

## SUN, SOLAR ACTIVITY AND ASTROBIOLOGY

DOI: <http://dx.doi.org/10.18524/1810-4215.2018.31.144543>

## NEW APPROXIMATION OF THE ENERGY SPECTRUM OF PROTON SCR

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**ABSTRACT.** In this paper, we consider a new approximation of the integrated energy spectrum of protons of solar cosmic rays (SCR) in the range  $E_p > 1-100$  MeV. The sample studied contains 342 proton events for the period from 03-02-1986 to 23-07-2016. This sample is complete, since it contains very weak and superimposed proton events. The superimposed events were separated and identified according to the criteria of protonity. Out of 342 proton events, 164 events were identified and processed by the author independently. For the analysis, original records of the intensity of the proton flux with energy  $E_p > 1-100$  MeV from the spacecraft GOES series were used. As the parameter characterizing the intensity of the proton flux, the maximum intensity of the proton flux  $I_p$  in each energy channel during the proton event was chosen. The intensity of the proton flux  $I_p$  was calculated from the preflare level. In the case of superposition of proton events, the intensity of the proton flux  $I_p$  was calculated from the level of the preceding event. Also, when processing original records of proton events, emissions associated with technical interference and with the of interplanetary shock waves were eliminated. Comparative analysis showed that all events can be conditionally divided into 5 types according to the form of the energy spectrum of protons. It is known that for most proton events, the energy spectrum of SCR protons is described quite accurately by two power-law models. However, there remains a large number of events for which the energy spectrum of protons can not be approximated accurately by two power-law models. In connection with this, another dependence was used in this work, which allows us to approximate the energy spectrum of the protons for all events quite accurately.

**АБСТРАКТ.** У даній статті розглядається нова апроксимація інтегрального енергетичного спектра протонів сонячних космічних променів (СКП) в діапазоні  $E_p > 1-100$  MeV. Досліджувана вибірка містить 342 протонних подій за період з 03-02-1986 по 23-07-2016 року. Дана вибірка є повною, оскільки містить дуже слабкі і накладені протонні події. Накладені події поділялися і ототожнювалися відповідно до критеріїв протонності. З 342 протонних подій 164 події були ототожені і оброблені автором самостійно. Для аналізу були використані оригінальні записи інтенсивності потоку протонів з енергією  $E_p > 1-100$  MeV з космічних апаратів серії GOES. Як параметр, що характеризує інтенсивність потоку протонів, було вибрано максимальне значення інтенсивності потоку протонів

$I_p$  в кожному енергетичному каналі під час протонної події. При цьому інтенсивність потоку протонів  $I_p$  обчислювалася від рівня перед спалахом. У разі накладення протонних подій інтенсивність потоку протонів  $I_p$  обчислювалася від рівня попередньої події. Також при обробки оригінальних записів протонних подій виключалися викиди, пов'язані з технічними перешкодами і з накладенням міжпланетних ударних хвиль.

Порівняльний аналіз показав, що всі події можна розділити умовно на 5 типів за формою енергетичного спектру протонів. Відомо, що для більшості протонних подій енергетичний спектр протонів СКП досить точно описується двоступеневими моделями. Однак залишається велика кількість подій, для яких енергетичний спектр протонів неможливо точно апроксимувати двоступеневими моделями. У зв'язку з цим в цій роботі була використана інша залежність, що дозволяє досить точно апроксимувати енергетичний спектр протонів для всіх подій.

**Keywords:** Proton events, energy spectrum of protons, intensity of the proton flux.

## 1. Introduction

The spectrum of solar cosmic rays (SCR) for most solar proton events can overlap 4-5 orders of magnitude in energy from 1 MeV to  $\geq 10-100$  GeV. The difference in intensities at the edges of the spectrum, due to the large steepness of the spectrum in the high-energy region, can reach 6-8 orders of magnitude (Miroshnichenko, 2000). And this creates certain difficulties in the approximation and interpretation of the observed energy spectra of proton events. In narrow energy intervals, SCR researchers most often use power-law and exponential functions to approximate the energy spectrum of SCR protons. Sometimes a more complex representation of the spectra is used in the form of a combination of a power-law and exponential function with a cutoff of the energy spectrum (Akin'ian et al., 1983; Ellison et al., 1985), and also a spectrum representation by two power-law functions with a inflection point at a certain energy (Band et al., 1993; Mewaldt et al., 2005; 2006; 2012). The variety of models for approximating the SCR spectra indicates that the formation of a spectrum taking into account the conditions at the source and taking into account transport effects in interplanetary space can not be accurately described by simple relations.

