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THE RELATIONSHIP OF THE INTENSITY OF THE SCR PROTON FLUX WITH THE PARAMETERS OF TYPE II SOLAR RADIO BURSTS

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ABSTRACT. 112 solar proton events (SPEs) were processed for the period from November 24, 2000 to December 20, 2014, which were accompanied by type II radio bursts. For the analysis, used original records of solar radio emission from a solar radio spectrograph in the range of 25-180 MHz, as well as original records of the flux intensity proton of solar cosmic rays (SCR) protons I_p with energy E_p in the range > 0.8-850 MeV according to data from the GOES series of devices. In this case, superimposed proton events were always separated and identified with the corresponding solar proton flares, and the maximum proton flux intensity I_p of superimposed proton events was determined from the level of the previous proton event.

Based on data from the solar radio spectrograph, regression models were obtained for 91 type II bursts that established the relationship between the frequency drift velocity $V_{i,j}$ and the frequency of type II bursts $f_{i,j}$, and for 73 type II bursts it was possible to obtain regression models which established the relationship between the intensity of type II bursts $I_{i,j}$ and type II burst frequency $f_{i,j}$ in the range 25-180 MHz. Detailed studies have shown that the intensity of type II bursts $I_{i,j}$, as well as the frequency drift velocity $V_{i,j}$, strongly depends on the frequency of type II burst $f_{i,j}$ and monotonically changes with time t_i along the harmonics of type II bursts.

As a result, the relationship between the maximum values of the SCR proton flux intensity I_p and the calculated values of the frequency drift velocity $V_{i,j}$ and intensity of type II bursts $I_{i,j}$ was investigated. A comparative analysis showed that the relationship between the intensity of the SCR proton flux I_p and the intensity of type II bursts $I_{i,j}$ is much stronger than with the frequency drift velocity $V_{i,j}$, where the correlation coefficient r is 0.82 and 0.71, respectively, for protons with energies E_p > 30 MeV. The relationship between the proton flux intensity I_p and the frequency drift velocity $V_{i,j}$ and the intensity of type II bursts $I_{i,j}$ was also studied as a function of the proton energy E_p and the frequency $f_{i,j}$ of type II radio bursts. It was shown that the strongest relationship between the intensity of the SCR proton flux I_p with the frequency drift velocity V_i and with the intensity of type II bursts $I_{i,j}$ is observed with subrelativistic SCR protons with energies E_p in the range > 30-100 MeV and for type II radio bursts at a frequency $f_{i,j}$ in the range 40-160 MHz.

Keywords: Proton events, proton flux intensity, frequency drift velocity, type II burst intensity.

АНОТАЦІЯ. Опрацьовано 112 сонячних протонних подій (СПП) за період з 24.11.2000 по 20.12.2014 роки, які супроводжувалися радіосплесками II типу. Для аналізу використовувалися оригінальні записи радіовипромінювання Сонця з сонячного радіоспектрографа в діапазоні 25-180 МГц, а також оригінальні записи інтенсивності потоку протонів сонячних космічних променів (СКП) I_p з енергією E_p в діапазоні > 0.8-850 МеВ за даними з апаратів серії GOES. При цьому накладені протонні події завжди поділялися та ототожнювалися з відповідними сонячними протонними спалахами, а максимальна інтенсивність потоку протонів I_p накладених протонних подій визначалася від рівня попередньої протонної події.

За даними із сонячного радіоспектрографа для 91 сплеску II типу були отримані регресійні моделі, що встановлюють зв'язок між швидкістю частотного дрейфу $V_{i,j}$ і частотою сплеску II типу $f_{i,j}$, а також для 73 сплесків II типу вдалося отримати регресійні моделі, що встановлюють зв'язок між інтенсивністю сплесків II типу $I_{i,j}$ і частотою сплесків II типу $f_{i,j}$ у діапазоні 25-180 МГц. Детальні дослідження показали, що інтенсивність сплесків II типу $I_{i,j}$ як і швидкість частотного дрейфу $V_{i,j}$ сильно залежить від частоти сплеску II типу $f_{i,j}$ і монотонно змінюється з часом t_i вздовж гармонік сплесків II типу.

