FORECAST OF PROBABILITY AND MAGNITUDE OF SOLAR PROTON EVENTS BASED ON FLARE AND EJECTION DATA

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This paper investigates various characteristics of solar flares and coronal mass ejections that either led or did not lead to the detection of solar proton events at Earth during the period from 1996 to 2023. A detailed catalog of events has been compiled, and regression relationships between solar source parameters and proton flux increases near Earth have been obtained. A new "proton index" of an event is proposed, based on which calculations of the probability of registering solar proton events and expected particle fluxes of different energies are made. Longitudinal distributions of various parameters characterizing proton flux increases have also been obtained. The established patterns will form the basis of an empirical model that allows estimating the probability of high-energy particles reaching Earth and the expected levels and times of registration of peak increases in proton fluxes with energies >10 and >100 MeV.

Keywords: solar flares, coronal mass ejections, solar proton events

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1. INTRODUCTION

Solar proton events (SPEs) pose a risk to the lives of astronauts, negatively affect satellite electronics, crews, and passengers of aircraft making transpolar flights [Dorman, 2006; Lario et al., 2009; Mishev et al, 2015; Townsend et al., 2018]. In this regard, there is significant interest in predicting the probability of SPE detection, as well as estimating maximum particle fluxes and other parameters (e.g., onset time of increase, total particle flux fluence, overall event duration, etc.) at a specific point in the heliosphere.

Despite the fact that fluxes of various high-energy particles have been recorded by spacecraft and ground-based instruments for several decades, our understanding of the physics of their acceleration processes and propagation in interplanetary space is still incomplete. SPEs are associated with solar X-ray flares, solar radio emission, as well as coronal mass ejections (CMEs) and interplanetary shock waves.

For example, a number of studies have established various relationships between the characteristics of X-ray flares and/or CMEs and parameters of proton flux enhancements [Belov, 2017; Burov and Ochelkov, 2020; Ochelkov, 2021; Belov et al., 2005, 2007; Bazilevskaya et al. 2006; Kahler, 2001; Cliver et al. 2012; Dierckxsens et al., 2015; Gopalswamy et al., 2015; Richardson et al. 2015; Papaioannou et al., 2016, 2023, 2024; Kahler and Ling, 2018; Kihara et al., 2020]. In addition, there are studies linking SPE parameters with characteristics of active regions [Marroquin et al., 2023], solar magnetic fields [Zhang and Zhao, 2017], or solar radio emissions of various types [Chertok, 1990; Chertok, 2006; Núñez and Paul-Pena, 2020].

Currently, dozens of proton enhancement models have already been created (see the review by [Whitman et al., 2023]), which can be conditionally divided into three main classes: empirical, theoretical (" *physics-based* ") and those using machine learning. The earliest studies include empirical models developed in the 1970s-80s [for example, Akinyan et al., 1978; Smart and Shea, 1979; Chertok, 1982], which already allowed for estimating not only the maximum flux but also the energy spectrum of particles. Also worth noting are still used and continuously improved empirical models by Balch [1999], Posner [2007], Falconer et al. [2011], Anastasiadis et al. [2017], Richardson et al. [2018], Kahle and Ling [2018]; Zhong et al. [2019]; Papaioannou et al. [2022] and others, based on various characteristics of CMEs, flares, or active regions. Theoretical SEP models based on patterns of particle propagation in solar and heliospheric magnetic fields include, for example, [Sokolov et al., 2004; Aran et al., 2006; Luhmann et al., 2007, 2017; Marsh et al., 2015; Hu et al., 2017; Zhang and Zhao, 2017; Borovikov et al., 2018; Dorman et al., 2019]. In recent decades, SEP models based on machine learning technologies have also become widespread [Engell et al., 2017; Aminalragia-Giamini et al., 2021; Lavasa et al., 2021; Kasapis et al., 2022; Núñez, 2022; Torres et al., 2022; Stumpo et al., 2024].

Thus, the scientific community has developed a diverse set of SEP models demonstrating a wide range of capabilities, although they have significant limitations, particularly due to gaps in real-time input data. Expanding the set of input parameters certainly leads to improved quality in forecasting both the probability and magnitude of proton enhancements; however, in the daily activities of Space Weather Forecast Centers, one should rely on a minimal set of easily accessible data and minimal time for issuing forecast values. Therefore, in our view, an empirical model that does not require significant computational power is a good option.

