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DIAGNOSTICS OF SOLAR PROTON EVENTS AND CORONAL SHOCK WAVES BY THE PARAMETERS OF SOLAR RADIO BURSTS OF TYPE II AND IV

E.A.Isaeva

Institute of Radio Astronomy of the NAS of Ukraine, *isaevaode@gmail.com*

ABSTRACT. This paper presents the results of a study of the relationship between solar cosmic rays (SCR) and coronal shock waves (CSW) with the parameters of solar microwave continuum radio bursts of type IV (μ–bursts), as well as with the parameters of type II radio bursts. A total of 349 solar proton events (SPE) were analyzed for the period from 03–02–1986 to 12–02–2018. For the analysis, we used original records of solar radio emission at 8 fixed frequencies in the range of 245–15400 MHz based on data from the Radio Solar Telescope Network (RSTN), original records of dynamic spectra from the SRS (Solar Radio Spectrograph) in the range of 25–180 MHz, tabular data for the velocity of coronal shock waves, as well as original records of the SCR proton flux intensity with proton energies E_p in the range of >1–100 MeV based on data from the GOES series devices.

It has been previously shown that for most proton events there is a strong relationship between the SCR proton flux and the parameters of type IV continuum microwave bursts, which indicates a dominant role of the SCR acceleration process in the flare region. However, as a result of recent detailed studies of the fine structure of type II radio bursts, a strong relationship was found between the intensity of the mid–relativistic SCR proton flux and certain parameters of type II radio bursts in the 25–180 MHz range. The presence of a strong relationship between the SCR proton flux and the parameters of type II radio bursts indicates an important role of SCR proton acceleration at the fronts of coronal shock waves. A fairly strong relationship was also found between the velocity of coronal shock waves and the parameters of type IV microwave bursts, which definitely indicates that coronal shock waves are associated with solar flares.

Keywords: proton events, proton flux intensity, type II radio bursts, coronal shock waves.

АНОТАЦІЯ. У цій роботі представлені результати дослідження зв'язку сонячних космічних променів (СКП) та корональних ударних хвиль (КУХ) з параметрами мікрохвильових континуальних радіосплесків IV типу, а також з параметрами радіосплесків II типу. Загалом було проаналізовано 349 сонячних протонних подій (СПП) за період із 03–02–1986 по 12–02–2018 роки. Для аналізу використовувалися оригінальні записи радіовипромінювання Сонця на 8 фіксованих частотах в діапазоні 245–15400 МГц за даними RSTN (Radio Solar Telescope Network), оригінальні записи динамічних спектрів з SRS (Solar Radio Spectrograph) в діапазоні 25–180 МГц, табличні дані корональних ударних хвиль, а також оригінальні записи інтенсивності потоку протонів СКП з енергією протонів у діапазоні >1–100 МеВ за даними апаратів серії GOES.

Раніше вже було показано, що для більшості протонних подій існує сильний зв'язок потоку протонів СКП з параметрами мікрохвильових континуальних сплесків IV типу, що вказує на домінуючу роль процесу прискорення СКП у спалахової області. Однак в результаті останніх детальних досліджень тонкої структури радіосплесків II типу також було виявлено сильний зв'язок між інтенсивністю потоку середньорелятивістських протонів СКП і певними параметрами радіосплесків II типу в діапазоні 25–180 МГц. Наявність сильного зв'язку потоку протонів СКП з параметрами радіосплесків II типу вказує на важливу роль прискорення протонів СКП на фронтах ударних корональних хвиль. Також було виявлено досить сильний зв'язок між швидкістю корональних ударних хвиль і параметрами мікрохвильових сплесків IV типу, що безумовно вказує на те, що корональні ударні хвилі пов'язані з сонячними спалахами.

Ключові слова: протонні події, інтенсивність потоку протонів, радіосплески II типу, корональні ударні хвилі.