В результаті було досліджено зв'язок максимальних значень інтенсивності потоку протонів СКП I_p з розрахунковими значеннями швидкості частотного дрейфу $V_{i,j}$ та інтенсивності сплесків II типу $I_{i,j}$. Порівняльний аналіз показав, що зв'язок інтенсивності потоку протонів СКП I_p з інтенсивністю сплесків II типу $I_{i,j}$ значно сильніший, ніж зі швидкістю частотного дрейфу $V_{i,j}$ де коефіцієнт кореляції r дорівнює 0.82 і 0.71, відповідно для протонів з енергією E_p > 30 МеВ. Також було досліджено зв'язок інтенсивності потоку протонів I_p зі швидкістю частотного дрейфу $V_{i,j}$ та інтенсивністю сплесків II типу $I_{i,j}$ залежно від енергії протонів E_p та від частоти $f_{i,j}$ радіосплесків II типу. Було показано, що найбільш сильний зв'язок інтенсивності потоку протонів СКП I_p зі швидкістю частотного дрейфу $V_{i,j}$ і інтенсивністю сплесків II типу $I_{i,j}$ спостерігається з субрелятивістськими протонами СКП з енергією E_p в діапазоні > 30-100 MeV і для радіосплесків II типу на частоті $f_{i,j}$ в діапазоні 40 -160 МГц.

Ключові слова: протонні події, інтенсивність потоку протонів, швидкість частотного дрейфу, інтенсивність сплеску II типу.

1. Introduction

It is currently believed that solar cosmic rays (SCRs) can be accelerated either in the region of flare energy release or at shock wave fronts, which can be generated by both flares and coronal mass ejections (CMEs) (Reames, 1999). The results obtained to date do not allow us to draw an unambiguous conclusion about which acceleration process is dominant.

The presence of a strong connection between the flux of SCR protons and the parameters of microwave radio bursts (Akinyan et al., 1977, 1978; Chertok, 1982; Chertok et al., 1987; Melnikov, Epifanov, 1979; Melnikov et al., 1986, 1991; Isaeva, 2010, 2018, 2020) 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).

Previously, in works (Tsap & Isaeva, 2011, 2012, 2013), some questions regarding the connection between the flux of SCR protons and the parameters of type II radio bursts were considered. In the course of studies of the relationship between the frequency drift velocity of meter-decameter type II bursts and the intensity of the proton flux I_p of SCRs of different energies, two types of events were discovered, which, according to Tsap (Isaeva and Tsap, 2011), suggests the generation of shock waves both in the region of flare energy release and and a moving coronal mass ejection (CME). The works (Isaeva & Tsap, 2011; Tsap and Isaeva, 2012, 2013) present the results of a study of the efficiency of SCR acceleration by coronal and interplanetary shock waves, and also provide arguments in favor of a model of a two-stage proton acceleration process (Wild et al., 1963; Tsap & Isaeva, 2012). A comparative analysis showed that the acceleration of protons by coronal shocks is more effective than by interplanetary shocks, and that the main acceleration of protons occurs in the flare region and additionally at the shock wave fronts (Tsap & Isaeva, 2012).

A study of the fine spectral structure of meter-decameter radio bursts of type II showed that there is a fairly strong connection between the intensity of the proton flux and the relative distance $b_i = (f_{i2}-f_{i1})/f_{i1}$ between the 1-st and 2-nd harmonics of type II bursts at a given time t_i , where the correlation coefficient r between the studied values is $\approx$ 0.70, while the relationship between the frequency drift velocity V_i and the proton flux intensity I_p turned out to be weak, where the correlation coefficient r between I_p and V_i does not exceed ≈ 0.40 (Tsap & Isaeva, 2013) .