In this connection, attempts are being made to empirically represent the spectrum from the observed values of the proton flux over a wide energy range. In reality, it is very difficult to obtain the true spectrum of accelerated protons in the source (Miroshnichenko, 2014; 2018). The influence of propagation effects of accelerated protons in interplanetary space leads to a large variety of spectra in form and intensity.

## 2. Initial data and methods for processing proton events

For the analysis, we used the original records of the intensity of the proton flux  $I_p$  with the energy  $E_p$  in the range  $E_p > 0.8-100$  MeV from data from apparatuses of the GOES series ([https://satdat.ngdc.noaa.gov/sem/goes/data/new\\_avg/](https://satdat.ngdc.noaa.gov/sem/goes/data/new_avg/)), and also a list of solar proton events (SPE). The sample studied contains 342 proton events for the period from 03-02-1986 to 23-07-2016. This sample is complete, since it contains almost all events registered for the specified period, including very weak events and superimposed events, which were separated and identified by the author independently. In this connection, errors associated with the separation and identification of proton events are possible. In this sample of 342 SEP 164 events were identified by the author, and the remaining events are present in the SEP directory (<ftp://ftp.swpc.noaa.gov/pub/indices/SPE.txt>). For all these events, an attempt was made to find a single empirical dependence of the proton flux intensity  $I_p$  on the proton energy  $E_p > 0.8-100$  MeV. To this end, original records of the intensity of the proton flux  $I_p$  with the energy  $E_p$  in the range  $E_p > 0.8-100$  MeV for all 342 proton events were processed. As a parameter characterizing the proton flux, the maximum intensity of the proton flux  $I_p$  of a given energy was chosen during the proton event. The value of the  $I_p$  parameter was calculated from the preflare level. In the case of superposition of proton events, the value of  $I_p$  was calculated from the level of the previous proton event. Emissions associated with interference and with the imposition of shock waves were also eliminated.

## 3. Types of integral energy spectra of protons SCR in the range $E_p > 1-100$ MeV and their approximation

After calculating the maximum values of the proton flux  $I_p$ , the observed integral energy spectra of protons for all proton events were constructed and analyzed in each energy channel. A comparative analysis showed that all proton events can be conditionally divided according to the form of the observed energy spectrum into 5 characteristic types, see Fig. 1 (left). The observed values of the intensity of the proton flux in Fig. 1 (on the left) are indicated by black badges, the fine black line shows the calculated values of  $I_p$  calculated using the regression model (1), where  $a$ ,  $b$ ,  $c$  and  $d$  are the coefficients of the regression model (1). The coefficients of the regression model were calculated using the method of least squares. This functional (1) contains three functions (2-4) and allows us to estimate the intensity of the proton flux  $I_p$  with the