The purpose of this work is to compile an extended catalog of SPEs (for energies >10 and >100 MeV) for 1996-2023, analyze and refine statistical relationships between the magnitude of proton enhancements and characteristics of X-ray flares and CMEs to create an empirical model of SPEs, allowing to estimate both the probability of its registration at Earth and the expected values of particle fluxes of different energies.

2. DATA AND METHODS

The basis for creating the catalog was a daily updated database of X-ray flares and proton enhancements [Belov, 2017 and references therein], supplemented with data on the initial velocity of corresponding CMEs identified on the LASCO coronagraph. Establishing the connection "flare –CME – proton enhancement" was carried out separately for each event, by analyzing all available information sources, including daily ultraviolet videos of the Sun (SDO, https://sdo.gsfc.nasa.gov/data/aiahmi/), coronagraphic observations (LASCO, https://www.swpc.noaa.gov/products/lasco-coronagraph), X-ray and particle fluxes of different energies (GOES, https://www.swpc.noaa.gov/products/goes-x-ray-flux , https://www.swpc.noaa.gov/products/goes-proton-flux), data on the speed and direction of CMEs (cdaw.gsfc.nasa.gov/CME_list/), models of CME propagation in interplanetary space (https://kauai.ccmc.gsfc.nasa.gov/DONKI/search/).

It should also be noted that when estimating particle fluxes and solar sources of SPEs, other previously published catalogs available in open access were taken into account (see, for example, http://www.wdcb.ru/stp/solar/solar_proton_events.ru.html , https://umbra.nascom.nasa.gov/SEP/ , https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/DZYLHK).

A total of 422 SEPs were identified, in which the particle flux with energy >10 MeV exceeded 0.15 pfu (group P10), of which 218 events had particle flux with energy >100 MeV >0.01 pfu (group P100) and 18 ground level enhancement events (GLE group). A control group of 806 "flare-CME" events was also selected that did not lead to the registration of any SEPs (No SEP group *)* . Data on the main parameters of all proton events are collected in a catalog available at the link (http://spaceweather.izmiran.ru/papers/2024/SEPs_1996_2023corr.pdf). Additionally, it should be noted that if an SEP began against the background of a previous event, the maximum particle flux values were determined by subtracting this elevated background.

3. RELATIONSHIPS BETWEEN SOLAR FLARE, CME, AND SEP PARAMETERS

Figure 1 shows the longitudinal distribution of all studied events depending on the magnitude of particle fluxes (light circles - without SEPs, dark circles - P10, squares - P100, diamonds - GLE), the class of the corresponding X-ray flare (left) and the initial velocity of the CME (right). Almost all points of the control group in both panels lie at the bottom of the figure, which confirms the necessity (but not sufficiency) of a high-class X-ray flare and fast CME for the registration of SEPs at Earth. It is also clearly visible that the solar sources of all proton enhancements are significantly shifted to the western hemisphere, and are most often associated with flares of class M and above. At the same time, for western sources, velocities can be significantly lower than for eastern ones, but the largest SEPs are observed at initial CME velocities of at least 1000-1200 km/s.

Fig. 1.

Table 1.

Table 1 shows the average values of various parameters for four groups of events: *Xm,* W/m^2 - maximum X-ray flux; *dt* , min - time from start to maximum of X-ray flare; φ, ° - heliolongitude; $P10_{max}$, pfu - maximum particle flux with energy >10 MeV; $P100_{max}$, pfu - maximum particle flux with energy >100 MeV; V_0, km/s - initial linear velocity of CME. Analysis of the table leads to the conclusion that higher values of parameters characterizing solar sources (*Xm* , *dt* , V_0) correspond to larger expected particle fluxes. The obtained results do not contradict the existing concept of "big flare syndrome" proposed in [Kahler, 1982]. Additionally, the sources of the most powerful events (P100 and GLE groups) are significantly shifted to the western part of the solar disk, which is fully consistent with the laws of charged particle propagation in interplanetary space along the Sun-Earth magnetic field line. *o*Larger particle fluxes should be expected. The results obtained do not contradict the existing concept of the "large flare syndrome" proposed in [Kahler, 1982]. In addition, the sources of the most powerful events (the P100 and GLE groups) are significantly shifted to the western part of the solar disk, which is quite consistent with the laws of propagation of charged particles in interplanetary space along the Sun-Earth field line.