However, further studies of the fine spectral structure of meter-decameter radio bursts of type II in the range 25-180 MHz showed that if instead of the frequency drift velocity V_i we use the parameter $V_{II} = (f_2-f_1)/(t_i-t_0)$, which to some extent characterizes the speed of displacement of the shock wave front over time t_i, where f_1 and f_2 are the frequencies at the 1-st and 2-nd harmonics at a given time t_i, and t_0 is the start time of a type II burst at the 1-st harmonic at a frequency of 180 MHz, then there is a fairly strong connection between the proton flux intensity I_p and parameter V_{II}, where the correlation coefficient r between the studied parameters is ≈ 0.79 (Isaeva, 2018), which is quite comparable with what is obtained from the parameters of microwave bursts (Melnikov et al., 1991; Isaeva, 2018). It should also be noted that a strong relationship between the proton flux intensity I_p and parameter V_{II} is observed in a narrow frequency range of 25-60 MHz. Moreover, as a result of detailed studies of the fine structure of type II radio bursts, a number of features were discovered. It has been shown that the relative distance b_i between harmonics of type II radio bursts varies monotonically over time (Isaeva, 2019; Tsap, Isaeva, Kopylova, 2020). All 112 type II radio bursts are characterized by a monotonic decrease in the relative distance b_i between harmonics to a minimum value $b_{min,1}$ with a subsequent increase (Isaeva, 2019, 2020;). A strong relationship was also found between the intensity of the proton flux I_p and the frequency $f_{min,1}$ at the 1-st harmonic at the time of the minimum relative distance between the harmonics of a type II burst (Isaeva, 2018, 2019, 2020). Recent studies have also been related to the study of the fine structure of type II radio bursts in the range 25-180 MHz. As a result of these studies, a strong relationship was discovered between the proton flux intensity I_p and the frequency drift velocity $V_{i,2}$ and the intensity of type II bursts $I_{i,2}$ at the 2-nd harmonic of type II radio bursts.

2. Initial data

For the analysis, we used original recordings of the dynamic spectra of solar radio emission in the range of 25-180 MHz according to data from the Solar Radio Spectrograph (SRS) (http://www.ngdc.noaa.gov/stp/space-weather /solar-data/solar-features/solar-radio/rstn-spectral/), as well as original records of the proton flux intensity I_p of solar cosmic rays (SCR) with energy E_p in the range > 0.8-850 MeV according to data from the GOES series of devices (https://satdat.ngdc.noaa.gov/sem/goes/data/new_avg/).

3. Processing solar proton events

We processed 112 proton events associated with type II radio bursts for the period from November 24, 2000 to December 20, 2014. For the analysis, the maximum values of the proton flux intensity I_p with energy E_p > 0.8-850 MeV were used. Superimposed proton events were separated and identified with corresponding solar flares according to protonity criteria. Then, in each channel, the maximum intensity of the proton flux I_p from the pre-flare level was determined. For superimposed proton events, the proton flux intensity I_p was determined from the level of the previous proton event. Fig. 1 shows an example of the processing of overlaid proton events in April 2001.

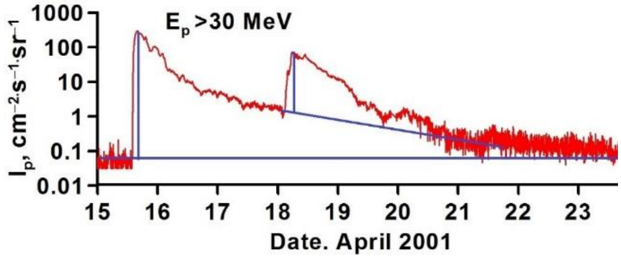

Figure 1: Example of processing superimposed proton events in April 2001

4. Processing of type II solar radio bursts in the range of 25-180 MHz

4.1. Determination of the frequency drift velocity $V_{i,j}$ of type II radio bursts

Harmonics of type II bursts were approximated using linear regression model (1)

$$\lg f_{i,j} = k1_j \cdot \sqrt{t_i} + k2_j\ , \tag{1}$$

where $f_{i,j}$ is the frequency at time t_i, $k1_j$ and $k2_j$ are linear regression coefficients, i=1…n – sample number, j=1,2 – harmonic number. Start timing for all events corresponded to the beginning of the first harmonic at 180 MHz. This model (1) gives a fairly good approximation for all 112 type II radio bursts (Isaeva, Tsap; 2017), which made it possible to study the dynamics of the parameters of type II radio bursts over time t_i. Therefore, having previously determined the coefficients $k1_j$ and $k2_j$ in the regression model (1), and then differentiated expression (1) by time t_i, it is possible to determine the instantaneous values of the frequency drift velocity $V_{i,j}$ (2) of type II bursts in any time t_i in the range 25-180 MHz (Tsap, Isaeva, Kopylova; 2023).

$$V_{i,j} = \frac{\ln 10}{2}\frac{k1_j f_{i,j}}{\sqrt{t_i}} = \frac{(k1_j \ln 10)^2}{2}\frac{f_{i,j}}{\ln f_{i,j} - k2_j \ln 10}\ . \tag{2}$$

4.2. Determination of the intensity of type II radio bursts $I_{i,j}$ in the range 25-180 MHz

Based on the original data from SRS, a dynamic spectrum was built on the computer screen, where all processing took place. Using two different linear regressions, which differed only in the values of the linear regression coefficients of type (1), the width of the 2-nd harmonic was limited, as shown in Fig. 2. When the harmonics of type II radio bursts were visible on the background of powerful continuum radiation of type IV, then the procedure was type IV burst filtering.

