were proposed earlier (see, for example, Castelli, Michael, and Aarons, 1967) which state that the larger the μ-burst intensity, the larger the SEP-event proton flux.

Cliver, Kahler, and McIntosh (1983a) argued that energetic protons in WIP-events are accelerated by a shock wave which is produced by a high-velocity plasmoid (CME), ejected from the active region (Kahler, Hildner, and van Hollebeke, 1978; Kahler *et al.*, 1984). So the protons observed in interplanetary space are accelerated outside of the impulsive phase of flares. This variant of the proton acceleration is more advantageous than the traditional scheme in which the shock wave is produced as a response to the energy release in the impulsive phase accompanied by strong electromagnetic radiation (Lin and Hudson, 1976).

As a rule, various modifications of the two-step acceleration concept do not consider the behaviour of energetic particles in a source during and just after acceleration. Meanwhile it is clear that the lifetime of accelerated particles in a source and the efficiency of their escape into interplanetary space are determined by both particle parameters and conditions in the coronal loop. This means that many features of

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SEP-events and their connections with flare electromagnetic radiation are determined by the particle dynamics in a source. Such an approach was used by Zaitsev and Stepanov (1985) to explain the relation between solar flare γ-ray events and proton escape into interplanetary space. Taking into account conditions in flare loops of different sizes, it became possible to understand the statistical dependence between parameters of μ-bursts and electron and proton fluxes in SEP-events (Mel'nikov *et al.*, 1986, 1990, 1991; Daibog *et al.*, 1989a). In addition, in the framework of such an approach it is possible to explain the e/p-ratio, the slope of proton and electron spectra, and the efficiency of sub- and mildly-relativistic electron escape in impulsive and long-duration flares (Daibog *et al.*, 1988, 1989b, c).

In the present paper such a concept is applied to SEP-events caused by flares with weak impulsive phases in μ-emission. We would like to see if the relation between particle fluxes and μ-burst parameters in WIP-events is the same as in the case of the usual 'classic' SEP-flares and to understand conditions for which the proportionality between the peak intensity F_m of a μ-burst and the proton flux I_p is violated. We note that WIP-flares have a long, effective duration T_μ and low-frequency f_m of the spectral maximum in the μ-band. We suggest that electron-generated μ-bursts and energetic particles observed in interplanetary space were accelerated in the same process in a large-sized loop. We may consider two circumstances leading to low F_m/I_p-ratio: (1) weak magnetic field in the loop and consequently low efficiency in μ-emission generation; (2) long proton lifetime and high probability of proton escape from the loop into interplanetary space.

The approach used in the present paper does not lay down conditions on the acceleration process. It works in the scope of one-step acceleration. If WIP-events are described by this approach we may suppose that they can still be accomodated within the context of a single acceleration process. At the same time the approach does not eliminate particle acceleration by flare shock high up in the corona (two-step process). So the present paper suggests that we take into account the different behaviour of energetic particles in flare loops of different sizes.

We consider the main results of an empirical study of interrelations between SEP-events and μ-bursts in Section 2 and argue the possibility of applying the statistical dependences obtained to WIP-events in Section 3. In Section 4 we discuss physical conditions in flare loops, in particular in the case of WIP-flares. Conclusions are summarized in Section 5.

2. Empirical Relationships

We accomplished the study of relationships between SEP-events and μ-bursts on the basis of data collected during the growth phase and maximum of the 21st solar activity cycle. Energetic particles were registered by means of detectors set on board satellites 'Prognoz 5, 6, 7' (1977–1979) and space probes 'Venera 11, 12' (1978–1979) and 'Venera 13, 14' (1981–1983). The orbits, detectors, and other details of the measurements were described earlier (Bel'yakov *et al.*, 1979, 1984; Daibog *et al.*, 1989c;

Grygoryan *et al.*, 1982). Here it is sufficient to mention that we received data about fluxes, spectra, and anisotropy of electrons and protons in energy ranges $0.025 < E_e < 1.6$ MeV and $0.5 < E_p < 230$ MeV, respectively. Measurements on board spacecraft 'Venera' occurred at distances ~ 0.7–1.1 AU at Earth–Sun spacecraft angles in the range 0–90°. To compare with electromagnetic radiation we used particle fluxes that were recalculated to 1 AU over the simple diffusion approximation.

In detail, the results of a statistical study of relations between SEP-events and μ-bursts were presented by Mel'nikov *et al.* (1986, 1990, 1991). As a rule, an analysis was done, starting from a list of selected SEP-events. In the present paper we would like to consider events with measurable flux of energetic protons. The search criteria, applied to our data, were as follows:

(a) Time profile of particle intensity is diffuse or close to diffuse.