In earlier works [Belov, 2017], it was already shown that the best correlations with SEP magnitude are demonstrated by the so-called flare index *Ix* , which represents the normalized product of maximum X-ray flux *Xm* (W/m^2) and the flare rise phase duration *dt* (min) *:*

$$Ix = \frac{Xm}{10^{-4}} * \frac{dt}{10}, \tag{1}$$

as well as *Iv* - normalized index of initial CME velocity V_0(km/s):

$$Iv = \frac{V_0}{1000}. \tag{2}$$

The analysis showed that for the studied sample of proton events, the most reliable relationship is between maximum proton fluxes with energies >10 MeV ($P10^*$) and >100 MeV ($P100^*$), presented as a power-law dependence on the aforementioned indices:

$$P10^* = k_{10} * (Ix)^{\alpha_{10}} * (Iv)^{\beta_{10}} \tag{3}$$

$$P100^* = k_{100} * (Ix)^{\alpha_{100}} * (Iv)^{\beta_{100}}, \tag{4}$$

where k_{10} and k_{100} are the corresponding constants for particle fluxes with energies >10 and >100 MeV, α_{10} and α_{100} are the power indices of the flare index, β_{10} and β_{100} are the power indices of the CME velocity index.

Fig. 2.

Figure 2 shows the relationship between the above-mentioned indices and the maximum particle fluxes with energies >10 MeV (left) and >100 MeV (right) (decimal logarithms of all values are presented). Various ranges across the entire solar disk were considered, and the longitudinal interval for which the correlation coefficients were highest was selected. In this case, the figure presents the "optimal" western longitudes (W22–W87) and only those events in which the connection between the solar source (flare+CME) and the subsequent SEP is established most reliably. There were 189 such events from the P10 group and 107 from the P100 group. The correlation coefficients are 0.72±0.05 and 0.72±0.07 for the left and right panels, respectively.

This relationship can be considered close, which means it can be used further to build an empirical SEP model.

For convenience, it is advisable to introduce a combined index that simultaneously includes important characteristics of the X-ray flare and the corresponding CME. Let's call it the "proton index" of the event; in fact, it represents the decimal logarithm of the expected maximum particle flux with energies >10 MeV and >100 MeV:

$$Ip_{10} = A_{10} * \lg(Ix) + B_{10} * \lg(Iv) + C_{10} \,, \quad (5)$$

$$Ip_{100} = A_{100} * \lg(Ix) + B_{100} * \lg(Iv) + C_{100}, \,, \quad (6)$$

where A_{10}, B_{10}, C_{10} and $A_{100}, B_{100}, C_{100}$ are the corresponding coefficients for particles with energies >10 MeV and >100 MeV, obtained from the double regressions described above (see Figure 2 and formulas (3) and (4)). In the future, this index will be used to predict both the probability of SEP registration and the expected fluxes of particles of different energies.

The values of the proton index vary within relatively small limits for the events in our catalog (from –0.8 to 3.4), but it should be taken into account, for example, that for particles with energy >10 MeV $Ip \approx 1$ corresponds to an X1 class solar flare with a rise phase duration of 10 minutes and a CME with an initial velocity of 1000 km/s.

4. EVALUATION OF THE PROBABILITY OF SEP REGISTRATION

A large number of events and a fairly uniform distribution of sources across the solar disk allows us to estimate the probabilities of registering SEPs of a certain level depending on the power and duration of the flare and the initial velocity of the corresponding CME, included in the combined proton index of the event. SEP registration occurs when the proton flux exceeds a certain threshold value, in our case 0.15 pfu for >10 MeV particles and 0.015 pfu for >100 MeV particles. The probability can be represented as the ratio of the number of SEP events with a certain value of the proton index (N_p) to the total number of events that have similar index values Ip , but including those events that did not lead to SEP registration (N):

$$P = \frac{N_p}{N} * 100\% \quad (7)$$

Thus, based on the available data on the solar flare and CME, one can calculate the expected values of the proton index and the corresponding probabilities, and then additionally take into account their longitudinal distribution.

Figure 3 shows the dependence of the probability of registering SEPs with a selected threshold flux value on the heliolongitude of the source and the value of the event's proton index: dark circles correspond to particles with energies >10 MeV, light circles - >100 MeV. The size of the circles is explained in the legend. The data were obtained by averaging the corresponding values in a longitudinal window with a width of ±15° with a step of 15°.