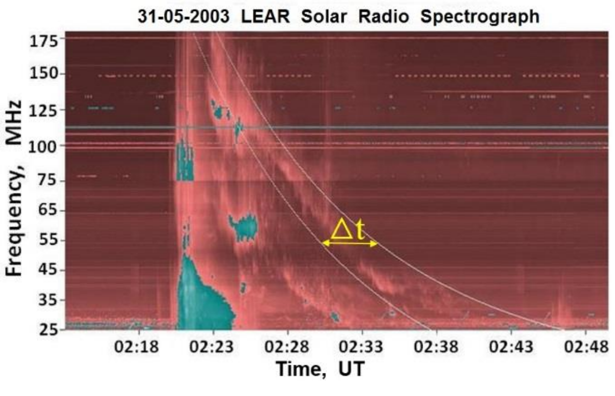

Figure 2: An example of identifying the width of the 2-nd harmonic of type II radio bursts

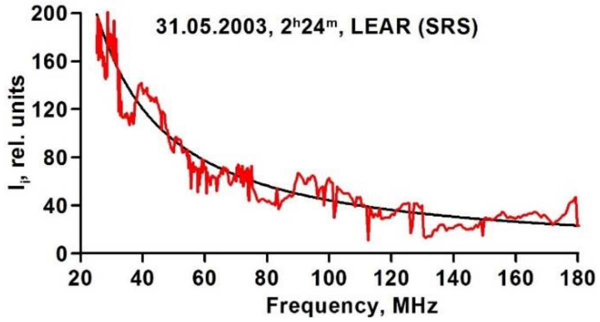

Figure 3: The observed intensity $I_{i,2}$ of a type II burst at the 2-nd harmonic is shown in red, and the calculated intensity in black.

Then, on the time interval Δt_i at a given frequency $f_{i,2}$ at the 2-nd harmonic, the maximum intensity values of the type II burst $I_{i,2}$ were determined. In Fig. 3 shows in red the observed values of the maximum intensity $I_{i,2}$ at a given frequency $f_{i,2}$ with filtering of type IV continuum radiation, and in black the calculated values of the intensity $I_{i,2}$ of a type II radio burst. As a result of this procedure, only 73 dynamic spectra out of 112 were processed, since against the background of a powerful continuum type IV burst it was not always possible to distinguish the width harmonic of a type II burst.

4.3. Relationship between frequency $f_{i,j}$ and intensity of type II radio bursts $I_{i,j}$ in the range 25-180 MHz

In order to understand how the intensity of type II bursts $I_{i,j}$ is related to the frequency $f_{i,j}$, a procedure was performed to average the intensity maxima of type II bursts $I_{i,j}$ at a given frequency $f_{i,j}$ for 73 bursts. The results of this procedure are shown in Fig. 4 a) and b) at the 1-st and 2-nd harmonics, respectively. In Fig. 4 a) and b) it is clear that when the harmonics of type II bursts go beyond the powerful continuum burst of type IV in the frequency range 25-50 MHz, then a clear relationship is visible between $I_{i,j}$ and $f_{i,j}$. In this regard, filtering of the continuum radiation of type IV bursts was performed.

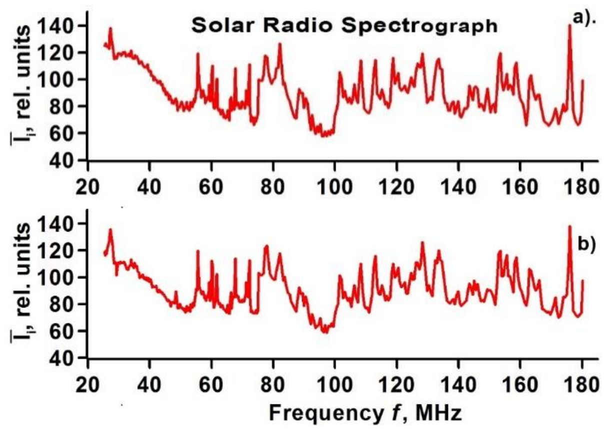

Figure 4: Averaged intensity values of type II bursts $I_{i,j}$ at a given frequency $f_{i,j}$ for 73 type II bursts at the 1-st (a) and 2-nd (b) harmonics, respectively

