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## THE RELATIONSHIP OF THE SCR WITH PARAMETERS OF RADIO BURSTS AND CME

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**ABSTRACT.** The relationship the intensity of the proton flux  $I_p$  of solar cosmic rays (SCR) with the parameters of continual radio bursts of the IV type, with the speed of coronal mass ejections (CME) of  $V_{CME}$ , as well as with the parameters of slowly drifting radio bursts of type II is investigated. Comparative analysis showed that for the vast majority of proton events a strong correlation of the intensity of the proton flux  $I_p$  with the integral flux  $\int F_{\mu} dt$  of microwave bursts and the CME velocity  $V_{CME}$  is observed, where the correlation coefficient  $r$  between the investigated parameters is 0.80 and 0.72, respectively. Earlier, the author reported on a strong connection between the integral flux  $\int F_{\mu} dt$  of the microwave bursts and the CME velocity  $V_{CME}$ , where the correlation coefficient  $r$  between the investigated quantities is about 0.80. The strong connection between the intensity of the proton flux  $I_p$  and the integral flux  $\int F_{\mu} dt$  of microwave bursts and the speed of the CME, as well as the strong connection between the integral flux  $\int F_{\mu} dt$  of the microwave bursts and the CME velocity  $V_{CME}$ , attests about the common origin of SCRs and CMEs during proton flares. In this paper it is also shown that there is a strong relationship between the intensity of the proton flux  $I_p$  and the parameter of type II burst  $V_{II}$ , which characterizes the shock front displacement velocity. Moreover, the relationship between the intensity of the proton flux  $I_p$  and the parameter  $V_{II}$  depends to a large extent on the frequency  $f_2$  of the maximum of the type II radio burst on the second harmonic at a given time  $t$  and on the energy of the protons  $E_p$ . The maximum correlation between the proton flux  $I_p$  and parameter  $V_{II}$  is observed for protons with an energy  $E_p > 30$  MeV and for the upper frequency  $f_2$  in the range 25-60 MHz.

**АБСТРАКТ.** Досліджено зв'язок інтенсивності потоку протонів  $I_p$  сонячних космічних променів (СКП) з параметрами континуальних радіосплесків IV типу, зі швидкістю корональних викидів маси (КВМ)  $V_{CME}$ , а також з параметрами повільно дрейфуючих радіосплесків II типу. Порівняльний аналіз показав, що для переважної більшості протонних подій спостерігається сильний зв'язок інтенсивності потоку протонів  $I_p$  з інтегральним потоком  $\int F_{\mu} dt$  мікрохвильових сплесків і швидкістю КВМ  $V_{CME}$ , де коефіцієнт кореляції  $r$  між досліджуваними параметрами дорівнює 0.80 і 0.72, відповідно. Раніше автором повідомлялося про сильний зв'язок між інтегральним потоком  $\int F_{\mu} dt$  мікрохвильових сплесків і швидкістю КВМ  $V_{CME}$ , де коефіцієнт кореляції  $r$  між досліджуваними величинами  $\approx 0.80$ . Наявність силь-

ного зв'язку інтенсивності потоку протонів  $I_p$  з інтегральним потоком  $\int F_{\mu} dt$  мікрохвильових сплесків і швидкістю КВМ, а також сильного зв'язку між інтегральним потоком  $\int F_{\mu} dt$  мікрохвильових сплесків і швидкістю КВМ  $V_{CME}$  свідчить про спільність походження СКП і КВМ під час протонних спалахів. У даній роботі також показано, що існує сильний зв'язок між інтенсивністю потоку протонів  $I_p$  і параметром сплесків II типу  $V_{II}$ , який характеризує швидкість зсуву фронту ударної хвилі. Причому, зв'язок між інтенсивністю потоку протонів  $I_p$  і параметром  $V_{II}$  значною мірою залежить від частоти  $f_2$  максимуму радіосплесків II типу на другій гармоніці в даний момент часу  $t$  і від енергії протонів  $E_p$ . Максимальна кореляція між потоком протонів  $I_p$  і параметром  $V_{II}$  спостерігається для протонів з енергією  $E_p > 30$  MeV і для верхньої частоти  $f_2$  в діапазоні 25-60 МГц.