It can be seen that if the index value *Ip* > 2 (for particles with energies >10 MeV) at longitudes in the range W30-W90, one should expect SEP registration with 100% probability. For particles with energies >100 MeV , the analogous "threshold" value of the proton index is ~ 0.5 (due to significantly lower fluxes of particles of these energies).

5. ESTIMATION OF REGISTRATION TIME FOR PEAK PARTICLE FLUX VALUES

Based on the compiled catalog of SPEs, we also obtained estimates of the time of maximum particle flux with energies >10 MeV with an accuracy of 1 hour. Figure 4 shows a histogram demonstrating the distribution of the parameter *dtP10* (h) – the time from the beginning of the corresponding X-ray flare to the registration of the maximum particle flux with energies >10 MeV. In most cases, it does not exceed 10–20 hours, however, there are also events with a very gradual flux increase, up to 80 hours. They have sources in the eastern part of the solar disk. The average value of the parameter *dtP10* for the studied sample is 12 hours.

Fig. 4.

Fig. 5.

The longitudinal dependence of this parameter, obtained using a sliding window with a width of 7° of helio-longitude, is no less interesting (see Fig. 5). The longest times correspond to distant eastern events (E20 and beyond).

Events in the central zone of the solar disk stand out: they are characterized by times between the beginning of the flare and the time of registration of maximum proton fluxes of 10–20 hours. It is also clearly noticeable that there are well-defined minima for which *dtP10* does not exceed 8 hours, corresponding to solar longitudes in the range W45–70. Apparently, they are associated not only with the position of the base of the solar magnetic field line (~W55) on which the Earth is located, but also with the peculiarities of the localization of particle acceleration processes on the Sun, which requires a separate detailed study. It should be noted that in the work of Kihara et al. [2020] it was also shown that the time period of the beginning and the total duration of SPEs decrease with decreasing longitudinal distance between the source of the coronal mass ejection and the base of the Parker spiral. Taking into account such longitudinal dependencies makes it possible to make predictive estimates of the times of registration of peak values of solar proton fluxes in the future.

6. ESTIMATION OF MAXIMUM PARTICLE FLUX VALUES FOR DIFFERENT ENERGIES.

Estimation of the maximum particle flux during an SPE, as mentioned above, can be made based on the proton event index developed by us. Figure 6 shows the relationships between the actually observed particle flux values and model calculations (in natural logarithms) obtained for particles with energies >10 and >100 MeV. To clarify, events with reliable attribution to solar sources are also considered here, but not only for the previously found optimal longitudinal range, but for events from the entire solar disk (E85-W88). At this stage, the longitudinal dependence of maximum particle fluxes of different energies is not yet taken into account, therefore the obtained relationships have slightly lower correlation coefficients than in Fig. 2 (0.69±0.04 (315 events of group *P10*) and 0.68±0.06 (160 events of group *P100*), but they are already high enough to rely on them in the future when building a model. In the future, we plan to introduce consideration of the longitudinal dependence of particle fluxes in order to refine the forecast values provided by our model under development.

Fig. 6.

Fig. 7.

Also, for convenience, calculations can be presented as contour diagrams. Figure 7 shows the expected values (decimal logarithms) of maximum particle fluxes with energies >10 MeV at different initial characteristics of the flare and CME. For example, if a flare of magnitude *X* 1 with a rise phase duration of 10 minutes and a corresponding ejection with a speed of 1400 km/s is registered, the expected maximum proton flux will be less than 10 pfu, and for a flare of *X* 10 with the same rise phase and speed - up to a hundred pfu.

The initial velocity of the ejection also has a great influence: the higher it is, the greater increase in particle flux should be expected: for example, for a flare of magnitude *X* 3 with a rise phase duration of 10 minutes and an initial ejection velocity of 600 km/s, fluxes of less than 10 pfu are expected, and for a similar flare and ejection with an initial velocity of 2000 km/s - already 200-300 pfu.

7. CONCLUSION

In the course of the work, a publicly available detailed catalog of SPEs (for energies >10 and >100 MeV) for 1996–2023 was compiled.to obtain various products such as CO and CH4. During plasma-chemical hydrogenation), which presents the main characteristics of both solar sources of SPS and the maximum particle fluxes recorded near the Earth and the times of their registration according to data from the GOES series of devices, which includes >500 events.