(b) > 25 MeV peak proton flux I_p of $> 10^{-3}$ cm^{-2} s^{-1} sr^{-1}.

(c) The SEP-event has an unambiguous association with parent Hα-flare and is well-connected to the observation point.

(d) The microwave burst is identified with the same flare.

The list of selected events is shown in Table I. They are characterized by the onset time of SEP-events t_{sp} in the observation point and peak fluxes of > 25 MeV protons I_p and > 0.5 MeV electrons I_e at 1 AU. It can be seen that the selected events have some discrepancy with those usually adopted as proton events (see, for example, Castelli, Aarons, and Michael, 1967; Lin and Hudson, 1976; Cliver, Kahler, and McIntosh, 1983). We worked with the > 25 MeV proton flux. Assuming a spectral index of -3 and > 10 MeV peak flux of > 10 cm^{-2} s^{-1} sr^{-1} as usually adopted in proton events, we would obtain a flux value of $> 6 \times 10^{-1}$ cm^{-2} s^{-1} sr^{-1} for > 25 MeV protons. From Table I it can be seen that in $\simeq 65\%$ of the events $I_p \leq 6 \times 10^{-1}$ cm^{-2} s^{-1} sr^{-1}. So we have considered the relationships between μ-bursts and SEP-events in a more broad range of proton fluxes than was done in previous papers.

As for μ-bursts, we used data of the worldwide network published in *Solar-Geophysical Data* (SGD) and the direct records at the Radio Observatory in Gorky (now Niznii Novgorod). We also used data published by radio observatories in Toyokawa and Nobeyama (*Atlas of Solar Radiobursts* for 1981–1982; Kosugi and Shiomi, 1983). μ-bursts parameters are shown in Table I. They include: the time of μ-burst maximum, t_μ, the frequency of spectral maximum, f_m, the peak flux density, F_m, at frequency f_m, and the effective duration of the burst; $T_\mu = (\int_T F\, dt)/F_m$; F is μ-wave flux at the moment t; T is the actual burst duration. In the case when we had no possibility to use actual burst profiles, the effective duration T_μ was determined as follows: $T_\mu = \langle F \rangle\, T/F_m$ where $\langle F \rangle$ is the mean μ-wave flux. The values of T, F_m, and $\langle F \rangle$ are tabulated in SGD. We have verified the correspondence $\int F\, dt$ to $\langle F \rangle\, T$ and obtained the result that $\int F\, dt \cong \langle F \rangle\, T$ with an accuracy of 20%. This answer is analogous to that obtained by Kahler (1982a) when he compared the peak flux density values reported by two or more observatories monitoring the Sun at the same or closely spaced frequencies with an average value of peak flux.

From Table I it can be seen that in all events > 0.5 MeV electrons were observed.