**Keywords:** Proton flux, coronal mass ejections, radio bursts.

### 1. Introduction

The fundamentals of short-term prognosis methods for the flux of solar cosmic ray protons (SCR) were laid in the works of a number of authors. In the work (Chertok, 1982) it was shown that the parameters of microwave radio bursts ( $\mu$ -bursts) can be used to judge the total number of accelerated particles and their energy spectrum. It was also shown that by the parameters of meter bursts one can judge the conditions for the exit of accelerated particles into interplanetary space. The presence of a sufficiently powerful meter component indicates favorable exit conditions, the absence on the unfavorable exit conditions (Akinian et al., 1977). (Melnikov et al., 1986) showed that the presence of a strong coupling between the flow of subrelativistic electrons of the SCR and the integral flux of  $\mu$ -bursts indicates that the SCR electrons and the electrons generating the radio burst are accelerated in a single process. On the basis of this, statistical models connecting proton and electron fluxes with parameters of microwave bursts were obtained (Melnikov et al., 1991).

In this paper, the emphasis is on investigating the connection between the SCR proton flux and the parameters of radio bursts of type II and comparing the results with what is obtained from the parameters of microwave bursts. Earlier in the works (Tsap & Isaeva, 2011; 2012; 2013) some questions were considered regarding the relation of

the SCR proton flux with the parameters of type II radio bursts. In the course of studies of the connection between the speed of the frequency drift of meter-decameter type II bursts and the intensity of the proton flux  $I_p$  of different energies, two families of events were discovered. This involves the generation of shock waves both in the region of flare energy release and by moving coronal mass ejection (CME) (Isaeva & Tsap, 2011). In the works (Isaeva & Tsap, 2011; Tsap & Isaeva, 2012; 2013), the results of the investigation of the efficiency of the acceleration of SCR by coronal and interplanetary shock waves are given, and arguments are also presented in favor of a two-step acceleration of protons. A comparative analysis showed that acceleration of protons by coronal shock waves is more effective than interplanetary shock waves, and that the main acceleration of protons occurs in the flare region and additional by the shock waves. A study of the fine spectral structure of the meter-decameter radio bursts of type II showed that there is a sufficiently strong connection between the proton flux and the relative distance  $b = (f_2 - f_1)/f_1$  between the first and second harmonics at a given time  $t$ , where the correlation coefficient  $r$  between the parameters  $\approx 0.70$ , while the connection between the drift velocity and the proton flux turned out to be weak, and the correlation coefficient  $r$  between the proton flux and the drift velocity does not exceed  $\approx 0.40$  (Tsap & Isaeva, 2013).

**2. Relationship between the intensity of the proton flux  $I_p$  SCR and the integral flux  $\int F dt$  of radio bursts in the range 245-15400 MHz**

For the analysis, the original records of the radio emission of the Sun were used at 8 fixed frequencies of 245, 410, 610, 1415, 2695, 4995, 8800 and 15400 MHz (<https://www.ngdc.noaa.gov/stp/space-weather/solar-data/solar-features/solar-radio/rstn-1-second/>), original recordings of the proton flux intensity  $I_p$  with proton energy  $E_p > 0.8-100$  MeV ([https://satdat.ngdc.noaa.gov/sem/goes/data/new\\_avg/](https://satdat.ngdc.noaa.gov/sem/goes/data/new_avg/)), as well as a list of proton events (<ftp://ftp.swpc.noaa.gov/pub/indices/SPE.txt>). The investigated sample contains 147 proton events for the period from 06-02-1986 to 14-10-2014. Protonic events were selected according to generally accepted criteria for protonity. It is known that for events having a U or W type of a frequency radio spectrum with maxima in the meter and centimeter wavelength bands and with a minimum in the decimeter band, the best correlation between the parameters of  $\mu$ -bursts and the intensity of the flux of the subrelativistic electrons and protons SCR is observed. Confirmation of this fact can be seen in Fig. 1 a), where the connection between the integral flux of continual  $\mu$ -bursts at a frequency of 8800 MHz and the intensity of the proton flux  $I_p$  with an energy  $E_p > 30$  MeV is shown. For such events, the correlation coefficient  $r$  between  $\int F dt$  and  $I_p \approx 0.80$ . At the same time, the relationship between the intensity of the proton flux  $I_p$  and the integral flux of the continual radio bursts depends to a large extent on the frequency  $f$  of the radio burst (see Fig. 1 b) and the energy of the