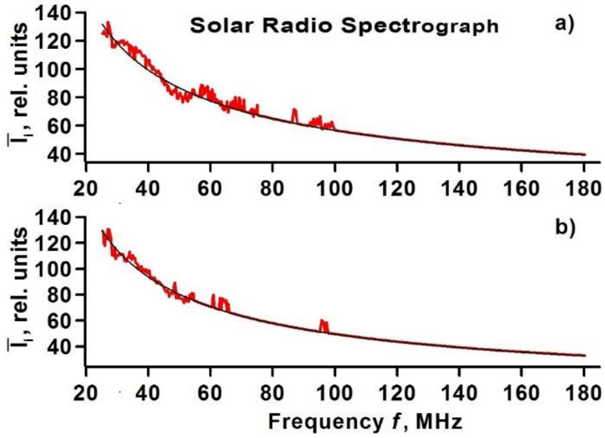

Figure 5: Averaged intensity values of type II bursts $I_{i,j}$ at a given frequency $f_{i,j}$ for 73 type II bursts after filtering type IV continuum radiation at the 1-st (a) and 2-nd (b) harmonics, respectively.

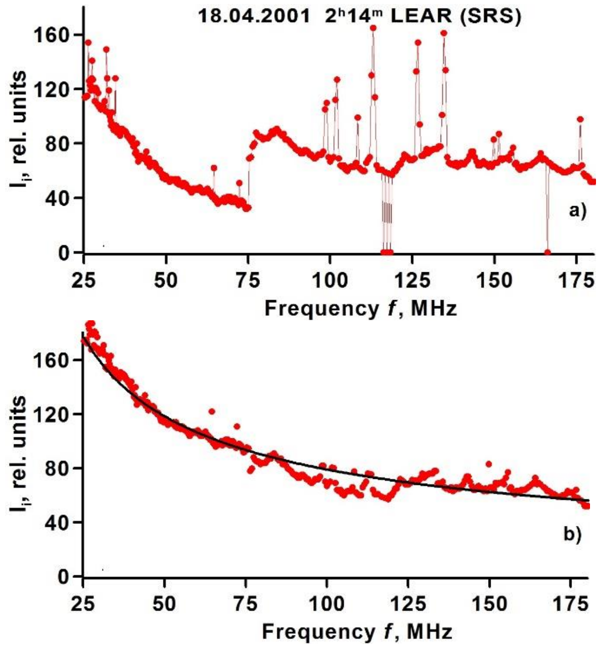

Figure 6: a) An example of a sharp gain reduction in the 25-75 MHz band is shown; b) An example of bringing the gain to one value is shown, as well as the result of filtering outliers and zero intensity values $I_{i,2}$ at the 2-nd harmonic.

In Fig. 5 a) and b) shows the dependence of the average intensity values of type II bursts $I_{i,j}$ after filtering the continuum radiation of type IV bursts on the frequency of type II bursts $f_{i,j}$.

In Fig. 5 a) and b) it is clear that the intensity of type II bursts $I_{i,j}$ strongly depends on the frequency of type II radio burst $f_{i,j}$, where the dependence of the intensity $I_{i,j}$ on the frequency $f_{i,j}$ can be quite accurately approximated by equation (3), where $k1_j$ and $k2_j$ – linear regression coefficients (3).

$$\lg I_{i,j} = k1_j \cdot \lg f_{i,j} + k2_j \tag{3}$$

4.4. Elimination of a gain jump when prcessing dynamic spectra, as well as filtering type IV continuum radiation

Fig. 6 a) shows an example of a sharp change in gain at the boundary of two frequency bands 25-75 and 75-180 MHz for the proton event of 04.18.2001, accompanied by a powerful type IV burst, as well as a type II burst according to data from LEAR (SRS), and Fig. 6 b) shows the procedure for bringing the gain in both bands to the same gain value, as well as filtering outliers, type IV continuum emission and zero values in the spectrum for the 2-nd harmonic of a type II burst.