TABLE I

The list of selected SEP-events and associated μ-bursts and their parameters

	Data	t_{sp} (UT)	I_p	I_e	t_μ (UT)	f_m (GHz)	F_m (s.f.u.)	T_μ (min)
			(cm^2 s sr)$^{-1}$					
1	Dec. 17, 1976	10:38	3.0E − 3	1.0E + 0	10:20	3	2.7E + 1	1
2	Sep. 24, 1977	06:05	2.0E + 1	1.0E + 2	05:55	6	3.8E + 3	8
3	Oct. 12, 1977	02:03	5.0E − 1	1.1E + 1	01:52	9	1.8E + 3	3
4	Nov. 22, 1977	10:15	9.0E + 1	2.2E + 2	10:03	9	4.0E + 3	11
5	Jan. 1, 1978	22:03	8.0E − 1	4.0E + 0	21:50	6	5.0E + 2	6
6	Jan. 8, 1978	07:10	7.0E − 2	3.0E + 0	07:01	9	1.4E + 3	12
7	Sep. 23, 1978	10:10	2.5E + 2	4.0E + 2	10:00	8	1.0E + 3	50
8	Oct. 7, 1978	20:20	5.0E − 1	1.6E + 2	20:10	9	2.2E + 1	82
9	Oct. 9, 1978	20:30	2.0E + 0	1.2E + 1	20:24	9	4.0E + 2	24
10	Nov. 7, 1981	04:20	1.1E − 2	1.4E + 2	03:56	9	5.1E + 2	1.4
11	Nov. 12, 1981	16:13	1.5E − 3	1.3E − 1	16:02	9	1.3E + 3	1.2
12	Nov. 13, 1981	03:26	3.5E − 3	4.0E − 1	03:00	9	1.1E + 2	1.9
13	Nov. 13, 1981	11:26	1.5E − 3	1.1E − 1	11:03	9	1.6E + 2	1.0
14	Nov. 14, 1981	22:50	4.1E − 1	7.5E − 1	22:08	8	1.1E + 3	11
15	Nov. 20, 1981	15:40	6.1E − 3	2.5E − 1	15:29	7	6.0E + 1	1.0
16	Nov. 22, 1981	03:41	6.0E − 3	1.0E + 0	03:22	5	1.7E + 2	1.2
17	Nov. 22, 1981	07:40	8.0E − 3	1.2E − 1	06:57	9	3.8E + 2	5.0
18	Dec. 9, 1981	20:00	5.9E + 1	7.1E + 0	19:28	4	5.9E + 2	18
19	Jan. 1, 1982	01:14	7.3E − 3	1.0E + 2	00:57	15	5.0E + 2	3.6
20	Jan. 2, 1982	06:21	8.0E − 3	2.1E + 1	06:11	9	7.1E + 2	1.4
21	Jan. 3, 1982	00:28	1.9E − 2	7.5E − 1	00:18	4	1.0E + 1	2.0
22	Jan. 31, 1982	00:03	5.7E + 1	1.1E + 2	23:52	9	1.6E + 3	10
23	Jan. 31, 1982	13:50	2.1E + 0	2.5E + 1	13:31	12	1.7E + 3	1.9
24	Feb. 1, 1982	14:20	6.0E + 1	1.0E + 2	14:03	12	2.0E + 3	12
25	Feb. 3, 1982	01:40	1.9E + 0	1.1E + 1	01:18	9	4.0E + 3	10
26	Feb. 4, 1982	08:56	2.0E − 2	1.7E + 1	08:32	4	4.0E + 1	1.5
27	Feb. 4, 1982	13:50	1.1E − 1	6.5E + 0	13:33	9	4.0E + 2	9.0
28	Feb. 4, 1982	15:55	2.0E − 1	1.1E + 1	15:42	5	1.6E + 2	2.8
29	Feb. 4, 1982	19:30	5.3E − 2	9.0E + 0	19:01	3	6.0E + 1	6.6
30	Feb. 7, 1982	00:10	2.1E − 1	4.1E + 0	23:57	5	2.5E + 2	8.0
31	Feb. 8, 1982	12:58	7.0E − 1	4.5E + 1	12:51	35	7.0E + 3	4.0
32	Feb. 9, 1982	04:19	1.7E − 2	2.6E + 0	04:07	15	1.8E + 3	2.5
33	Feb. 9, 1982	14:16	8.0E − 3	8.0E − 1	14:09	5	1.0E + 2	4.5
34	Feb. 10, 1982	19:16	1.7E − 2	4.0E + 0	18:52	5	3.0E + 2	3.7
35	Feb. 10, 1982	20:26	1.4E − 2	4.0E + 0	20:01	15	1.2E + 3	1.1
36	Feb. 12, 1982	22:23	7.0E − 3	7.0E − 1	21:58	9	8.0E + 2	1.8
37	Feb. 14, 1982	10:00	1.0E − 3	3.0E − 1	09:41	9	4.0E + 2	0.6
38	Feb. 20, 1982	09:35	3.0E − 3	4.0E − 1	09:25	9	5.0E + 2	3.0
39	Mar. 7, 1982	03:17	3.6E + 1	3.2E + 1	03:08	9	5.0E + 3	7.0
40	Mar. 8, 1982	20:17	1.0E − 2	3.5E − 1	20:13	9	1.1E + 2	5.3
41	Mar. 31, 1982	08:47	1.0E − 2	9.5E − 1	08:34	15	1.2E + 2	2.0
42	Mar. 31, 1982	22:37	8.5E − 3	7.5E − 1	22:25	15	2.7E + 2	2.6
43	Apr. 2, 1982	09:12	1.6E − 3	1.1E − 1	09:08	9	2.5E + 2	1.5
44	Nov. 1, 1982	03:41	4.2E − 3	3.5E − 1	03:36	4	7.5E + 1	0.5
45	Nov. 21, 1982	06:41	2.2E − 2	1.8E + 0	06:08	7	4.6E + 1	10
46	Nov. 22, 1982	10:41	6.4E − 3	1.4E + 0	10:23	3	6.0E + 1	2.2
47	Nov. 22, 1982	18:06	1.9E + 0	2.9E + 1	17:43	4	1.8E + 3	6.0
48	Nov. 23, 1982	11:29	1.6E − 1	3.5E + 0	11:19	4	1.2E + 2	2.1
49	Nov. 25, 1982	04:36	1.9E − 2	1.4E + 0	04:14	9	9.0E + 2	0.8
50	Nov. 26, 1982	02:36	1.1E + 3	4.3E + 2	02:34	7	9.0E + 3	18
51	Dec. 7, 1982	00:06	1.2E + 2	5.0E + 2	23:58	9	2.5E + 4	18
52	Dec. 17, 1982	19:36	1.8E + 1	1.3E + 2	18:54	15	4.0E + 3	7.7
53	Dec. 19, 1982	16:36	4.2E + 2	4.2E + 2	16:35	3	1.3E + 2	70