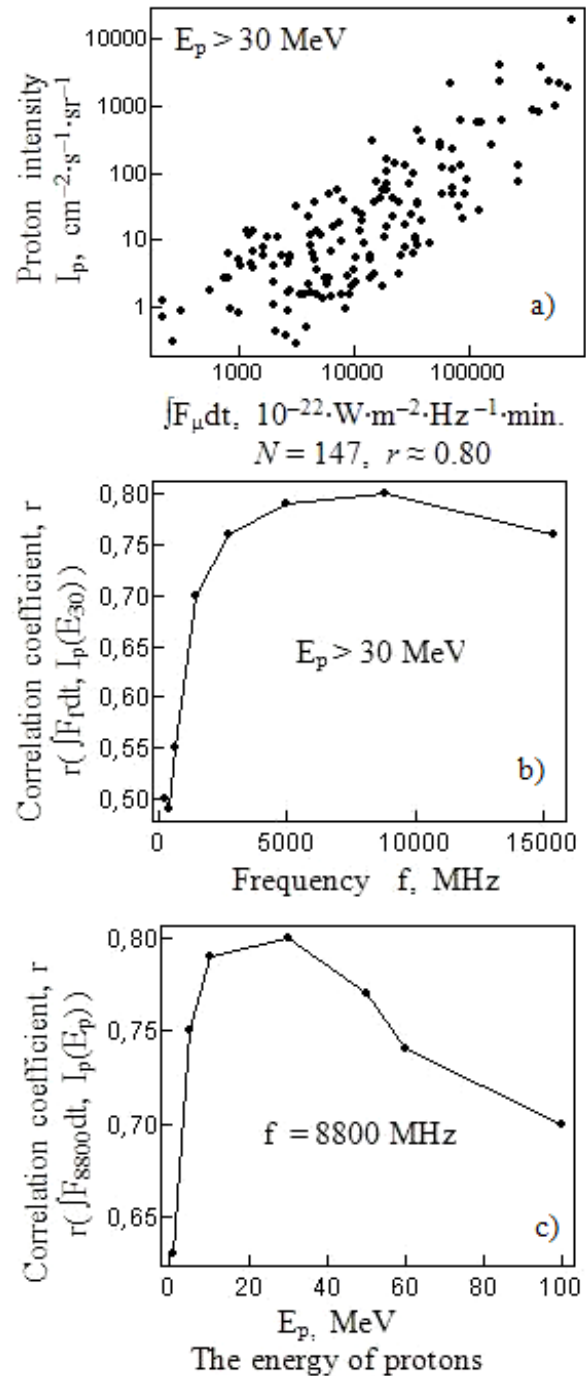


Figure 1 : The connection between the proton flux  $I_p$  and the integral flux  $\int F dt$  of the continuum radio bursts

protons  $E_p$ , see Fig. 1 c). The relationship between  $I_p$  and the integral flux of radio bursts  $\int F dt$  sharply decreases in the decimeter range and is practically absent in the meter range, see Fig. 1 b). The strongest connection between  $I_p$  and  $\int F dt$  is observed for the subrelativistic protons with energy  $E_p > 30$  MeV and the integral flux of  $\mu$ -bursts, see Fig. 1 c).