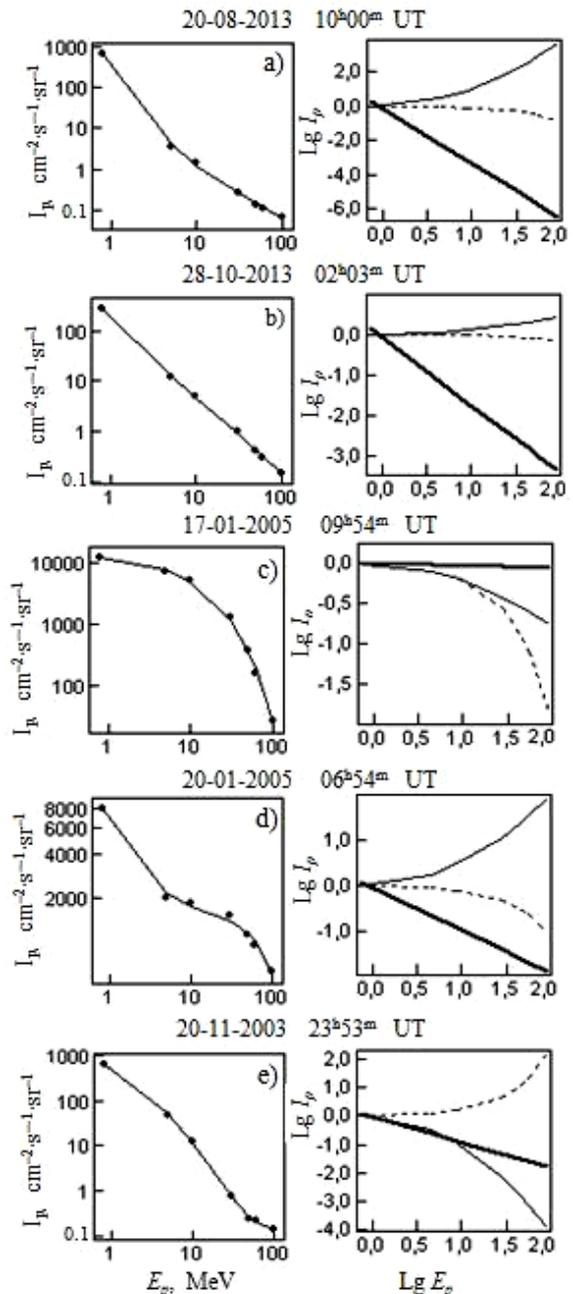


Figure 1: Types of spectra and their approximations

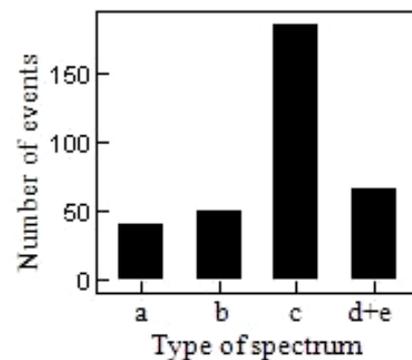


Figure 2: Histogram of the distribution of events with this type of spectrum

$$I_p = 10^d \cdot E_p^a \cdot 10^{bE_p} \cdot 10^{c \cdot (\log_{10} E_p)^2} \quad (1)$$

$$I_p = E_p^a \quad (2)$$

$$I_p = 10^{bE_p} \quad (3)$$

$$I_p = 10^{c \cdot (\log_{10} E_p)^2} \quad (4)$$

$$I_p = 10^d \cdot E_p^a \cdot e^{bE_p} \quad (5)$$

energy  $E_p$  in the range  $E_p > 0.8-100$  MeV quite accurately. This functional is obtained exclusively empirically and this is its main drawback, since it is impossible to estimate the real contribution of these or those mechanisms to the acceleration of SCR protons. But nevertheless, this functional allows us to estimate the contribution of a parameters (2-4) in the functional (1) to the observed intensity of the proton flux  $I_p$ . In Fig. 1 (right) shows the contribution of each parameter to the intensity of the proton flux. For convenience, the values of the logarithms  $E_p$  and  $I_p$ , respectively, are plotted along the X and Y axes. In Fig. 1 (right) shows that for events having different characteristic types of spectra, a different contribution of the parameters (2-4) in the functional (1) to the intensity of the proton flux is observed.

Thus, in Fig. 1 b) (right), it is clear that the main contribution to the proton flux  $I_p$  comes from processes that are described by a power-law function (2) (a thick line), while the contribution of the remaining parameters is insignificant. For events with the characteristic type of the spectrum in Fig. 1 c) (on the right), on the contrary, the main contribution is made by processes described by exponential functions, denoted by a dashed (3) and thin solid line (4). While the contribution from the power-law function (2) is insignificant and constant. For events having a combined type of spectrum, see Fig. 1 d) and e) (right), the processes described by the three parameters (2-4) contribute to the observed proton flux. In Fig. 2 shows a histogram of the distribution of the number of events with a given type of energy spectrum of protons SCR. The X-axis shows the type of the spectrum. On the histogram, events having the type of the spectrum d) and e) in Fig. 2 are summed. Figure 2 shows that more than half of all proton events have the type of spectrum shown in Fig. 1c).