We have calculated the correlation coefficient between $\log I_p$ and $\log I_e$ and obtained for that value $r \simeq 0.94$. Such a strong correlation implies that > 25 MeV protons and mildly relativistic electrons in SEP-events were accelerated in the same flare process. We compared the electron component of the SEP-events listed in Table I with μ-burst parameters and confirmed the conclusions that were obtained by Mel'nikov *et al.* (1986, 1990). It was established that mildly relativistic electrons related with μ-emission are stronger than subrelativistic (10–100 keV) ones. Also it was established that the correlation was increased if the radio index included not only the peak flux density F_m but also f_m and T_μ. In other words, the correlation became stronger under the multi-parameter approach. It can be seen from Table II, where the correlation coefficients between particle fluxes and different indices of the μ-bursts are shown. The first line in Table II refers to electrons. Here $\varphi = (g/f_m)^\alpha$, $\alpha \simeq 1.5$. The parameter $I_{(e,\,p)\mu}$ will be explained below.

TABLE II

Correlation coefficients

$Y \diagdown X$	$\log F_m$	$\log(\varphi F_m)$	$\log \int F\,\mathrm{d}t$	$\log(\varphi \int F\,\mathrm{d}t)$	$\log I_{(e,\,p)\mu}$
$\log I_e$	0.59	0.68	0.79	0.82	0.84
$\log I_p$	0.53	0.62	0.79	0.82	'0.87

Such a correlation increase may be understood if it is supposed that SEP-events' electrons and electrons generating μ-bursts are accelerated in the same flare process. In this case each parameter considered has a simple physical meaning. In the framework of the diffusion approach, the value $I_{e,\,p}$ characterizes the total number of energetic particles, N_{esc}, escaping into interplanetary space during a flare. In the framework of the gyrosynchrotron mechanism, the value F_m characterizes the maximum instantaneous number of energetic electrons in the radiation source (flare loop), T_μ characterizes the duration of the injection process and electron lifetime in the loop. Variations of f_m and φ characterize magnetic field, B, variations in the source and, hence, the efficiency of μ-emission generation. Therefore, $\varphi \int F\,\mathrm{d}t \sim \int N_e\,\mathrm{d}t$, where N_e is the instantaneous number of accelerated electrons in the radio source. It has become clear that the real explanation of relationships between SEP-events and μ-bursts may be achieved only in the scope of the multi-parameter approach.

Taking into account the strong correlation between I_e and I_p, we may suppose that electrons and energetic protons in a μ-burst are accelerated in the same process and apply the multi-parameter approach in the case of protons. The results of such a study are shown in the second line of Table II. It can be seen that adequate representation of source conditions corresponds to an increase of the correlation. Using the matrix of mutual correlation coefficients between all parameters given in Table I, we obtained a regression model to describe the connection between particle fluxes and μ-burst parameters F_m, T_μ, and f_m. In the case of protons the regression equation is written as

$$\log I_{p\mu} = (1.2 \pm 0.2) \log F_m + (2.0 \pm 0.2) \log T_\mu - (2.0 \pm 0.7) \log f_\mu - 3.4 \,. \tag{1}$$

Using (1) we obtained $I_{p\mu}$ for every event from Table I and then calculated the correlation coefficient between I_p and $I_{p\mu}$. In the same manner the values $I_{e\mu}$ and the correlation coefficient between I_e and $I_{e\mu}$ were obtained. These coefficients are shown in the last column of Table II. It can be seen that the multiple correlation coefficients are larger than the correlation coefficients between $I_{e,\,p}$ and $\varphi \int F \, \mathrm{d}t$, especially in the proton case. This means that in the case of the linear regression model an influence of T_μ and f_m on $I_{p,\,e}$ are taken into account more properly (for details see Mel'nikov *et al.*, 1990, 1991).

Scatter plots of I_p versus F_m and $I_{p\mu}$ are given in Figures 1(a) and 1(b), respectively. Figure 1 was constructed from the statistics, including all events from Table I. This figure confirms that when estimating I_p with the help of μ-emission, the contribution of f_m and T_μ cannot be neglected. From Figure 1(b) it can be seen that the slope of the regression line is 45°. Hence, a statistical linear dependence is realized between I_p and the multi-parameter radio index $I_{p\mu}$, i.e., $I_p \sim I_{p\mu}$.