5. Relationship between the intensity of the SCR proton flux I_p and the drift velocity $V_{i,2}$ and the intensity of type II bursts $I_{i,2}$ at the 2-nd harmonic in the range 25-180 MHz

A comparative analysis has shown that there is a fairly strong connection between the intensity of the SCR proton flux I_p and the frequency drift velocity $V_{i,2}$. In Fig. 7 a) shows a scatter diagram between the frequency drift velocity $V_{i,2}$ at a frequency $f_{i,2}$ = 70 MHz and the proton flux intensity I_p with energy E_p > 30 MeV for 91 proton events, where the correlation coefficient r between the studied parameters is ≈ 0.71. The black line in Fig. 7 a) shows the calculated values of the proton flux intensity $I_{p,c}$, calculated

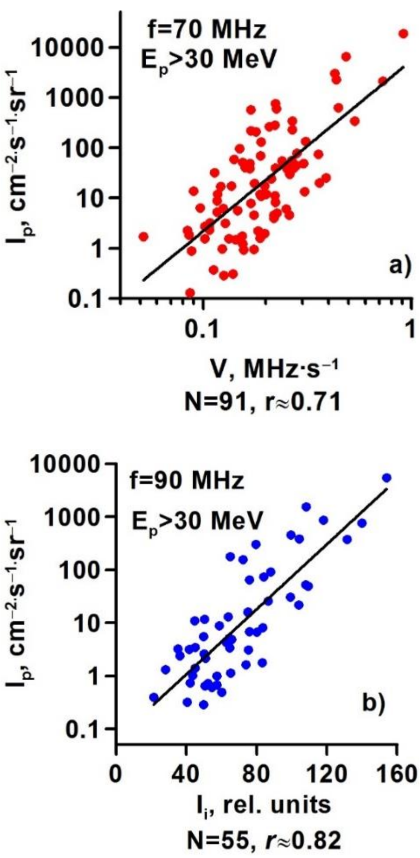

Figure 7: Dependence of the flux intensity of SCR protons I_p with energy E_p > 30 MeV on the frequency drift velocity $V_{i,2}$ (a) and the intensity of type II bursts $I_{i,2}$ (b).

using the regression model (4), which establishes a connection between the frequency drift velocity $V_{i,2}$ and the observed values of the proton flux intensity I_p with energy E_p > 30 MeV.

$$\lg I_p \approx \lg I_{p,c} = 3.4 \cdot \lg V_{i,2} + 3.7 \quad (4)$$

As a result of detailed studies of the relationship between the SCR proton flux and various parameters of type II radio bursts, a strong relationship was discovered between the intensity of the proton flux I_p and the intensity of type II bursts $I_{i,2}$. Moreover, the connection between I_p and $I_{i,2}$ is much stronger than with the frequency drift velocity $V_{i,2}$. In Fig. 7 b) shows a scatter diagram between the intensity of the proton flux with E_p >30 MeV and the intensity of type II bursts $I_{i,2}$ at a frequency $f_{i,2}$ = 90 MHz for 55 proton events, where the correlation coefficient r between I_p and $I_{i,2}$ is approximately 0.82. The black line in Fig. 7 b) shows the calculated values of the proton flux intensity $I_{p,c}$, calculated using the regression model (5), establishing a relationship between the intensity of type II bursts $I_{i,2}$ and the observed values of the proton flux intensity I_p with energy E_p > 30 MeV.

$$\lg I_p \approx \lg I_{p,c} = 0.031 \cdot I_{i,2} - 1.196 \quad (5)$$

It should be noted that when studying the connection between I_p and $I_{i,2}$, the heliolongitudinal attenuation of the proton flux was not taken into account, since taking into account the heliolongitudinal attenuation coefficient leads to a decrease in the correlation between I_p and $I_{i,2}$, while taking into account the heliolongitudinal attenuation between I_p and $V_{i,2}$ leads to an increase in the correlation. It was not possible to establish the reason for the decrease in the correlation between the proton flux I_p and the intensity of type II burst $I_{i,2}$ taking into account the heliolongitudinal attenuation coefficient of the proton flux.