1. Introduction

In this paper, we present the results of a comparative analysis of the relationship between SCRs and coronal shock waves (CSWs) with the parameters of type IV continuum radio bursts in the 245–15400 MHz range and with the parameters of type II radio bursts in the 25–180 MHz range. Previously, some issues regarding the relationship between the SCR proton flux and the parameters of type II radio bursts were considered in (Tsap & Isaeva, 2011; 2012; 2013). As a result of studying the relationship between the frequency drift velocity of meter-decameter type II bursts and the SCR proton flux intensity I_p of different energies, two families of proton events were discovered, which, according to Tsap (Isaeva & Tsap, 2011), suggests the generation of shock waves both in the region of flare energy release and by a moving coronal mass ejection (CME). The works (Isaeva & Tsap, 2011; 2012; 2013) present the results of the study of the efficiency of SCR acceleration by coronal and interplanetary shock waves, and also provide arguments in favor of the model of a two-stage process of proton acceleration (Wild et. al., 1963; Tsap & Isaeva, 2012). A comparative analysis showed that the acceleration of protons by coronal shock waves is more efficient than by interplanetary shock waves, and that the main acceleration of protons occurs in the flare region and additionally at the fronts of shock waves (Tsap & Isaeva, 2012).

2. The relationship between the intensity of the proton flux of the SCR I_p and the parameters of type IV microwave bursts

Previously, the relationship between the ntensity of the proton flux of solar cosmic rays I_p and various parameters of solar microwave bursts
of type IV (μ-bursts) was studied based on a large sample of proton events. The studied sample contained 143 proton events accompanied by solar continuous bursts of type IV for the period from 06–02–1986 to 14–10–2014.

Proton events were selected according to generally accepted criteria of protonity. It is known that for events with a *U*- or *W*-shaped type
of frequency radio spectrum of solar radio bursts with maxima in the meter and centimeter wavelength ranges and with a minimum in the decimeter range, the best correlation between the parameters of μ-bursts and the intensity of the flux of subrelativistic electrons and protons of solar cosmic rays is observed.

Previously, in the works (Isaeva, 2018; 2020), the relationship between the integral flux $\int F_f dt$ of type IV radio bursts at a given frequency *f* and the flux of SCR protons I_p with an energy of > 30 MeV was already investigated. It was shown that the maximum relationship between I_p and $\int F_f dt$ is observed for microwave bursts (μ-bursts) and for subrelativistic protons.

In this work, the relationship between the proton flux intensity I_p and three microwave burst parameters, namely the maximum value F_m , the rise time t_{rise} and the duration of type IV μ-bursts *t* at a frequency of 8800 MHz, was investigated simultaneously. Figures 1 a) and b) show the scattering diagrams between the proton flux and the μ-burst parameters F_m, and *t*, and Figure 1c) shows the scattering diagram between the calculated $I_{p,c}$ (1) and the observed values of the SCR proton flux I_p. A comparative analysis showed

$$\log_{10} I_{p,c} = 1.209 \cdot \log_{10} F_m + 0.725 \cdot \log_{10} t_\mu + 1.110 \cdot \log_{10} t_{rise} - 4.087 \qquad (1)$$

that the correlation coefficient *r* between the observed I_p and calculated values of the proton flux $I_{p,c}$ (1) is slightly higher ($r \approx 0.83$) than with the integral flux of μ-bursts $\int F_\mu dt$ at a frequency of 8800 MHz (Isaeva, 2018, 2020), where the correlation coefficient *r* between I_p and $\int F_f dt \approx 0.80$.

The presence of a strong connection between the SCR proton flux and the parameters of microwave radio bursts definitely indicates the acceleration of SCR protons in the flare region. However, there are many indications that shock waves also play an important role in the acceleration of solar cosmic rays (Gopalswamy et al., 2002; Cliver et al., 2004). In this regard, detailed studies of the fine structure parameters of type II radio bursts and their connection with SCRs were carried out.