An applicability of the multi-parameter radio index $I_{p\mu}$ for the estimation and forecast of the proton flux I_p was discussed by Mel'nikov *et al.* (1991). In the main this discussion concerned the estimation accuracy. The use of the μ-burst parameters F_m, f_m, and T_μ

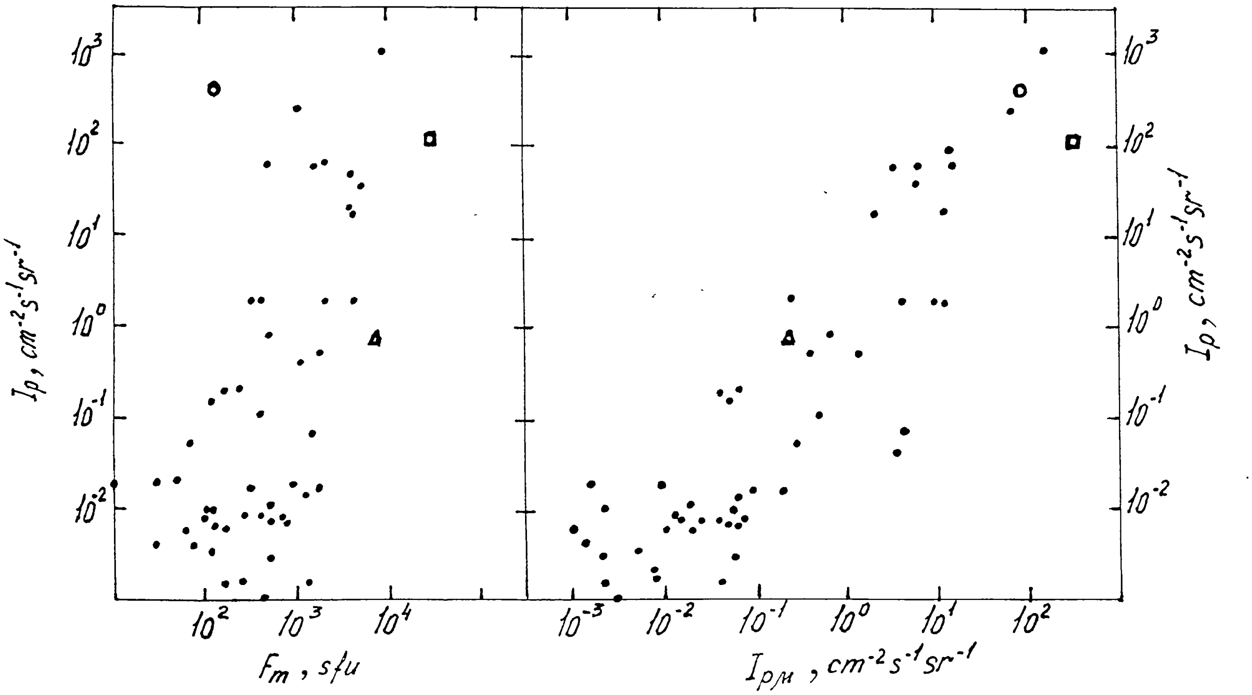

Fig. 1. Scatter plots of observed > 25 MeV proton flux I_p vs F_m, the peak flux density of μ-burst (a), and $I_{p\mu}$, proton flux calculated from Equation (1) (b). One can see that the inclusion of T_μ and f_m intensities the correlation between observed and calculated proton fluxes. The event with weak impulsive phase is marked by a circle, the usual long-duration event with high F_m and f_m = 9 GHz by a square, and the impulsive event with high f_m (35 GHz) by a triangle.

only leads to the accuracy limit that is determined by the residual dispersion $\sigma^2(I_p, I_{p\mu}) \simeq 0.63$.

It is obvious that some contribution to σ^2 is due to different particle escape conditions in different flares and the adopted μ-burst parameters, most probably, do not characterize all these conditions. But it is possible to take into account this contribution if we suppose that the efficiency of energetic proton escape is proportional to that of mildly relativistic electrons. μ-bursts are generated by electrons, and the ratio $K = I_e/I_{e\mu}$ may be considered as the measure of electron escape efficiency (by the way, $\sigma^2(I_e, I_{e\mu}) \simeq 0.38$). If we have simultaneous data on electrons and protons, we can use K to normalize the particle escape conditions and to calculate a more precise value of proton flux $I^*_{p\mu}$. It was shown by Mel'nikov *et al.* (1990) that the correlation coefficient between I_p and $I^*_{p\mu}$ increases to $r \simeq 0.97$ and $\sigma^2(I_p, I^*_{p\mu}) \simeq 0.19$ if $\log I^*_{p\mu} = \log I_{p\mu} + 1.13 \log K$. Such a value of σ^2 seems to be the limit of the estimation accuracy of proton fluxes according to μ-bursts parameters.