The relationship between the intensity of the SCR proton flux I_p and the frequency drift velocity $V_{i,2}$ and the intensity of type II bursts $I_{i,2}$ was also studied depending on the proton energy E_p in the range >1-850 MeV and on the frequency of type II radio bursts $f_{i,2}$ in the range 25- 180 MHz. A comparative analysis showed that the relationship between the SCR proton flux I_p and the frequency drift velocity $V_{i,2}$ and the intensity of type II bursts $I_{i,2}$ largely depends on the proton energy E_p (Fig. 8 a). In Fig. 8 a) red color indicates the dependence of the correlation coefficients r between I_p and $V_{i,2}$, and blue color between I_p and $I_{i,2}$. In Fig. 8 a) it is clear that the strongest connection between I_p and $V_{i,2}$ and $I_{i,2}$ is observed for subrelativistic protons with E_p >30-100 MeV and sharply decreases for protons with energy E_p >850 MeV.

If we consider the relationship between the intensity of the proton flux I_p with $V_{i,2}$ and $I_{i,2}$ from the frequency of the type II radio burst $f_{i,2}$ in the range 25-180 MHz, then as can be seen in Fig. 8 b) the connection I_p with $V_{i,2}$ and $I_{i,2}$ remains almost constant. The sharp drop at low frequencies $f_{i,2}$ < 30 MHz is due to the fact that at the edges of the spectrum it is not possible to accurately determine the behavior of the regression model (6), which was obtained from data in the range 25-180 MHz. In order to obtain a more accurate model (6), data is needed at frequencies <25 MHz and >180 MHz. Thin lines in Fig. 8 a) and b) show the dependences of the correlation coefficients I_p with $V_{i,2}$ and $I_{i,2}$ on the energy E_p and on the frequency $f_{i,2}$ without taking into account the heliolongitudinal attenuation of the SCR proton flux.

6. Conclusion

The results obtained related to the study of the relationship between the intensity of the flux of SCR protons and the frequency drift velocity and intensity of type II bursts definitely indicate the important role of coronal shock waves in the acceleration of subrelativistic SCR protons. However, a sharp decrease in the relationship between the intensity of the flux of SCR protons I_p with energy E_p > 850 MeV with the frequency drift velocity $V_{i,2}$ and the intensity of type II bursts $I_{i,2}$ indicates that high-energy SCR protons with energy E_p > 850 MeV are probably accelerated in the flare region in current layers.

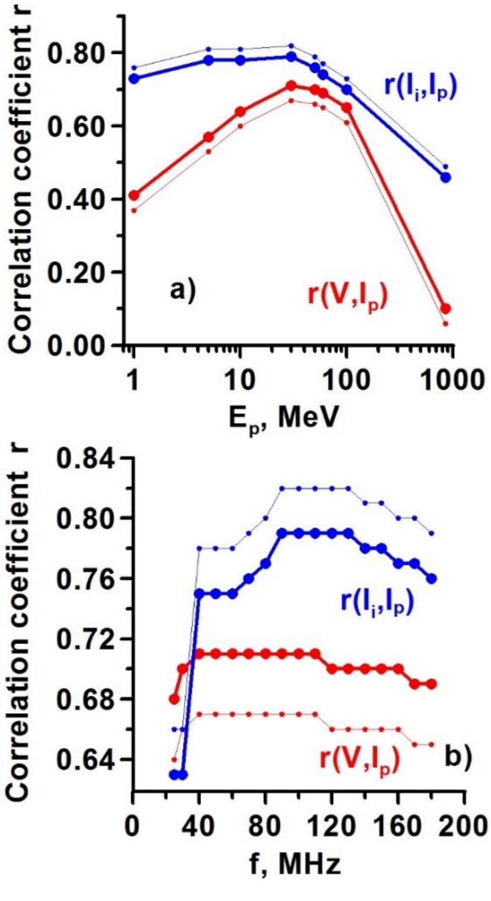

Figure 8: a) Relationship between the intensity of the proton flux I_p and the frequency drift velocity $V_{i,2}$ (red) and the intensity of type II bursts $I_{i,2}$ (blue) from the proton energy E_p; b) Relationship between the proton flux intensity I_p and the frequency drift velocity $V_{i,2}$ (red) and with the intensity of type II bursts $I_{i,2}$ (blue) from the type II radio burst frequency $f_{i,2}$. Thin lines show the values of the correlation coefficients without taking into account the heliolongitudinal weakening of the SCR proton flux.

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