ISSN 0010-9525, Cosmic Research, 2013, Vol. 51, No. 2, pp. 108–113. © Pleiades Publishing, Ltd., 2013.
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Acceleration of Solar Cosmic Rays and the Fine Spectral Structure of Type II Radio Bursts

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Received April 31, 2012

Abstract—On the basis of data, obtained by means of the ground-based solar service RSTN (Radio Solar Telescope Network) and the geostationary satellite system GOES, the relationship between the solar cosmic rays (SCR) intensity I_p with the proton energy $E_p > 1$ MeV and parameters of meter–decameter type II radio bursts in the frequency range of 25–180 MHz is studied. The process of proton acceleration by shock waves was characterized by the frequency drift velocity of radio bursts $V_{m\mathrm{II}}$ and the relative difference between radio emission frequencies at the first two harmonics b. It is shown that the coefficient of correlation between I_p and b increases with E_p growing from 0.40 to 0.70, while a similar coefficient between I_p and $V_{m\mathrm{II}}$ does not exceed 0.30. Indications in favor of the two-stage SCR acceleration model are obtained.

DOI: 10.1134/S0010952513020068

1. INTRODUCTION

Now it is commonly believed that solar cosmic rays (SCR), 90% of which consist of protons, are accelerated either in regions of flare energy release (in current sheets), or on shock wave fronts, which can be generated both by flares and by coronal mass ejections. Though the results obtained till now do not allow one to draw an unambiguous conclusion, which of scenarios is more adequate, nevertheless, the available data convincingly testify in favor of a crucial role of shock waves [1, 2].

One of the most reliable shock wave indicators in the solar corona are type II radio bursts. It is believed that the plasma radio emission mechanism is responsible for generation of bursts (see, e.g., [3]). The nonequilibrium electrons, accelerated on the shock wave front, excite Langmuir waves L with a frequency close to the electron plasma frequency f_p, which are then transformed into electromagnetic waves T through their decay ($L \to T(f_p) + S'$, where S' is the ion-sound wave) or coalescence ($L + L' \to T(2f_p)$). This should result in the radio emission generation at the first $f_1 = f_p$ and second $f_2 = 2f_p$ harmonics (see Fig. 1).

One of interesting features of type II radio bursts consists in the fact that, as a rule, the ratio of the radiation frequency of the second harmonic f_2 to the first one f_1 is not equal to 2 accurately [4–6]. This can be explained by plasma heterogeneity in a source that results in stronger absorption of electromagnetic waves in the low-frequency radio emission band at the first harmonic [6]. Meanwhile, magneto-hydrodynamic irregularities are responsible for reflection of accelerated particles near the shock wave front; therefore, they will essentially influence the efficiency of action of the diffusive acceleration mechanism. Hence, one can expect the existence of a close link between the SCR proton flux intensity I_p and the relative harmonic radio emission detuning $b = (f_2 - f_1)/f_1$.

The important information about proton acceleration in the solar corona can also be obtained proceeding from measurements of the frequency drift velocity of meter–decameter (mII) type II radio bursts $V_{m\mathrm{II}}$. Tsap and Isaeva [7] have considered earlier the correlation between the flux of intensity of solar cosmic ray protons I_p and $V_{m\mathrm{II}}$. However, the drift velocity was found from the tabular data presented on the web site of the World Sun Service Network and determined as the ratio of the frequency interval, in which the Type II burst was observed, to its duration, which is a too rough approximation and can result in essential errors. Thereof, in this work we turned to the analysis of original data.

The purpose of the present paper is to try clarifying the role of coronal shock waves in the acceleration of SCR protons by means of radio monitoring.