The comparison of proton flux increases with the characteristics of CMEs and solar flares showed that there are fairly reliable links between the quantities characterizing solar sources and the SPEs subsequently recorded near the Earth. These links were used to calculate a new index of the event's proton content – *can be increased up to* , which allows us to estimate both the probability of registering a SPE and the value of the expected maximum fluxes of protons with energies >10 and >100 MeV based on solar data available with a minimum time delay (maximum X-ray flare value, time of the soft X-ray flux growth phase, and the initial velocity of the corresponding CME).

Additionally, an analysis of the times of registration of the maximum flux of particles with energies >10 MeV (with an accuracy of 1 h) was conducted. It was shown that there is a pronounced longitudinal dependence of this parameter, which must be taken into account when predicting the radiation situation.

All the above results provide the basis for an empirical predictive model of the SPS, the detailed description of which is beyond the scope of this work and will be given in the future.

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REFERENCES

- *Akinyan S.T., Alibegov M.M., Kozlovsky V.D., Chertok I.M.* On the quantitative diagnosis of proton flares based on the characteristics of microwave radio bursts at frequencies of ~9 GHz // Geomagnetism and Aeronomy. Vol. 18. No. 3. PP. 410-414. 1978.
- *Belov A.V.* Flares, emissions, proton events // Geomagnetism and aeronomy. Vol. 57. No. 6. pp. 1-12. 2017. https://doi.org/10.7868/S0016794017060025

– *Burov V.A., Ochelkov Yu.P.*On the possibility of forecasting the intensity of solar proton events by thermal X-ray radiation of solar flares // Heliogeophysical Research. Issue 25. P. 30–36. 2020.
– *Ochelkov Yu.P.* A model of the probabilistic relationship between maximum intensities of solar proton events and X-ray flares // Heliogeophysical Research. Issue 31. P. 29–40. 2021. https://doi.org/10.54252/2304-7380_2021_31_29
– *Chertok I.M.* Estimates of the proton energy spectrum index based on data on solar microwave bursts // Geomagnetism and Aeronomy. V. 22. No. 2. P. 182–186. 1982.
– *Chertok I.M.* Coronal mass ejections in the aspect of space weather: I. On the diagnostics of proton flares by radio bursts // Bull. Russian Acad. Sci. Physics. V. 70. No. 10. P. 1495–1497. 2006.
– *Aminalragia-Giamini S., Raptis S., Anastasiadis A., Tsigkanos A., Sandberg I., Papaioannou A., Papadimitriou C., Jiggens P., Aran A., Daglis I.A.* Solar energetic particle event occurrence prediction using solar flare soft x-ray measurements and machine learning // J Space Weather Space Clim. V. 11. Article ID 59. 2021. https://doi.org/10.1051/swsc/2021043
– *Anastasiadis A., Papaioannou A., Sandberg I., Georgoulis M., Tziotziou K., Kouloumvakos A., Jiggens P* . Predicting Flares and Solar Energetic Particle Events: The FORSPEF Tool // Solar Phys. V. 292. N 9. Article ID. 134. 2017. https://doi.org/10.1007/s11207-017-1163-7
– *Aran A., Sanahuja B., Lario D* . SOLPENCO: A solar particle engineering code // Adv Space Res. V. 37. N 6. P. 1240–1246. 2006. https://doi.org/10.1016/j.asr.2005.09.019
– *Balch C.* SEC proton prediction model: verification and analysis // Radiat Meas. V.30. N 3. P. 231–250. 1999. https://doi.org/10.1016/s1350-4487(99)00052-9
– *Bazilevskaya G.A., Sladkova A.I., Svirzhevskaya A.K.* Features of the solar X-ray bursts related to solar energetic particle events // Adv Space Res. V. 37. № 8. P. 1421−1425. 2006. https://doi.org/10.1016/j.asr.2005.04.065
– *Belov A., Garcia H., Kurt V., Mavromichalaki H., Gerontidou M.* Proton enhancements and their relation to *x* -ray flares during the three last solar cycles // Solar Phys. V. 229. N 1. P. 135−159. 2005. https://doi.org/10.1007/s11207-005-4721-3
– *Belov A., Kurt V., Mavromichalaki H., Gerontidou M.* Peaks **s** ize distributions of proton Fluxes and Associated Soft *X* -Ray Flares // Solar Phys. V. 246. N 2. P. 457−470. 2007. https://doi.org/10.1007/s11207-007-9071-x