Convinced that the regression model (1) gives a fairly good approximation of the SCR proton flux for 5 events with the characteristic types of observed spectra, proton fluxes for all 342 proton events were calculated. In Fig. 3 shows the scattering diagrams between the observed and calculated values of the proton flux with energy in the range  $E_p > 5-100$  MeV. The X and Y axes show the calculated and observed values of the proton flux  $I_p$ , respectively. Figure 3 shows that the regression model (1) gives a fairly good approximation for all 342 proton events.

#### 4. Comparison and discussion of the results

It was noted above that the functional (1) is purely empirical and does not allow us to estimate the real contribution of these or other mechanisms (processes) to the acceleration of SCR protons. Therefore, it is advisable to compare

the calculated values of the intensity of the proton flux with the help of the functional (1) and standard functionals, which predict the models of the proton acceleration of SCR. For comparison, a functional containing the power-law and exponential function (5) was chosen.

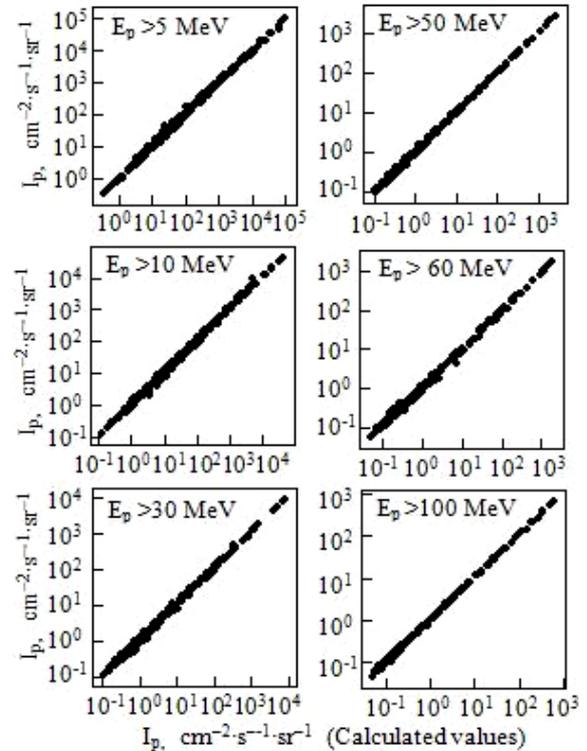


Figure 3: Diagrams of scattering between observed and calculated values of  $I_p$

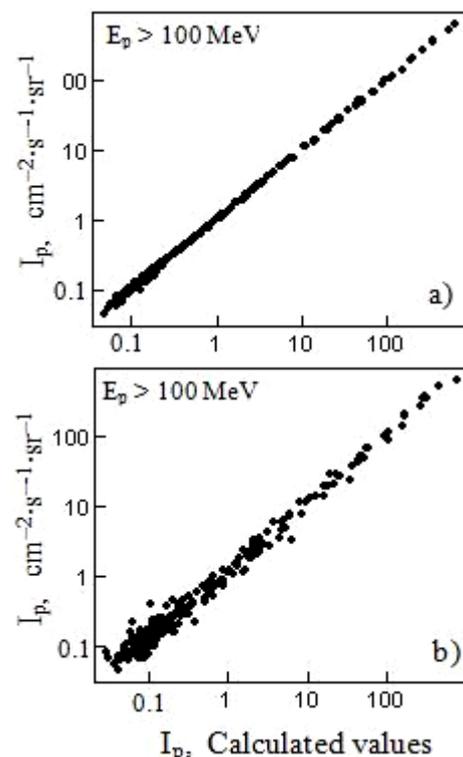


Figure 4: Diagrams of scattering between observed and calculated values of  $I_p$