2. INITIAL DATA, ASSUMPTIONS, AND PROCESSING TECHNIQUE

The original observational data, accessible via Internet, were used in the paper. In total, 69 proton events were recorded during the period since 2000 till 2006. These events were accompanied by proton fluxes with energies $E_p > 1$ MeV (see Table 1). Measurements of integral intensities of the SCR proton flux I_p were carried out on the *GOES* series satellites. Maximum I_p values in various spectral intervals were used for analysis. In so doing, the apparatus effects (outlying obser-

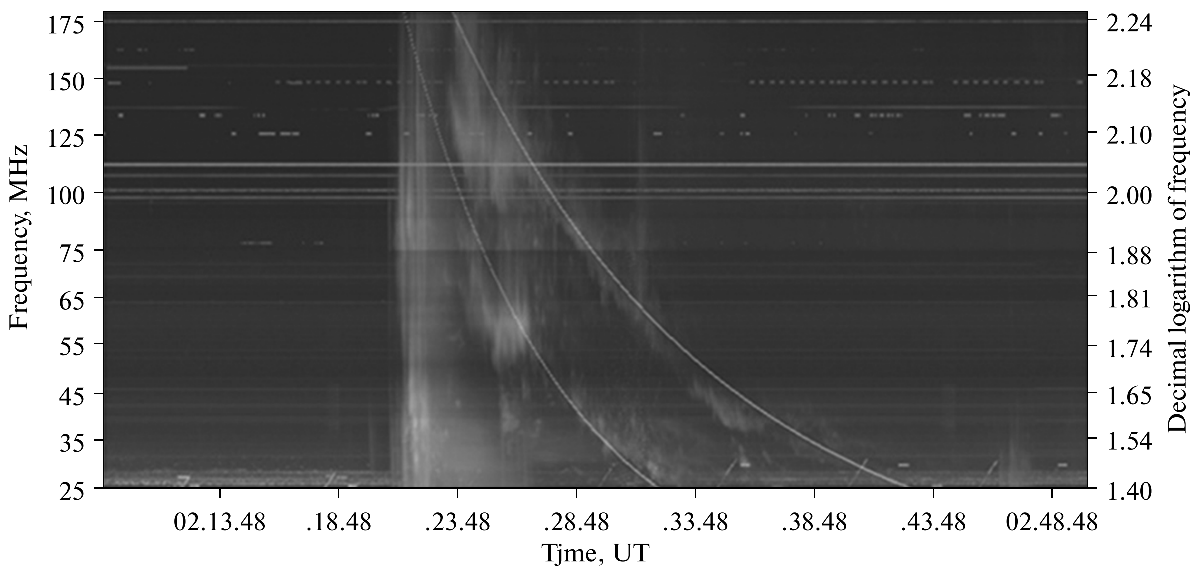

Fig. 1. Dynamic spectrum of the type II radio burst obtained by means of the SRS radio spectrograph in Learmonth (Western Australia).

vations) were excluded, and if superposition of proton events took place, the I_p values were taken from the level of a preceding event.

We have selected 35 events out of 69 recorded ones, because only for these events there were original records of continual and mII radio bursts in the ranges of 245–15400 MHz and 25–180 MHz, respectively. This explains, in particular, a comparatively small number of studied proton events for the period mentioned above (see Table 1). Moreover, for some very strong events one did not always manage to distinguish precisely enough the harmonics of mII radio bursts against the powerful continuum background (for example, the event of October 28, 2003); so, they were also excluded from consideration.

The observations obtained by the RSTN ground network were analyzed. The RSTN (Radio Solar Telescope Network) is the world Sun service network produced by the Air Force Research Laboratory (USA) for the purpose of monitoring solar flares, noise storms, and other solar activity manifestations. It includes the RIMS (Radio Interference Measurement Set) antenna system, as well as the SRS (Solar Radio Spectrograph), disposed in various parts of the Earth. The RSTN network includes 4 ground stations: Palåhua (Hawaii), San Vito dei Normanni (Italy), Sagamore Hill (Massachusetts, USA), RAAF (Royal Australian Air Force) Learmonth (Western Australia), which makes it possible to perform continuous monitoring of solar radio emission. To study the relationship between the SCR proton flux and mII radio bursts' parameters we made use of the original records of dynamic spectra obtained on the SRS with time resolution of about 3 s. It should be noted at once that for all proton events the zero time instant corresponded to the beginning of type II burst in the first harmonic, at a frequency of 180 MHz.