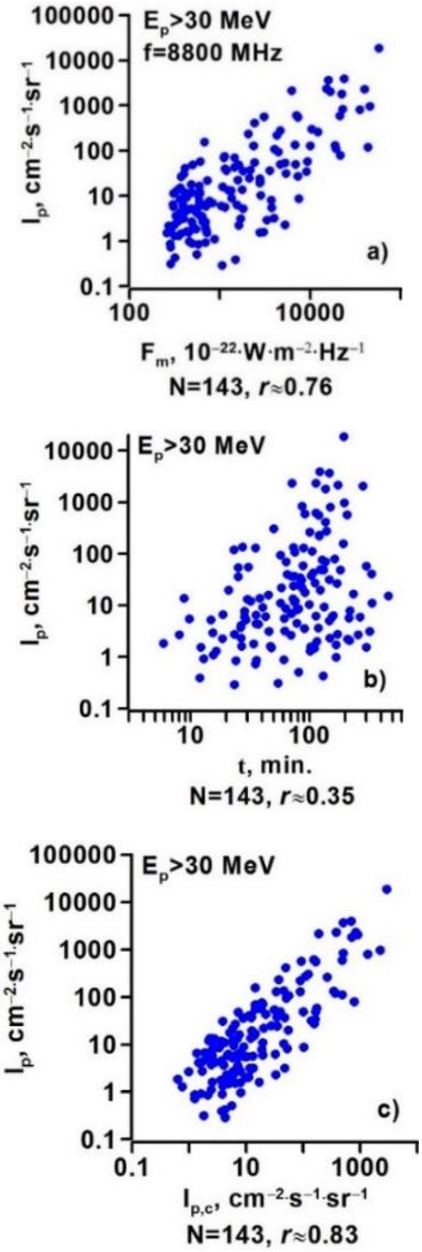

Figure 1: a). and b). Relationship of the proton flux of solar cosmic rays I_p with the parameters of μ-bursts F_m and *t*; c). scattering diagram between the calculated $I_{p,c}$ (1) and observed values of the intensity of the proton flux of solar cosmic rays I_p.

3. The relationship between the intensity of the proton flux I_p of the SCR and the parameters of type II radio bursts

The relationship between the proton flux intensity of the solar cosmic rays I_p and various parameters of type II radio bursts has been previously studied. As a result of these studies, a strong relationship was found between the proton flux intensity I_p and the parameters $f_{min,1}$ and V_{II} (Isaeva, 2019; 2020). In the present work, multiple correlation and regression analysis was used to study the relationship between the proton flux I_p simultaneously with three parameters $f_{min,1}$, V_{II} and λ (2),

$$\log_{10} I_{p,c} = -4.608 \cdot \log_{10} f_{min,1} + 1.707 \cdot \log_{10} V_{II} + 0.596 \cdot \log_{10} \lambda + 11.882 \quad (2)$$

$$b_{min} = \frac{f_{min,2} - f_{min,1}}{f_{min,1}} \quad (3)$$

$$V_{II} = \frac{f_2 - f_1}{t_i - t_0} \quad (4)$$

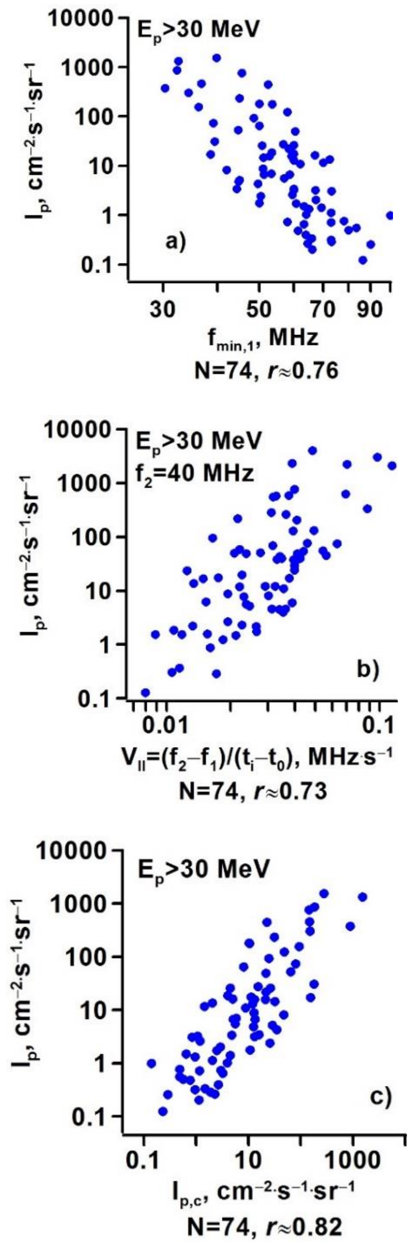

Figure 2: a). The relationship between the proton flux intensity I_p and the frequency $f_{min,1}$; b). The relationship between the proton flux intensity I_p and the parameter of type II radio bursts V_{II}; c). Scattering diagram between the observed I_p and calculated values of the proton flux intensity $I_{p,c}$ (2) with proton energy E_p > 30 MeV.

where $f_{min,1}$ is the frequency at the first harmonic at the time t_{min} of the minimum relative distance b_{min} (3) (Isaeva, 2019; 2020) between the harmonics of type II bursts, and V_{II} (4) (Isaeva, 2018; 2020) is a parameter that to some extent characterizes the shift of the shock front over time t_i, where f_1 and f_2 are the frequency of the type II burst at the 1-st and 2-nd harmonics, and λ is the heliolongitude attenuation coefficient of the solar cosmic ray proton flux I_p (Ochelkov, 1986).