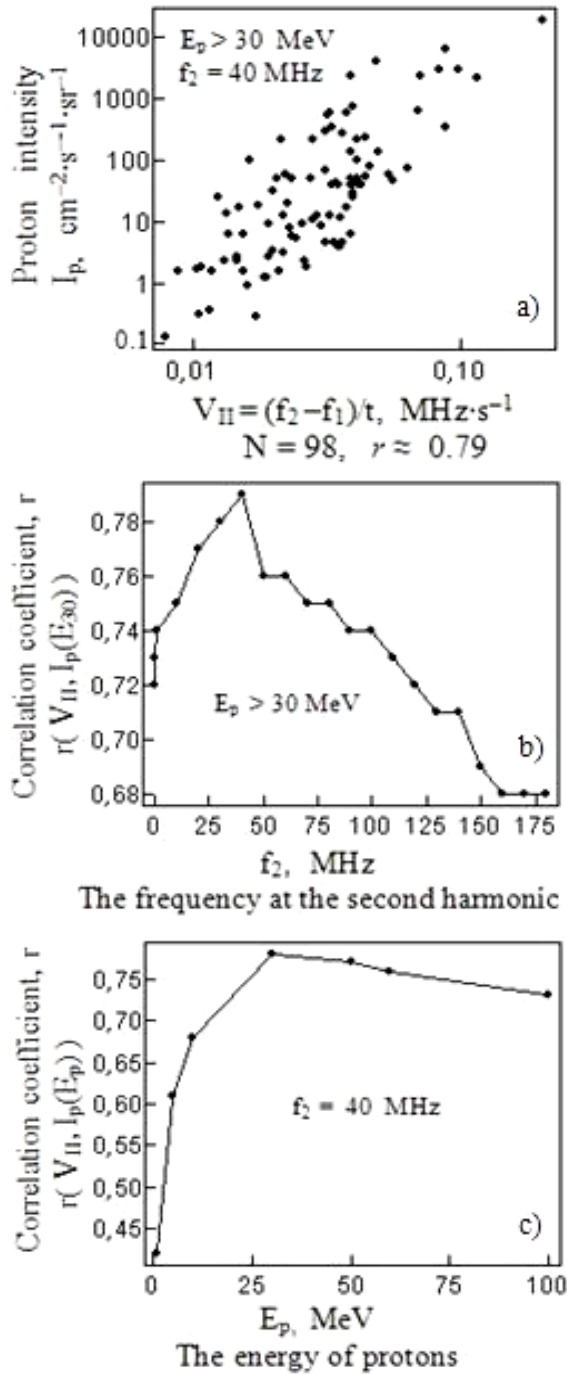


Figure 2 : The connection between the proton flux  $I_p$  and the parameter  $V_{II}$  of radio bursts of type II

### 3. Relationship between the intensity of the proton flux $I_p$ SCR and the parameters of radio bursts of type II in the range 25-180 MHz

The relationship between the intensity of the proton flux  $I_p$  of SCR and the parameters of radio bursts of type II in the range 25-180 MHz is studied. The sample under study contains 98 proton events for the period from 24-11-2000 to 20-12-2014. For the analysis, original records of dynamic spectra in the range 25-180 MHz from the solar radio spectrograph (SRS) were used (<http://www.ngdc.noaa.gov/stp/space-weather/solar-data/solar-features/solar-radio/rstn-spectral/>).

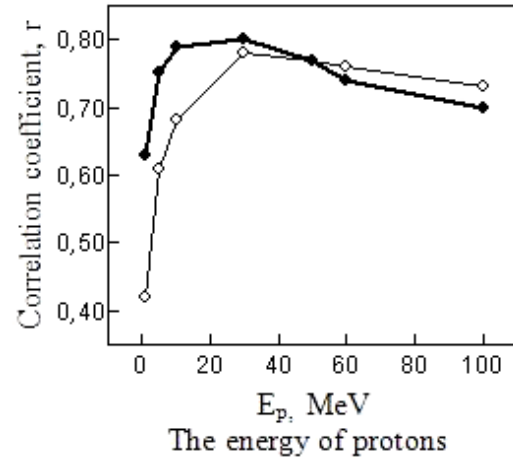


Figure 3 : Dependence of the correlation coefficient  $r$  between  $I_p$  and  $V_{II}$  (a thin line) and between  $I_p$  and the integral flux of microwave bursts  $\int F dt$  (a bold line) on the proton energy  $E_p$

In this paper, a new regression model was used to approximate the harmonics of the type II burst (1), where  $f_{i,j}$  - the frequency of the maximum of the type II burst on the given harmonic at a given time  $t$ ,  $i$  - the count number, and  $j$  - the number of the harmonic,  $a$  and  $b$  - a coefficients of linear regression.

$$\log_{10} f_{i,j} = a \cdot \sqrt{t} + b. \quad (1)$$

This dependence allows us to estimate the rate of frequency drift sufficiently accurately for 95% of type II bursts in the range 25-180 MHz, for which the correlation coefficient  $r$  between the observed and calculated values of the frequency  $r > 0.98$ . The zero point of time for all events corresponded to the beginning of the first harmonic at a frequency of 180 MHz.