Some comments on the applicability of this linear regression model in the case when we start from a list of μ-bursts: microwave bursts are more numerous events than proton bursts, and direct employment of Equation (1) implies a greater number of proton events than is actually observed. Actually, approximately 60 long-duration ($T \geq 4$ hr) μ-bursts, with $F_m \geq 5$ s.f.u., were observed per year during the 1980–1982 solar maximum (Kahler and Cliver, 1989). It can be assumed that in such bursts the average peak flux density F_m is 15 s.f.u., the frequency of spectral maximum is 3 GHz, and the effective duration is 2 hr (for a triangular shape). Hence from Equation (1) it follows that $I_{p\mu} \simeq 0.1$ cm^{-2} s^{-1} sr^{-1} as a lower limit. Similarly one can consider more numerous smaller μ-events, say of ≥ 3 hr duration ($T_\mu \simeq 1.5$ hr) with $F_m \simeq 5$ s.f.u. and $f_m \simeq 5$ GHz (Guidice and Castelli, 1975) and obtain $I_{p\mu} \simeq 0.01$ cm^{-2} s^{-1} sr^{-1} as a lower limit. It is clear that despite the good connection these additional μ-burst will increase the scatter in the plot of Figure 1, mainly for small values of $I_{p\mu}$, and further limitations are required for the applicability of Equation (1).

However, we must recall that Equation (1) was obtained for μ-bursts with parameters ranged in the following limits: $10 \leq F_m \leq 2.5 \times 10^4$ s.f.u., $0.6 \leq T_\mu \leq 82$ min, $3 \leq f_m \leq 35$ GHz. So it is not clear whether Equation (1) is applicable to μ-bursts with $T_\mu \geq 90$ min and $F_m \leq 10$ s.f.u.

From Figure 1 it can be seen that in practice the radio index $I_{p\mu}$ covers all ranges of proton fluxes observed in interplanetary space following solar flares. From Figure 1 it can be derived that numbers of small SEP-events with proton flux I_p values of ≤ 0.1 and ≤ 0.01 cm^{-2} s^{-1} sr^{-1} are 54% and 32%, respectively, of the whole number of events considered (53). From Table I we obtained size distributions of these small proton events of the parameters f_m, T_μ, and F_m. In ~60% of the small SEP-events μ-bursts are characterized by f_m of 7–9 GHz and only in ~25% – f_m of 3–6 GHz. In ~88% of small events μ-bursts are characterized by T_μ of 1–5 min and only in ~5% – T_μ of > 10 min. In ~70% of small SEP-events F_m is in the range of 100–1000 s.f.u. So μ-bursts that are associated with proton events are distinguished from GRF-bursts (gradual rise and fall) considered above.

There are at least two physical reasons limiting the applicability of Equation (1) when starting from a list of μ-bursts. The first has already been mentioned: it seems that the adopted μ-burst parameters do not properly describe particle escape conditions. It is known that intense radio emission in m- and dkm-range implies the favourable particle escape into the high corona and interplanetary space (e.g., Kahler, 1982b). We also considered ~ 70 well-connected flares without the escape of energetic particles into interplanetary space and ~ 70 well-connected flares followed by SEP-events in 1981–1983. The data of particle measurements aboard 'Venera 13, 14' were used. However, in this investigation there were no limitations on > 25 MeV proton fluxes, i.e., we considered not only proton flares. We analysed time profiles and spectra of radio emission and inferred that in practice there was no sporadic emission in m- and dkm-bands in the first case. When solar flares were accompanied by SEP-events, all the bursts, including those with WIP, were followed by an intense m-component (Mel'nikov, Daibog, and Stolpovskii, 1992). So it seems that the applicability of Equation (1) becomes well-grounded when the radio emission spectrum is characterized by an intense m-component.

The second reason is conditioned by the suggestion of the common source of particles in SEP-events and electrons generating μ-emission. So microwave spectra in the bursts associated with SEP-events must be nonthermal. GRF-bursts, mentioned above, seem to be caused by a thermal plasma with a temperature of $\sim 10^7$ K (Kosugi, Dennis, and Kai, 1988). This is inevitably revealed in the radio spectrum at frequencies $f \gg f_m$. In addition, GRF-bursts are practically never accompanied by sporadic radio emission in the m-band. So the shape of the microwave spectrum is the same feature which permits one to select bursts which are associated with SEP-events including bursts with a weak impulsive phase.

3. Application of Empirical Dependencies to WIP-Events

Analysis of μ-emission in proton flares with weak impulsive phases shows that such flares differ from others just in parameters f_m and T_μ. In this case, μ-bursts are characterized by a smooth time-intensity profile, a large duration and a low frequency of spectral maximum. As a rule, in the case of μ-bursts with weak impulsive phases, $T_\mu \geq 10$–30 min, i.e., longer than the average. In turn, the frequency of the spectral maximum $f_m \approx 3$ GHz, i.e., less than the average, $\langle f_m \rangle \approx 9$ GHz (Furst, 1971; Kosugi, Dennis, and Kai, 1988).