Figures 2 a) and b) show the relationship of the SCR proton flux intensity I_p with the parameters $f_{min,1}$ and V_{II}, respectively. Figure 2a) shows that the relationship of I_p with $f_{min,1}$ and V_{II} is slightly worse than for the full sample in (Isaeva, 2020). This is due to the fact that in this case only those events were selected for which the parameters $f_{min,1}$ and V_{II} could be determined simultaneously with sufficient accuracy. Therefore, the results differ somewhat from the results presented in (Isaeva, 2020). But despite this, the relationship of I_p with three parameters $f_{min,1}$, V_{II} and λ is much higher (see Figure 2c) than with each parameter separately. Figure 2c) shows the scattering diagram between the calculated $I_{p,c}$ (2) and the observed values of the proton flux I_p.

As can be seen in Figure 2c), the correlation coefficient *r* has significantly increased from 0.73-0.76 to 0.82. The increase in the connection of I_p with two parameters $f_{min,1}$ and V_{II} also indicates that the parameters $f_{min,1}$ and V_{II} are closely related to each other.

4. The relationship between the intensity of the proton flux of SCR I_p and the integral flux of μ-bursts $\int F_\mu dt$ and with the parameter of type II radio bursts V_{II}

The discovered high correlation of the intensity of the proton flux of SCR I_p with the parameters of μ-bursts, as well as with the parameters of type II radio bursts, does not allow us to unambiguously answer the question of where and how the acceleration of SCR protons occurs.

In this connection, the connection between the intensity of the SCR proton flux I_p and three parameters (5) was investigated simultaneously, namely, with the integral flux of μ-bursts $\int F_\mu dt$ at a frequency f=8800 MHz, with the parameter V_{II} (4), which to some extent characterizes the displacement of the shock wave front over time t_i,

$$\lg I_{p,c} = 0.461 \cdot \lg \int f_\mu \, dt + 2.493 \cdot \lg V_{II} + 0.835 \cdot \lg \lambda + 3.216 \quad (5)$$

and with the coefficient of heliolongitudinal attenuation of the SCR proton flux λ (Ochelkov, 1986).

For this purpose, only those proton events were selected that were simultaneously accompanied by type IV microwave bursts at a frequency of 8800 MHz and type II radio bursts in the range of 25–180 MHz. Original records of solar radio emission were used for the analysis. The parameters $\int F_\mu dt$ and V_{II} were not chosen by chance, since it was previously shown that there is a strong connection between I_p and $\int F_\mu dt$ and V_{II} (Isaeva, 2018; 2020), where the correlation coefficient *r* between I_p and the parameters $\int F_\mu dt$ and V_{II} ≈ 0.80. Figure 3a) shows the scattering diagram between the integral flux of μ-bursts $\int F_\mu dt$ at a frequency of 8800 MHz and the intensity of the SCR proton flux I_p, and Fig. 3b) between the parameter V_{II} and I_p . In Fig. 3a) it is evident that for proton events for which a strong correlation between the proton flux I_p and the parameter of type II V_{II} radio bursts is observed (Fig. 3b), the correlation between I_p and the integral flux of μ-bursts $\int F_\mu dt$ turned out to be significantly worse ($r \approx 0.65$) compared to what was previously established based on a large sample of proton events (N = 147) (Isaeva, 2018; 2020), where the correlation coefficient r between $\int F_\mu dt$ and $I_p \approx 0.80$.

Thus, based on the obtained results, it can be concluded that for the overwhelming majority of proton events (and there were 147 of them), the main acceleration of SCR protons occurred in the flare region in current sheets, and for other proton events that were accompanied by meter-decameter type II bursts, the main acceleration of SCR protons occurred at the fronts of coronal shock waves. And therefore, for such events, a lower correlation is observed between the integral flux of microwave bursts $\int F_\mu dt$ and the flux of SCR protons I_p, where the correlation coefficient between $\int F_\mu dt$ and I_p does not exceed 0.65. But despite the fact that the connection of I_p with $\int F_\mu dt$ for such events is low, nevertheless, if we consider the connection of I_p simultaneously with three parameters $\int F_\mu dt$, V_{II} and the coefficient of heliolongitudinal attenuation of the proton flux of solar cosmic rays (5) (Ochelkov, 1986), then a significant increase in the connection between I_p and the studied parameters is observed, where the correlation coefficient r increases to ≈ 0.86 (Fig. 3c).