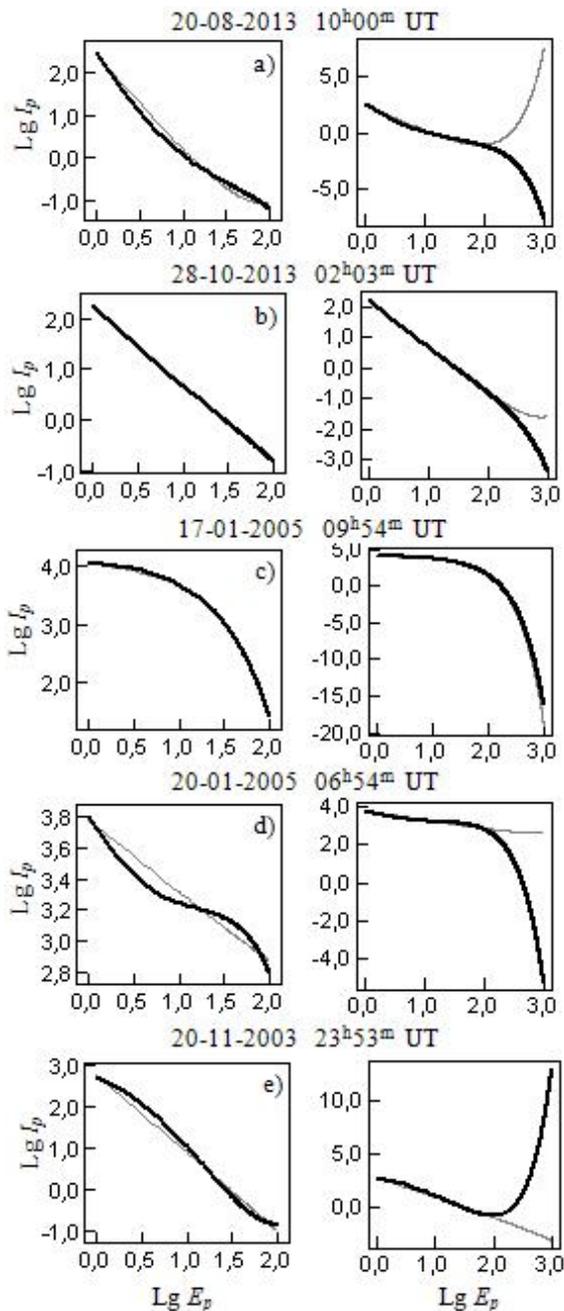


Figure 5: A comparison of the dependences of  $Lg I_p$  on  $Lg E_p$  in the range  $E_p > 1-1000$  MeV obtained with the help of the functionals (1) and (5)

In Fig. 4 a) and b) are diagrams of the scattering between the observed and calculated values of the proton flux with energy  $E_p > 100$  MeV, calculated with the help of the functionals (1) and (5). In Fig. 4b), it is seen that for the values of the proton flux calculated with the help of the functional (5), there are quite large deviations between the calculated and observed values of the intensity of the proton flux, while for the values of the proton flux calculated with the help of the functional (1), the calculated and observed values of the proton flux practically coincide.

It is known that the behavior of the limiting integral empirical spectrum (Mirishnichenko et al., 1994; 1996; 2013;) and the limiting physical spectrum (Struminsky, 2015) of SCR protons significantly differs at the spectral

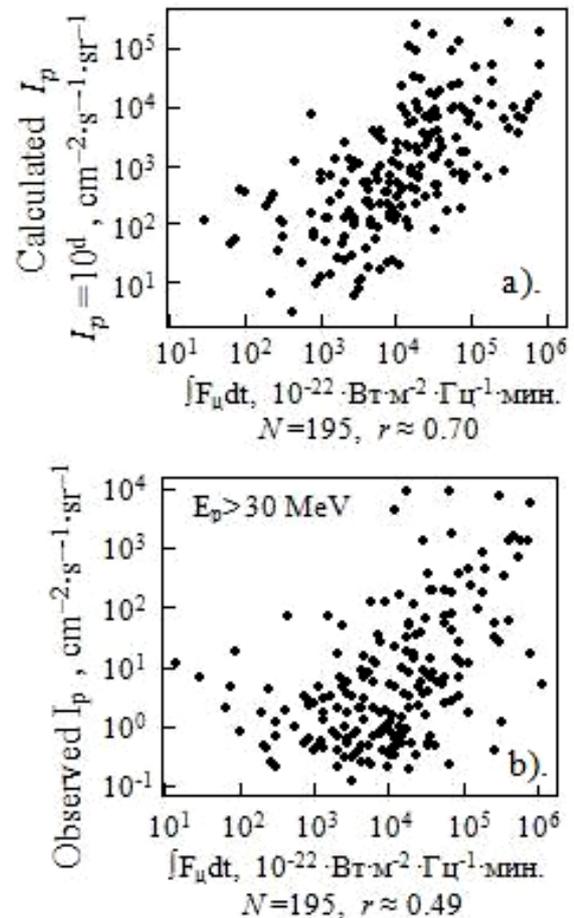


Figure 6: The relationship  $I_p$  and parameter  $10^u$  with the integral flux of microwave bursts  $[F_p dt]$