The example of dynamic spectrum of the radio burst of the mII proton event of May 31, 2003, which was constructed according to the standard technique (http://www.docstoc.com/docs/86561095/Srsdispl), is presented in Fig. 1. As is seen, two bands can be distinguished, which correspond to the fundamental and second harmonics. They are well enough approximated by functions $\log f_{i,j} = k_j \cdot \log t_i + d_j$ (light lines in Fig. 1), where t_i is the time corresponding to the maximum intensity of type II burst at frequency $f_{i,j}$, k_j and d_j are linear regression coefficients, $i = 1, 2...n$ are counting numbers, and $j = 1, 2$ are numbers of harmonics.

Table 2 presents linear regression coefficients k_j and d_j, as well as the mean errors σ_j of frequency determination.

In this paper we calculated the values of a drift velocity of meter radio bursts $V_{m\mathrm{II}}$ and detuning b (see Table 1), which were found by the formulas

$$V_{m\mathrm{II}} = \frac{1}{n}\sum_{i=1}^{n}\frac{f_{i+1,1} - f_{i,1}}{t_{i+1} - t_i}, \quad b = \frac{1}{n}\sum_{i=1}^{n}\frac{f_{i,2} - f_{i,1}}{f_{i,1}}.$$

They were used in order to characterize the process of acceleration by shock waves.

The involvement of the frequency drift velocity $V_{m\mathrm{II}}$ is explained by the fact, that the plasma frequency $f_p \propto \sqrt{n}$, where n is the electron density; therefore,

$$V_{m\mathrm{II}} = \frac{df}{dt} = \frac{df}{dR}\frac{dR}{dt} \propto \frac{1}{\sqrt{n}}\frac{dn}{dR}u_1,$$

Table 1

Date	Time, UT	Coord., H_α	b	V_{mII}, MHz/min	$E_p > 30$ MeV
Nov. 25, 2000	18.40	N20W05	0.78	10.40	$9.04 \cdot 10$
Jan. 20. 2001	21.15	S07E46	0.51	10.28	$4.93 \cdot 10^{-1}$
Apr. 10, 2001	05.26	S23W09	0.89	14.66	$1.29 \cdot 10$
Apr. 12, 2001	10.31	S19W43	0.66	8.54	4.30
Apr. 18, 2001	02.14	S20W90	1.73	7.64	$7.31 \cdot 10$
May 20, 2001	06.00	N20E54	1.18	6.63	1.76
June 15, 2001	16.48	WLIMB	0.54	4.41	2.39
Sept. 15, 2001	11.28	S21W49	0.45	4.85	1.12
Oct. 19, 2001	16.30	N15W29	0.87	5.35	2.17
Oct. 22, 2001	17.59	S18E16	0.64	8.69	4.82
Dec. 26, 2001	05.40	N08W54	0.93	5.50	$1.78 \cdot 10^2$
Jan. 14, 2002	06.27	WLIMB	0.85	10.76	1.41
Feb. 20, 2002	06.12	N12W72	0.39	8.81	$9.88 \cdot 10^{-1}$
Apr. 21, 2002	01.57	S14W84	1.73	3.35	$2.33 \cdot 10^2$
July 20, 2002	21.30	SELIMB	0.73	8.92	2.60
Aug. 22, 2002	01.57	S07W62	0.78	10.09	8.17
Aug. 24, 2002	01.12	S08W90	0.93	10.89	$9.33 \cdot 10$
Sept. 5, 2002	17.06	N09E28	0.51	6.94	3.24
Nov.9, 2002	13.23	S12W29	0.44	7.77	$1.17 \cdot 10$
Dec. 19, 2002	22.06	N15W09	0.63	8.18	$6.52 \cdot 10^{-1}$
May 31, 2003	02.24	S07W65	0.95	4.94	5.55
Oct. 26, 2003	18.19	N02W38	0.75	12.69	$4.16 \cdot 10$
Oct. 29, 2003	20.45	S15W02	1.73	6.77	$8.69 \cdot 10^2$
Nov. 4, 2003	19.29	S19W83	1.17	12.36	$3.09 \cdot 10$
Sept. 12, 2004	00.56	N04E42	1.05	5.77	6.61
Sept. 19, 2004	17.12	N03W58	1.04	5.77	8.83
Oct. 30, 2004	06.54	N13W22	0.84	10.81	$6.53 \cdot 10^{-1}$
Nov.7, 2004	16.06	N09W17	0.52	11.52	$2.60 \cdot 10$
Nov.10, 2004	02.26	N09W49	0.94	12.56	$4.94 \cdot 10$
Jan. 15. 2005	23.02	N15W05	0.93	13.09	$5.27 \cdot 10$
Jan. 17. 2005	09.54	N15W25	1.07	49.06	$1.33 \cdot 10^3$
May 13, 2005	16.57	N12E11	0.68	12.94	$1.09 \cdot 10$
July 27, 2005	05.02	N11E90	0.87	11.05	3.42
Sept. 7, 2005	17.40	S06E89	1.58	10.44	$1.82 \cdot 10^2$
Dec. 13, 2006	02.40	S05W23	1.53	8.35	$3.72 \cdot 10^2$