Figure 3c) shows the scatter diagram between the calculated $I_{p,c}$ values of the SCR proton flux intensity (5) and the observed I_p values. The significant increase in the correlation of $I_{p,c}$ with the parameters $\int F_\mu dt$ and V_{II} in model (5) indicates that the parameters $\int F_\mu dt$ and V_{II} are related, which in turn confirms the relationship between coronal shock waves and solar flares.

5. Relationship between coronal shock waves and parameters of type IV microwave radio bursts

It is known that shock waves can be generated by both solar flares and coronal mass ejections. It is believed that meter-wave type II bursts are associated with shock waves generated in flares (Wagner et al., 1983; Vrsnak et al., 1995), and bursts in the decameter-hectometer range are associated with the propagation of interplanetary shock waves generated by CMEs (Gopalswamy et al., 1998; Classen et al., 2002). The most reliable indicator of shock waves in the solar corona are slowly drifting type II bursts. It is believed that the plasma mechanism of radio emission is responsible for their generation (Cairns et al., 2003).

Further detailed studies showed that there is a certain connection between the parameters of microwave bursts IV and the parameters of bursts II type in the range of 25-180 MHz. The original records of dynamic spectra of radio emission of the Sun in the range of 25-180 MHz were used for the analysis.

$$\lg f_{i,j} = a_j \cdot \sqrt{t_i} + b_j \qquad (6)$$

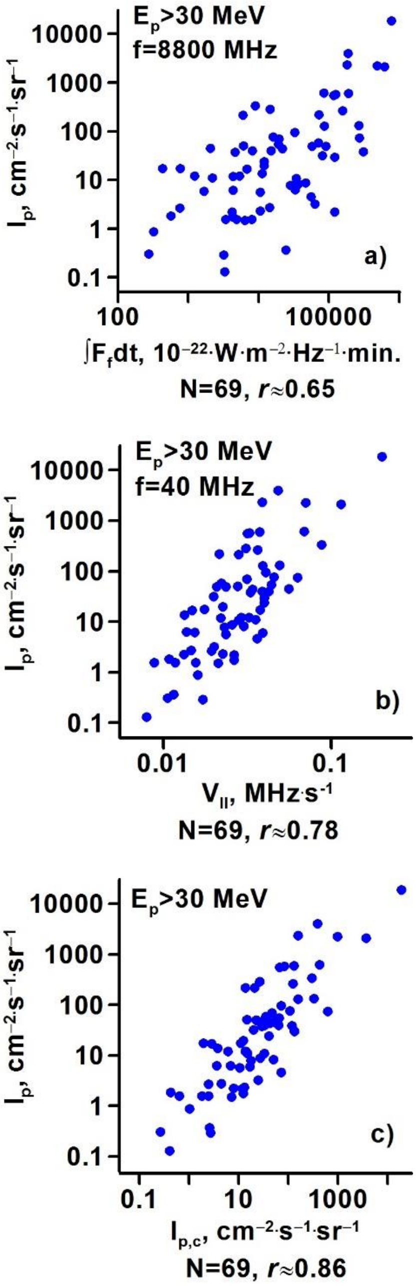

Figure 3: a). The relationship of the proton flux of solar cosmic rays I_p with the integral flux of μ-bursts. b). The relationship of I_p with the parameter of radio bursts of type II bursts. c). Scattering diagram between the calculated $I_{p,c}$ (5) and the observed values of the intensity of the proton flux of solar cosmic rays I_p.

Comparative analysis showed that there is a fairly strong relationship between the parameter a_j in the regression model (6) (Isaeva & Tsap, 2017) characterizing the decrease in the frequency drift rate of type II radio bursts in the range of 25–180 MHz and the rise time of t_{rise} μ-bursts at a frequency of 8800 MHz. The correlation coefficient r between t_{rise} and a_j is ≈ 0.68 (see Fig. 4a). Due to the fact that μ-bursts differ significantly in duration, the rise time of t_{rise} is expressed as a percentage of the duration of μ-bursts. In this case, the burst duration for each event was equal to 100%.