If we use these parameters, the relation between the observed I_p and calculated $I_{p\mu}$ is the same for events with weak impulsive phases and events accompanied by more intense μ-bursts. Indeed, the expression for $I_{p\mu}$ is very sensitive to variations of the parameters T_μ and f_m. Therefore, the WIP-flare with the typical radio emission parameters $F_m \approx 10^2$ s.f.u., $T_\mu \geq 30$ min, $f_m \approx 3$ GHz can be accompanied by approximately the same proton flux, I_p, as a flare with a very strong microwave burst ($F_m \approx 10^4$ s.f.u.) but with $T_\mu \leq 10$ min and $f_m \approx 9$ GHz.

To illustrate just how the inclusion of parameters T_μ and f_m affects the relationship of observed I_p and calculated $I_{p\mu}$, we selected three events with different characteristics in 1982 (see Table III). These are: (1) an event with a weak impulsive phase (December 19), (2) a 'normal' proton flare (December 7), and (3) an impulsive burst with a high frequency of spectral maximum (February 8).

TABLE III

Three selected events

Data	$t_{\mu\max}$ (UT)	F_m (s.f.u.)	f_m (GHz)	T_μ (min)	I_p $(\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1})$	$I_{p\mu}$	e/p
1. Dec. 19, 1982	16:35	1.6×10^2	3	70	4.2×10^2	8.2×10^1	1
2. Dec. 7, 1982	23:50	2.5×10^4	9	18	1.2×10^2	3.3×10^2	4.1
3. Feb. 8, 1982	12:51	7.0×10^3	35	4	0.7×10^0	2.2×10^0	64

The points (F_m, I_p) and $(I_{p\mu}, I_p)$ corresponding to these events are shown in Figures 1(a) and 1(b). They are marked with a circle, a square, and a triangle, as the events are listed in Table III. It can be seen that in the case of $(I_p, I_{p\mu})$ all marks lie practically on the same line.

December 7 and 19 SEP-events belong to major solar proton events listed by Shea and Smart (1990). For the December 7 flare the values of the peak proton fluxes in Table III and those given by Shea and Smart (1990) are in agreement if we take into account the spectral index. For the December 19 flare it follows from Table III that the peak > 25 MeV proton flux is $\sim 420\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$, but the peak > 10 MeV proton flux given by Shea and Smart is only $85\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$. This discrepancy may be explained by different locations of measurement points, in particular different heliolongitudes. On December 19, 'Venera 13, 14' spacecrafts were at heliocentric distance $r \sim 0.77$ AU and the Sun–Earth spacecraft angle was $\sim 43°$. Hence, with the solar wind $w_{\mathrm{SW}} \sim 500\ \mathrm{km\,s}^{-1}$, the observation point was projected to the Sun along the interplanetary magnetic field line at heliolongitude ~W78. The flare location was N10 W75. So the connection conditions were more favourable in the case of 'Venera 13, 14' (Shea and Smart used data obtained near the Earth). The comparison of particle fluxes observed by 'Venera' and 'Helios 1' s/c's points out the importance of connection conditions for the December 19 flare. On December 19 'Helios 1' was at $r \sim 0.45$ AU. It projected to the Sun along the magnetic field line at longitude W116. The peak > 12.8 MeV and > 26.5 MeV proton fluxes measured aboard 'Helios 1' were ~ 330 and $\sim 40\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$, respectively (Kallenrode, 1990). These relatively low proton fluxes are due to the less favourable connection conditions in the case of 'Helios 1'. On December 7 the connection conditions were close for both s/c's: 'Helios 1' and 'Venera' were projected to the Sun at longitudes W91 and W76, respectively, and the flare occurred at W86. The peak > 26.5 MeV proton flux, $I_p \sim 220\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$, at 'Helios 1' was in agreement with the peak > 25 MeV proton flux, $I_p \sim 190\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$, at 'Venera' ($r \sim 0.6$ AU for 'Helios 1' and ~ 0.8 AU for 'Venera').

From Table I it can be seen that on December 19 WIP-flare electrons were accelerated up to relativistic energies. The ratio of > 0.5 MeV electron fluxes to > 25 MeV proton fluxes (e/p) in all three events is shown in Table III. It can be seen that for the December 19 flare the e/p-ratio is close to that for the December 7 flare and much smaller than that for the February 8 flare. So for the e/p-ratio, WIP-events are similar to long-duration ones.

At last it may be noted that in all events from Table III, including the December 19 WIP-event, there were type II radiobursts.