– *Borovikov D., Sokolov I.V., Roussev I.I., Taktakishvili A., Gombosi T.I.* Toward a quantitative model for simulation and forecast of solar energetic particle production during gradual Events. I. Magnetohydrodynamic background coupled to the SEP Model // Astrophys J. V. 864. N 1. 2018. https://doi.org/10.3847/1538-4357/aad68d
– *Chertok I.M* . On the correlation between the solar gamma-ray line emission, radio bursts and proton fluxes in the interplanetary space // Astronomische Nachrichten . V. 311. N 6. P. 379–381. 1990.
– *Cliver E.W., Ling A.G., Belov A., Yashiro S.* Size distributions of solar flares and solar energetic particle events // Astrophys J Lett. V. 756, № 2, P. L29−L33. 2012. https://doi.org/10.1088/2041-8205/756/2/L29
– *Dierckxsens M., Tziotziou K., Dalla S., Patsou I., Marsh M.S., Crosby N.B., Malandraki O., Tsiropoula G.* Relationship between solar energetic particles and properties of flares and CMEs: Statistical analysis of Solar Cycle 23 events // Solar Phys. V. 290. P. 841–874. 2015. https://doi.org/10.1007/s11207-014-0641-4
– *Dorman L.* Cosmic ray interactions, propagation, and acceleration in space plasmas. Springer, Dordrecht, 2006. 847 p.
– *Dorman L., Pustil'nik L., Dai U., Idler M., Keshtova F., Petrov E.* Is it possible to organize automatic forecasting of expected radiation hazard level from Solar Cosmic Ray (SCR) events for spacecraft in the heliosphere and magnetosphere and for aircraft in the low Atmosphere? // Adv Space Res. V. 64. N 12. P. 2490–2508. 2019. https://doi.org/10.1016/j.asr.2019.09.038
– *Engell A.J., Falconer D.A., Schuh M., Loomis J., Bissett D.* SPRINTS: A Framework for Solar-Driven Event Forecasting and Research // Space Weather. V. 15. N 10. P. 1321–1346. 2017. https://doi.org/10.1002/2017SW001660
– *Falconer D., Barghouty A.F., Khazanov I., Moore R.* A tool for empirical forecasting of major flares, coronal mass ejections, and solar particle events from a proxy of active-region free magnetic energy // Space Weather. V. 9. N 4. Article ID S04003. 2011. https://doi.org/10.1029/2009SW000537
– *Gopalswamy N., Mäkelä P., Akiyama S., Yashiro S., Xie H., Thakur N., Kahler S.W.* Large solar energetic particle events associated with filament eruptions outside of Active Regions // Astrophys J Lett. V. 806. N 1. Article ID 8. 2015. https://doi.org/10.1088/0004-637X/806/1/8

- *Hu J., Li G., Ao X., Zank G.P., Verkhoglyadova O.* Modeling particle acceleration and transport at a 2-D CME-Driven shock // J Geophys Res: Space Phys. V. 122. N 11. P. 10938–10963. 2017. https://doi.org/10.1002/2017JA024077
- *Kahler S.W.* The role of the big flare syndrome in correlations of solar energetic proton fluxes and associated microwave burst parameters // Iulia Zagainova . V. 87. N A5. P. 3439–3448. 1982. https://doi.org/10.1029/JA087iA05p03439
- *Kahler S.W.* The correlation between solar energetic particle peak intensities and speeds of coronal mass ejections: Effects of ambient particle intensities and energy spectra // J Geophys Res. V. 106. P. 20947−20956. 2001. https://doi.org/10.1029/2000JA002231
- *Kahler S.W., Ling A.G.* Forecasting Solar Energetic Particle (SEP) events with Flare X-ray peak ratios // J. Space Weather Space Clim. V. 8. Article ID A47. 2018. https://doi.org/10.1051/swsc/2018033
- *Kasapis S., Zhao L., Chen Y., Wang X., Bobra M., Gombosi T.* Interpretable Machine Learning to Forecast SEP Events for Solar Cycle 23 // Space Weather. V. 20. N 2. Article ID e2021SW002842. 2022. https://doi.org/10.1029/2021SW002842
- *Kihara K., Huang Y., Nishimura N., Nitta N.V., Yashiro S., Ichimoto K., Asai A.* Statistical analysis of the relation between coronal mass ejections and solar energetic particles // Astrophys J. V. 900. N 1. Article ID 75. 2020. https://doi.org/10.3847/1538-4357/aba621
- *Lario D., Aran A., Decker R.B.* Major solar energetic particle events of solar cycles 22 and 23: Intensities close to the streaming limit // Solar Phys. V. 260 P. 407–421. 2009. https://doi.org/10.1007/s11207-009-9463-1
- *Lavasa E., Giannopoulos G., Papaioannou A., Anastasiadis A., Daglis I.A., Aran A., Pacheco D., Sanahuja B.* Assessing the predictability of solar energetic particles with the use of machine learning techniques // Solar Phys. V. 296. N 7. Article ID 107. 2021. https://doi.org/10.1007/s11207-021-01837-x
- *Luhmann J.G., Ledvina S.A., Krauss-Varban D., Odstrcil D., Riley P.* A heliospheric simulation-based approach to SEP source and transport modeling // Adv Space Res. V. 40. N 3. P. 295–303. 2007. https://doi.org/10.1016/j.asr.2007.03.089
- *Luhmann J.G., Mays M.L., Odstrcil D., Li Y., Bain H., Lee C.O., Cohen C.M.S., Mewaldt R.A., Leske R.A., Futaana Y.* Prospects for Modeling and Forecasting SEP Events with