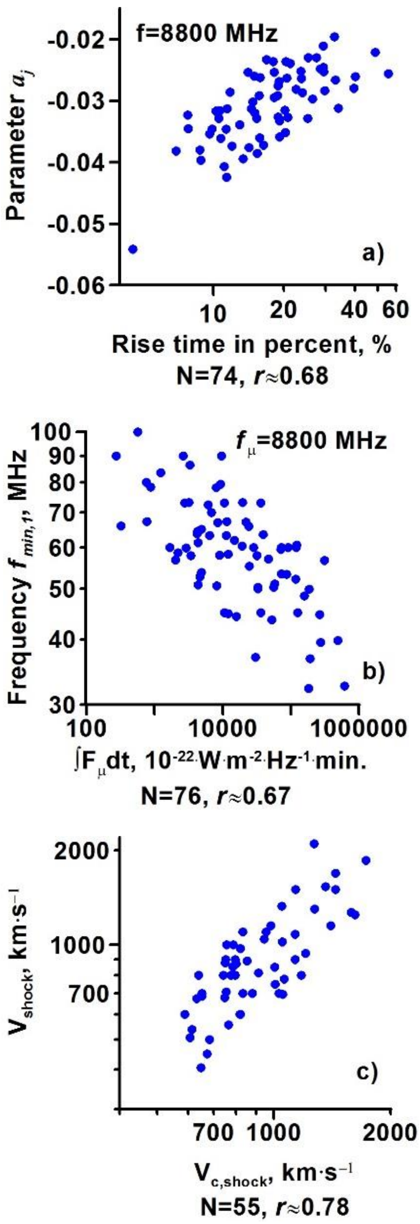

Figure 4: a). The relationship between the parameter a_j and the rise time t_μ of type IV microwave bursts at 8800 MHz; b). The relationship between the frequency $f_{min,1}$ and the integral flux $\int F_\mu dt$ of type IV microwave bursts at 8800 MHz; c). The scattering diagram between the calculated $V_{c,shock}$ (7) and the observed values of shock wave velocity V_{shock}

A fairly strong connection was also found between the integral flux of μ-bursts $\int F_\mu dt$ at a frequency of 8800 MHz and the value of the frequency $f_{1,min}$ at the 1-st harmonic at the moment of the minimum relative distance between the harmonics of type II bursts (3), where the correlation coefficient r between the studied parameters is ≈ 0.67 (see Fig. 4 b)).

$$\log_{10} V_{c,shock} = 0.197 \cdot \log_{10} F_m + 0.242 \cdot \log_{10} t_\mu - 0.243 \cdot \log_{10} t_{rise} + 2.111 \quad (7)$$

In the present work, the relationship between the coronal shock wave velocity V_{Shock} (tabular data) and various parameters of type IV radio bursts was also investigated. A comparative analysis showed that there is a strong relationship between the coronal shock wave velocity $V_{c,shock}$ and the parameters of microwave bursts (7) (see Fig. 4c), where F_m is the maximum value, t_μ is the duration and t_{rise} is the rise time of the μ-burst at a frequency of 8800 MHz, where the correlation coefficient r between the calculated $V_{c,shock}$ (7) and the observed values of shock waves V_{shock} is ≈ 0.78. In Fig. 4c), the number of events is significantly smaller (N=55) than in Fig. 4 a) and b). This is due to the fact that not all type II bursts have original records or estimated values for the coronal shock wave velocity V_{shock}.

The presence of a fairly strong connection between the parameters of type IV continuous microwave bursts and the parameters of type II meter-decameter bursts, as well as with the velocity of shock waves, definitely indicates that coronal shock waves are associated with flares, which is quite consistent with the results of other authors (Wagner et al., 1983; Vrsnak et al., 1995).

6. Conclusion

As a result of detailed studies, it was shown that for the overwhelming majority of proton events, the main acceleration of SCR protons occurs in the flare region and for such events, a strong relationship is observed between the proton flux and the parameters of type IV continuum microwave bursts. For the remaining part of the proton events, which were accompanied by type IV and type II radio bursts in the range of 25–180 MHz, the main or additional acceleration of SCR protons occurs at the fronts of coronal shock waves and for such events, a strong relationship is observed between the SCR proton flux and the parameters of type II radio bursts. It was also shown that for proton events, which were simultaneously accompanied by type IV and type II radio bursts, a sufficiently strong relationship is observed between the velocity of coronal shock waves and the parameters of type IV microwave bursts, which definitely indicates that coronal shock waves are generated by solar flares.

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