Here, R is the distance to the radiation source, and $u_1 = dR/dt$ is the shock wave front velocity. Where from we obtain the relation for the Alfven Mach number

$$M_A = \frac{u_1}{V_A} \propto \left(V_A \frac{1}{\sqrt{n}} \frac{dn}{dR}\right)^{-1} V_{mII}, \qquad (1)$$

where V_A is the Alfven velocity. Thus, according to (1), the larger Mach number values M_A characterizing the shock wave intensity and, accordingly, the rate of energetic proton acceleration dE/dt should correspond to larger values of drift velocity V_{mII}. And with growing dE/dt the threshold velocity of accelerated particles decreases, which will lead to increase of their total number.

The analysis of the relationship between the proton flux intensity I_p and harmonic detuning b, as it was

Table 2

Date	k_1	d_1	σ_1, MHz	k_2	d_2	σ_2, MHz
Nov. 25, 2000	−0.81	2.30	1.06	−0.93	2.64	1.09
Jan. 20. 2001	−0.91	2.26	1.06	−1.17	2.62	1.04
Apr. 10, 2001	−0.93	2.37	1.12	−1.25	2.85	1.04
Apr. 12, 2001	−0.78	2.22	1.05	−0.93	2.55	1.05
Apr. 18, 2001	−0.89	2.29	1.05	−1.10	2.89	1.04
May 20, 2001	−0.82	2.26	1.05	−1.07	2.79	1.04
June 15, 2001	−0.58	1.98	1.10	−1.03	2.49	1.05
Sept. 15, 2001	−0.61	2.23	1.08	−0.73	2.50	1.06
Oct. 19, 2001	−0.69	2.28	1.08	−0.91	2.75	1.05
Oct. 22, 2001	−0.73	2.30	1.10	−0.97	2.70	1.04
Dec. 26, 2001	−0.73	2.36	1.09	−0.97	2.86	1.03
Jan. 14, 2002	−0.84	2.27	1.06	−1.02	2.67	1.04
Feb. 20, 2002	−0.73	2.53	1.20	−0.82	2.77	1.15
Apr. 21, 2002	−0.83	2.43	1.12	−1.67	3.71	1.03
July 20, 2002	−0.75	2.34	1.09	−0.93	2.72	1.09
Aug. 22, 2002	−0.81	2.33	1.06	−1.08	2.78	1.03
Aug. 24, 2002	−0.84	2.28	1.07	−1.02	2.70	1.04
Sept. 5, 2002	−0.72	2.34	1.07	−0.85	2.64	1.08
Nov.9, 2002	−0.69	2.36	1.14	−0.83	2.64	1.10
Dec. 19, 2002	−0.74	2.33	1.08	−0.88	2.66	1.07
May 31, 2003	−0.68	2.22	1.06	−0.93	2.72	1.02
Oct. 26, 2003	−0.93	2.30	1.10	−1.27	2.77	1.08
Oct. 29, 2003	−0.79	2.22	1.07	−1.14	2.92	1.04
Nov. 4, 2003	−1.01	2.24	1.05	−1.18	2.68	1.05
Sept. 12, 2004	−0.60	2.12	1.09	−0.77	2.57	1.04
Sept. 19, 2004	−0.71	2.32	1.09	−0.97	2.86	1.06
Oct. 30, 2004	−0.88	2.28	1.05	−1.01	2.63	1.04
Nov.7, 2004	−0.69	2.25	1.06	−0.75	2.48	1.08
Nov.10, 2004	−0.94	2.30	1.07	−1.02	2.64	1.05
Jan. 15. 2005	−0.92	2.26	1.08	−1.13	2.67	1.05
Jan. 17. 2005	−1.43	2.23	1.08	−1.55	2.59	1.06
May 13, 2005	−0.95	2.31	1.06	−1.03	2.59	1.04
July 27, 2005	−0.91	2.24	1.08	−1.04	2.60	1.07
Sept. 7, 2005	−0.95	2.22	1.07	−0.94	2.62	1.05
Dec. 13, 2006	−0.95	2.17	1.09	−1.24	2.76	1.09