Earlier in the work (Tsap & Isaeva, 2013) it was pointed out that there is a sufficiently strong connection between the proton flux  $I_p$  and the relative distance between the harmonics of the type II burst at a given instant  $t$ , where the correlation coefficient  $r$  between the investigated values of  $\approx 0.70$ , while the relationship between  $I_p$  and the drift velocity turned out to be low ( $r \approx 0.40$ ). However, it was noted that if when calculating the frequency drift velocity  $V_{II}$  (2), take into account the frequency distance between the harmonics of the type II burst at a given time  $t$ , then the relationship between  $I_p$  and parameter  $V_{II}$  increases sharply.

$$V_{II} = \frac{f_2 - f_1}{t}, \quad (2)$$

where  $f_1$  and  $f_2$  are the frequencies of the maximum of the type II burst at a given time  $t$  at the first and second harmonics, respectively. Time  $t$  is measured from the beginning of the second harmonic at a frequency of 180 MHz. In Fig. 2 a) shows the relationship between the proton flux  $I_p$  and the parameter  $V_{II}$  for protons with an energy  $E_p > 30 \text{ MeV}$  and an upper frequency  $f_2 = 40 \text{ MHz}$ . In Fig. 2 b) shows the dependence of the correlation coefficient between  $I_p$  and  $V_{II}$ , depending on the upper frequency  $f_2$ , and

in Fig. 2 c), depending on the energy of the protons  $E_p$ . In Fig. 2 b) and c) it is seen that the maximum correlation between the proton flux  $I_p$  and the parameter  $V_{II}$  is observed for the upper frequency  $f_2$  in the range 25-60 MHz and for protons with the energy  $E_p > 30$ -100 MeV. In Fig. 3 shows the relationship the intensity of the proton flux  $I_p$  with the parameter  $V_{II}$  (a thin line) and the integral flux  $\int F_{\mu} dt$  of microwave bursts (a bold line) as a function of the proton energy  $E_p$ . In Fig. 3), it is seen that the relationship of  $I_p$  with the parameter  $V_{II}$  and with the integral flux  $\int F_{\mu} dt$  of microwave bursts is approximately the same for protons with an energy  $E_p > 30$  MeV. However, the relationship of  $I_p$  with the parameter  $V_{II}$  decreases sharply for protons with an energy  $E_p < 30$  MeV, while the relationship  $I_p$  with the microwave flux  $\int F_{\mu} dt$  remains strong enough for protons with an energy  $E_p < 30$  MeV. It follows that the contribution of shock waves to proton acceleration is much higher for high-energy protons.

**4. Relationship between the intensity of the proton flux  $I_p$  and the velocity of coronal mass ejections  $V_{CME}$**

Almost all proton events are accompanied by coronal mass ejections (CME). Earlier in the work (Isaeva & Tsap, 2017) it was shown that there is a strong relationship between the speed of the CME  $V_{CME}$  and the integral flux of the continuum microwave bursts  $\int F_{\mu} dt$ . Moreover, the connection between the speed of the CME and the integral flux of the continual radio bursts of the IV type weakens with a decrease in the frequency of the burst of the IV type and is practically absent already in the meter-decameter range. The presence of a high correlation between the speed of the CME and the integral flux of microwave bursts during proton events indicates the flare origin of the CME. Such CMEs are formed in the region of flare energy release and are associated with the exit of high-energy particles into the interplanetary space. And so these CMEs have the strongest influence on space weather.

The sample studied contains 177 coronal mass ejections (CME) associated with proton events for the period from 04-11-1997 to 26-01-2015. For the analysis, tabular data of the CME velocity ([https://cdaw.gsfc.nasa.gov/CME\\_list/UNIVERSAL/text\\_ver/univ\\_all.txt](https://cdaw.gsfc.nasa.gov/CME_list/UNIVERSAL/text_ver/univ_all.txt)) was used. A comparative analysis showed that there is a fairly strong relationship between the intensity of the flux of the subrelativistic protons  $I_p$  and the velocity of the CME  $V_{CME}$ . In Fig. 4 a) shows the relationship between  $I_p$  with the proton energy  $E_p > 30$  MeV and the velocity of the CME, where the correlation coefficient  $r$  between the investigated quantities is  $\approx 0.72$ . In Fig. 4 b) shows the dependence of the correlation coefficient  $r$  between  $\int F_{\mu} dt$  and  $V_{CME}$  (thin line), as well as between  $\int F_{\mu} dt$  and  $I_p$  (bold line) from the frequency  $f$  of the continual radio burst type IV. In Fig. 4 c) shows the dependence of the correlation coefficient between  $I_p$  and  $V_{CME}$  (thin line), and also between  $I_p$  and the integral flux of microwave bursts  $\int F_{\mu} dt$  at 8800 MHz (bold line) from the energy of protons  $E_p$ . It is noteworthy that the connection between  $V_{CME}$  and  $I_p$  with  $\int F_{\mu} dt$  as a function of frequency  $f$  is very similar (see Fig. 4 b)). The same tendency is seen in Fig. 4c), where it is seen that the behavior of the relationship of the  $I_p$  with  $V_{CME}$  and with  $\int F_{\mu} dt$  as a function of the proton energy  $E_p$  is also very

similar. However, the relationship of  $I_p$  with  $V_{CME}$  is somewhat lower than  $I_p$  with  $\int F_{\mu} dt$ .