ENLIL and SEPMOD // Proceedings of the International Astronomical Union. V. 13. N S335. P. 263–267. 2017. https://doi.org/10.1017/S1743921317007396

- *Marroquin R.D., Sadykov V., Kosovichev A. et al.* // Astrophys J. V. 952. N 2. Article ID 97. 2023. https://doi.org/10.3847/1538-4357/acdb65
- *Marsh M.S., Dalla S., Dierckxsens M., Laitinen T., Crosby N.B.* SPARX: A modeling system for solar energetic particle radiation space weather forecasting // Space Weather. V. 13. N 6. P. 386–394. 2015. https://doi.org/10.1002/2014SW001120
- *Mishev A.L., Adibpour F., Usoskin I.G., Felsberger E.* Computation of dose rate at flight altitudes during ground level enhancements no. 69, 70 and 71 // Adv Space Res. V. 55. P. 354–362. 2015. https://doi.org/10.1016/j.asr.2014.06.020
- *Núñez M, Paul-Pena D.* Predicting >10 MeV SEP Events from solar flare and radio burst data // Universe. V. 6. N 10. Article ID 161. 2020. https://doi.org/10.3390/universe6100161
- *Núñez M.* Evaluation of the UMASEP-10 Version 2 Tool for Predicting All >10 MeV SEP Events of Solar Cycles 22, 23 and 24 // Universe. V. 8. Article ID 35. 2022. https://doi.org/10.3390/universe8010035
- *Papaioannou A., Sandberg I., Anastasiadis A., Kouloumvakos A., Georgoulis M.K., Tziotziou K., Tsiropoula G., Jiggens P., Hilgers A.* Solar flares, coronal mass ejections and solar energetic particle event characteristics // J Space Weather. Space Clim. V. 6. Article ID A42. 2016. https://doi.org/10.1051/swsc/2016035
- *Papaioannou A., Vainio R., Raukunen O., Jiggens P., Aran A., Dierckxsens M., Mallios S.A., Paassilta M., Anastasiadis A.* The probabilistic solar particle event forecasting (PROSPER) model // J Space Weather Space Clim. V. 12. Article ID 24. 2022. https://doi.org/10.1051/swsc/2022019
- *Papaioannou A., Herbst K., Ramm T., Cliver E.W., Lario D., Veronig A.M.* Revisiting empirical solar energetic particle scaling relations. I. Solar flares // A&A. V. 671. Article ID A66. 2023. https://doi.org/10.1051/0004-6361/202243407
- *Papaioannou A., Herbst K., Ramm T., Lario D., Veronig A.M.* Revisiting empirical solar energetic particle scaling relations. II. Coronal mass ejections // A&A. V. 690. Article ID A60. 2024. https://doi.org/10.1051/0004-6361/202450705