already noted in the Introduction, is explained by the dependence of the magneto-hydrodynamic turbulence level on the plasma heterogeneity and, accordingly, b, near the shock wave front.

3. DATA PROCESSING RESULTS

Figure 2 shows the dependences of the proton flux intensity I_p on: (a) frequency drift velocity V_{mII} and (b) harmonic detuning b. As is seen, the relationship between I_p and b is better pronounced than that between I_p and V_{mII}. This is convincingly testified by the dependences of coefficients of correlation between intensity I_p and parameters of mII radio bursts $r(I_p, b)$ and $r(I_p, V_{mII})$ on the proton energy E_p. (Fig. 3). If the maximum value of $r(I_p, V_{mII})$ does not exceed 0.30 (Fig. 3a), then a rather convincing relationship is observed between I_p and b (Fig. 3b). This can be judged by the correlation values $r(I_p, b) > 0.65$ for protons with $E_p > 30$ MeV. One can also pay attention to

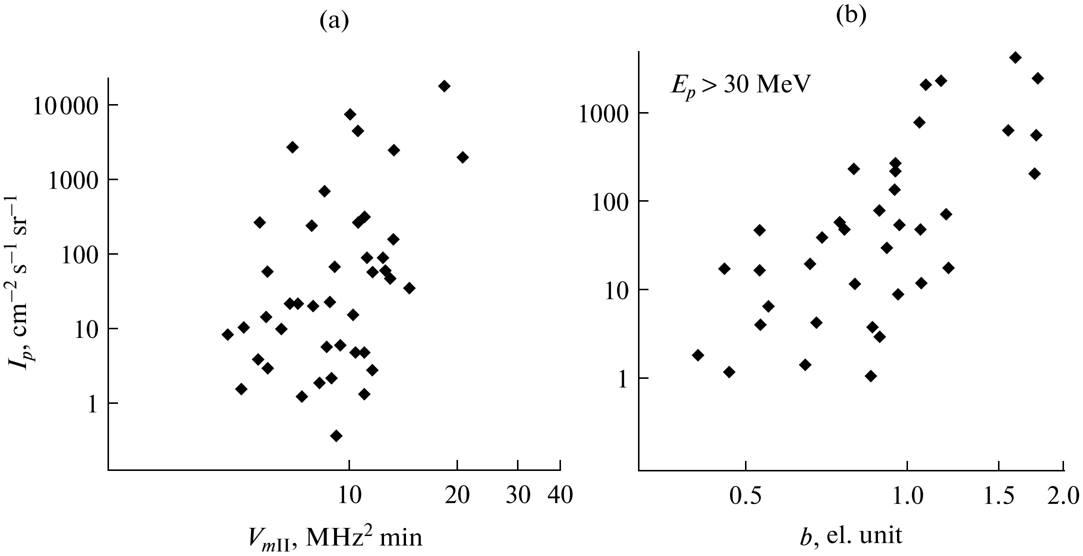

Fig. 2.