**5. Conclusion**

In this paper, on the basis of a new independent sample of proton events, the presence of a strong coupling between the intensity of the proton flux SCR  $I_p$  and the integral flux of microwave bursts  $\int F_{\mu} dt$  was confirmed. Also

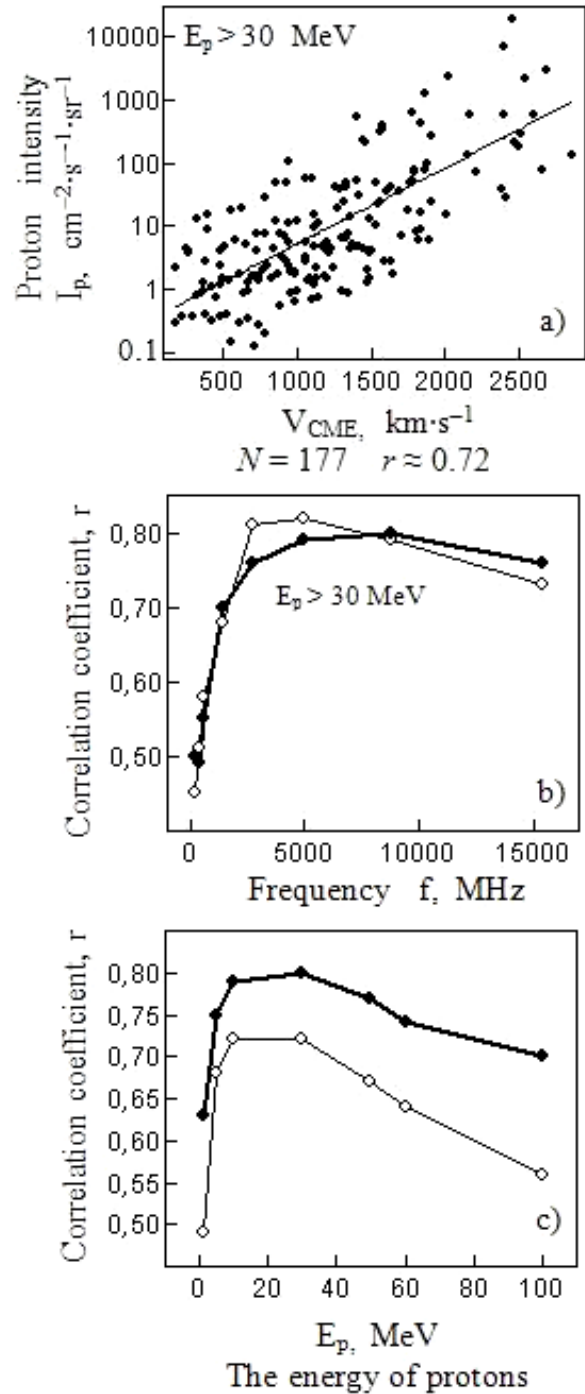


Figure 4 : The relationship between the proton flux and the CME

in this paper, arguments are given indicating the presence of a strong connection between the proton flux  $I_p$  and the frequency drift velocity  $V_{II} = (f_2 - f_1) / t$ , calculated with allowance for the frequency distance between the first and second harmonics of the type II burst at a given time  $t$ . It is shown that the relationship between the proton flux  $I_p$  and the parameter  $V_{II}$  depends to a large extent on the frequency of the maximum of the type II burst at the second harmonic  $f_2$  at a given time  $t$  and on the proton energy  $E_p$ . The maximum correlation between  $I_p$  and  $V_{II}$  is observed for protons with an energy  $E_p > 30-100$  MeV and in a narrow frequency range of values for the upper frequency  $f_2$  from 25 to 60 MHz. Also, for a large sample of CMEs associated with proton events, it is confirmed that there is a sufficiently strong connection between the proton flux  $I_p$  and the velocity of the CME, as previously reported (Grechnev et al., 2015).

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