4. Physical Conditions in Flare Loops

The features of SEP-events with a weak impulsive phase are connected with the conditions in loops where energetic particles appear immediately after acceleration. The reason for the inverse relation of proton fluxes, I_p, with the frequency, f_m, is the following. The expressions for the gyrosynchrotron emission from electrons with an isotropic pitch-angle distribution and a power-law energy spectrum have been obtained by Dulk and March (1982). By making use of Equations (13) and (17) of their paper, we have

$$\begin{aligned} f_m &\sim B^{0.68 + 0.03\gamma}, \\ F(f > f_m) &\sim NB^{0.9\gamma - 0.22} f^{1.22 - 0.9\gamma}, \end{aligned} \tag{2}$$

where N is the number of electrons with $E > E_0$ in the radio source and γ is the exponent of the spectrum of radiating electrons. A low-frequency f_m suggests a weak magnetic field in the radio source and, hence, a low-radiation efficiency.

It follows from (2) that the largest discrepancy between observed and expected particle numbers will be in the case when we estimate this number on the basis of $F(f)$ at $f \gg f_m$. If we take $\gamma = 4$ we shall have $F(f) \sim B^{3.4}$ at $f \neq f_m$ and $F(f_m) \sim B^{1.5}$. In the case of events with low-frequency, f_m, the number of accelerated particles is much greater than one would expect from the low peak flux density, F_m.

This reason for protons (which do not generate radio emission) is supported by the observed close correlation between the influences of γ-radiation in lines and in continuum (Forrest, 1983).

According to Daibog *et al.* (1988, 1989a, b) the reason that the flux, I_p, increases strongly with increasing effective duration, T_μ, is related to the specific features of proton dynamics in flare loops of different sizes. Whatever the escape mechanism, the fraction of particles that escapes into interplanetary space is directly connected with their lifetimes in the loop, since

$$N_{\text{esc}} = N_{\text{tot}} \tau_p / \tau_{\text{esc}}, \qquad \tau_p = \tau\tau_{\text{esc}}/(\tau + \tau_{\text{esc}}), \tag{3}$$

where N_{tot} is the total number of accelerated particles, N_{esc} is the number of escaping particles, τ_{esc} is the characteristic escape time, τ is the characteristic time of the energy losses and precipitation into the loss cone, and τ_p is the effective lifetime of protons in the loop.

In impulsive flares (T_μ is small) the proton acceleration takes place in compact flare loops. In these loops τ is determined by precipitation into the loss cone. It is small due to strong scattering in the Alfvén turbulence generated by protons themselves. The minimum value is achieved in the moderate diffusion limit

$$\tau = (\sigma L)/2v, \tag{4}$$

where σ is the magnetic mirror ratio, L is the size of a loop, and v is the proton velocity. For typical values $\sigma = 3$, $L = 10^9$ cm, $v = 6 \times 10^9$ cm s^{-1} the lifetime $\tau \approx 0.25$ s.

In flares with large T_μ the proton acceleration occurs in high coronal loops. In such loops the density of energetic protons and the level of excited turbulence are low. In this case a weak diffusion regime is obtained. Thus the proton lifetime is large and equal to the Coulomb lifetime in the limit:

$$\tau \approx \tau_C = 1.3 \times 10^{11} E^{3/2}/n_0 , \tag{5}$$

where n_0 is the plasma density, and E is the energy of protons in MeV. For $n_0 \leq 10^{10}$ cm^{-3}, $E = 25$ MeV, and the lifetime $\tau \geq 10^3$ s.

It is clear that in long-duration flares the number of escaping protons will be disproportionately large in comparison with impulsive flares.

Note that the presence of the coronal transients and the type IV meter radio emission in most events can be considered as indicating the existence of open structures of magnetic field in the vicinity of flare loops. Actually, the coronal transient itself, owing to its large mass and velocity can withdraw the frozen closed lines into interplanetary space and, thereby, produce favourable escape conditions for particles which have been trapped for a long time in the loop. In this case the time τ can become comparable with τ_{esc} and the number of escaped protons N_{esc} can approach the total number of accelerated protons. This could account for the deficit of γ-emission in lines observed in SEP events with weak impulsive phases in radio emission (Cliver *et al.*, 1989).

5. Conclusion

We confirm that proton events with weak impulsive phase in radio emission are not an exclusive class of SEP-events. The only unusual aspects are the conditions for protons just after their acceleration. These conditions are one of the limiting cases: namely, the flare loops, where the acceleration occurs, have large dimensions and lie high (10^4–5×10^4 km) in the corona, the magnetic field is not large, and the level of Alfvén turbulence excited in the loops is low. The latter results in the weak diffusion of protons into the loss cone, the large proton lifetime and, as a consequence, rather effective escape into interplanetary space.

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