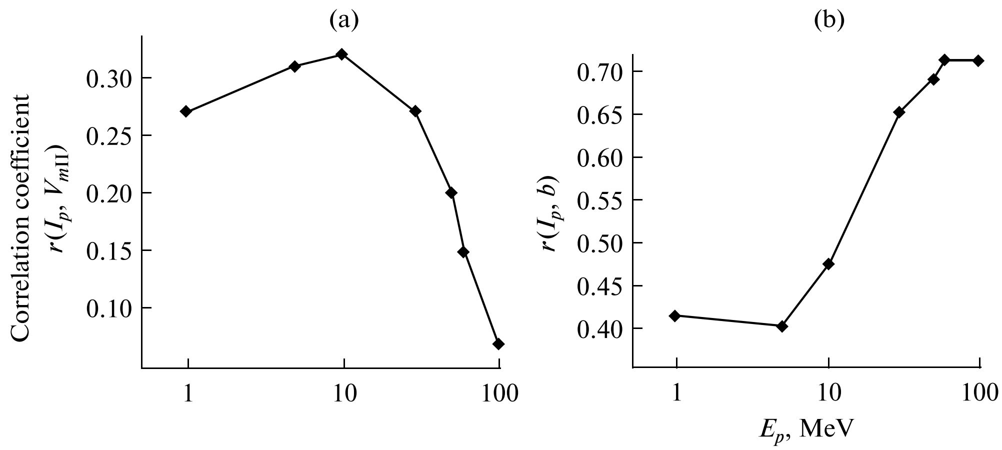

Fig. 3.

considerable growth of correlation $r(I_p, b)$ with increasing proton energy E_p in the range of values E_p = 10–80 MeV. In our opinion, this is an evidence of noticeable contribution of shock waves into acceleration of high-energy protons.

DISCUSSION OF RESULTS AND CONCLUSIONS

We have considered in the presented paper the relationship between the proton flux intensity I_p and parameters of mII radio bursts. We have found a correlation between I_p with energy E_p > 30 MeV and the relative harmonic detuning b in the vicinity of the front of coronal shock waves. Also, a noticeable growth of $r(I_p, b)$ values with increasing E_p values is observed. They increase from 0.40 to 0.70, which suggests essential contribution of shock waves to acceleration of particles with E_p > 30 MeV.

As follows from obtained results, there is no correlation between I_p and V_{mII} (< 0.30), which can be explained by considerable changes of conditions of propagation for shock waves from event to event. According to relation (1), this should result in noticeable scatter of points on the $I_p(V_{mII})$ plots because of strong dependence of shock wave intensity on medium's parameters. However, in case of involving the detuning b, characterizing plasma heterogeneity, this effect is leveled.

Rather recently Chertok et al. [9] have found the dependence between the microwave radiation spectra and energetic protons. From the data of measurements carried out since 1987 till 2008 it was found that the proton fluxes with small energy spectrum indices (≤1.5) correspond to microwave bursts with hard radio frequency spectrum, for which the ratio of peak densities of fluxes at 9 and 15 GHz are ≤ 1, and the spectral maximum frequency is ≥15 GHz. From this the conclusion was drawn that SCR are accelerated in the process of impulsive and post-eruptive energy release, rather than on fronts of shock waves generated by coronal mass ejections.

The results obtained by Kiplinger [10] (see also [11, 12]) can also serve as a weighty argument in favor of the above conclusion. Kiplinger was the first who paid attention to a close link between the dynamics of hard X-ray radiation spectrum and SCR. He has found that the increase of a relative abundance of high-energy electrons at the post-impulsive phase (the spectral index behaves itself as soft-hard-hard one) is more characteristic for proton rather than for impulsive events. In turn, Kahler's investigations [13] suggest the necessity of a more careful approach to the "Kiplinger effect".

In our opinion, the results mentioned above give evidence in favor of the model of two-stage SCR acceleration put forward by Wild et al. half a century ago [14]. In this case the acceleration of charged particles proceeds both in the flare-type energy release region and at shock wave fronts.

In conclusion, we would like to note that in our reasoning we ignored the proton propagation effects. Taking them into account one can essentially correct the conclusions made in this work. However, the detailed consideration of the SCR transport equation is beyond the scope of this paper.

ACKNOWLEDGMENTS

The authors express their sincere gratitude to the editor and reviewer for their comments, which greatly contributed to improvement of the manuscript.

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