edges in the region of low energies and in the region of relativistic energies. In this connection, the behavior of the functionals (1) and (5) for protons with energy in the range  $E_p > 1-1000$  MeV was investigated. Comparative analysis showed that for protons with energies in the range  $E_p > 1-100$  MeV, both functionals give a fairly good agreement between the calculated values of  $I_p$  for the 5 characteristic types of the spectrum, see Fig. 5 (left). However, for protons with energies  $E_p > 100-1000$  MeV, considerable deviations are observed between the calculated values of the proton flux calculated with the help of the functionals (1) (black bold line) and (5) (gray thin line), see Fig. 5 (right). In this figure, for proton events with characteristic types of the spectrum a), b) and d), the calculated values of the proton flux  $I_p$  increase with increasing proton energy  $E_p$  (thin gray line), which is unrealistic. The same situation is observed for the calculated proton fluxes with the help of the functional (1) for events having the characteristic type of the spectrum in Fig. 5 (e) (left). However, for the vast majority of proton events, the functional (1) predicts more or less real values of the computed proton fluxes with an energy  $E_p > 100-1000$  MeV. It should be noted that both functional (1) and (5) give a fairly good agreement between the calculated values of the intensity of the proton flux with energy in the range  $E_p > 1-1000$  MeV for events having the characteristic type of the spec-

trum in Fig. 5 (c). As noted above, events with this type of spectrum account for more than 50% of the total number of proton events.

### 5. Relationship between the observed and calculated values of the intensity of the proton flux $I_p$ with the integral flux $\int F_{\mu} dt$ of microwave bursts

Also, the connection between the parameters in the functional (1) and the integral flux  $\int F_{\mu} dt$  of microwave bursts at a frequency of 8800 MHz was investigated. The investigated sample contains 195 proton events for the period from 06-02-1986 to 20-12-2014. Comparative analysis showed that there is a sufficiently strong connection between the integral flux  $\int F_{\mu} dt$  of microwave bursts and the parameter  $10^d$  in the functional (1), where the correlation coefficient  $r$  between the investigated quantities is about 0.70 (see Fig. 6 a)). At the same time, the connection between  $\int F_{\mu} dt$  and the observed intensity of the proton flux  $I_p$  ( $E_p > 30$  MeV) is much worse ( $r \approx 0.49$ ), see Fig. 6 b). Recall that the parameter  $10^d$  in the functional (1) characterizes the initial (total) number of accelerated protons with  $E_p > 1-100$  MeV. The presence of a strong connection between the integral flux  $\int F_{\mu} dt$  of microwave bursts and the parameter  $10^d$  agrees with the previously obtained results in the work (Chertok, 1982), which states that the parameters of microwave bursts can be used to estimate the total number of accelerated particles and their energy spectrum.

The presence of a sufficiently strong connection between  $\int F_{\mu} dt$  and the parameter  $10^d$ , indicates that the main acceleration of protons occurs in the flare region. In Fig. 6 b) there are significant deviations of the observed values of the intensity of the proton flux  $I_p$  relative to the values of the integral fluxes  $\int F_{\mu} dt$  of microwave bursts. Significantly overestimated observed values of the intensity of the proton flux  $I_p$  can probably be explained by the additional acceleration of protons by shock waves, and significantly underestimated values can be explained by the effects of propagation of accelerated protons in the solar corona and in interplanetary space.

### 6. Conclusion

The results obtained are preliminary, since the final conclusion regarding the accuracy of the approximation of the observed energy spectra of the SCR protons with the help of the functional (1) can be made only after careful studies have been carried out between the calculated and observed values of the proton flux with energy  $E_p > 100-1000$  MeV. Which is supposed to be done in the next work.

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