- *Posner A.* Up to 1-hour forecasting of radiation hazards from solar energetic ion events with relativistic electrons // Space Weather. V. 5. N 5. Article ID 05001. 2007. https://doi.org/10.1029/2006SW000268
- *Richardson I.G., Mays M.L., Thompson B.J.* Prediction of solar energetic particle event peak proton intensity using a simple algorithm based on CME speed and direction and observations of associated solar phenomena // Space Weather. V. 16. N 11. P. 1862–1881. 2018. https://doi.org/10.1029/2018SW002032
- *Richardson I.G., von Rosenvinge T.T., Cane H.V.* The properties of solar energetic particle event-associated coronal mass ejections reported in different CME catalogs // Solar Phys. V. 290. N 6. P. 1741–1759. 2015. https://doi.org/10.48550/arXiv.1505.03071
- *Smart D.F., Shea M.A.* PPS76: A computerized event mode solar proton forecasting technique. In: Donnelly, R.F. (Ed.), NOAA Solar-Terrestrial Predictions Proceedings. V. 1. P. 406–427. 1979.
- *Sokolov I.V., Roussev I.I., Gombosi T.I., Lee M.A., Kóta J., Forbes T.G., Manchester W.B., Sakai J.I.* A new field line advection model for solar particle acceleration // Astrophys J Lett. V. 616. N 2. P. L171–L174. 2004. https://doi.org/10.1086/426812
- *Stumpo M., Laurenza M., Benella S., Marcucci M.F.* Predicting the energetic proton flux with a machine learning regression algorithm // Astrophys J. V. 975. N 1. Article ID 8. 2024. https://doi.org/10.3847/1538-4357/ad7734
- *Torres J., Zhao L., Chan P. K., Zhang M.* A machine learning approach to predicting SEP events using properties of coronal mass ejections // Space Weather. V. 20. Article ID e2021SW002797. 2022. https://doi.org/10.1029/2021SW002797
- *Townsend L.W., Adams J.H., Blattnig et al.* Solar particle event storm shelter requirements for missions beyond low Earth orbit // Life Sci. Space Res. V.17 P. 32–39. 2018. https://doi.org/10.1016/j.lssr.2018.02.002
- *Whitman K., Egeland R., Richardson IA.G. et al.* Review of solar energetic particle prediction models // Adv Space Res. V. 72. N 12. P. 5161–5242. 2023. https://doi.org/10.1016/j.asr.2022.08.006
- *Zhang M., Zhao L.* Precipitation and release of solar energetic particles from the solar coronal magnetic field // Astrophys J. V. 846. N 2. Article ID 107. 2017. https://doi.org/10.3847/1538-4357/aa86a8

– *Zhong Q., Wang J., Meng X., Liu S., Gong J.* Prediction model for solar energetic proton events: Analysis and verification // Space Weather. V. 17. N 5. P. 709–726. 2019. https://doi.org/10.1029/2018SW001915

Table 1. Average values of various event characteristics.

	No SEP (806)	P10 (422)	P100 (218)	GLE (18)
Xm *10^{6}, W/m^2	32 ± 2	98 ± 1	141 ± 2	479 ± 1
dt , min	26 ± 1	34 ± 2	32 ± 2	35 ± 10
φ, °	0 ± 2	28 ± 3	34 ± 3	54 ± 9
V_0, km/s	617 ± 13	1114 ± 28	1252 ± 43	1991 ± 164
$P10_{max}$, pfu	0	295 ± 93	557 ± 179	3310 ± 1747
$P100_{max}$, pfu	0	7 ± 2	13 ± 4	134 ± 47

Figure Captions

Fig. 1. The relationship between the helio-longitude of the solar source with: *(a)* the X-ray flux magnitude and *(b)* the initial CME velocity for different groups of studied events (light circles – No SEP, dark circles – P10, squares – P100, diamonds – GLE).

Fig. 2. Correlation between the actually observed maximum particle flux with energies (*a*) >10 MeV and (*b*) >100 MeV with fluxes calculated using formulas (3) and (4), for events with reliable attribution to solar sources in the longitude range W22–W87.

Fig. 3. Dependence of the SEP detection probability on helio-longitude and proton index of the event.

Fig. 4. Distribution of parameter *dtP10* (h) – time from the beginning of the corresponding X-ray flare to the registration of the maximum particle flux with energies >10 MeV.

Fig. 5. Longitudinal dependence of parameter *dtP10* .

Fig. 6. Correlation between actually observed particle flux values and model calculations for groups (*a*) P10 and (*b*) P100 for events from the entire solar disk (E85–W88).

Fig. 7. Correlation between the expected maximum particle flux with energies >10 MeV (decimal logarithm) with the initial CME velocity and flare index.

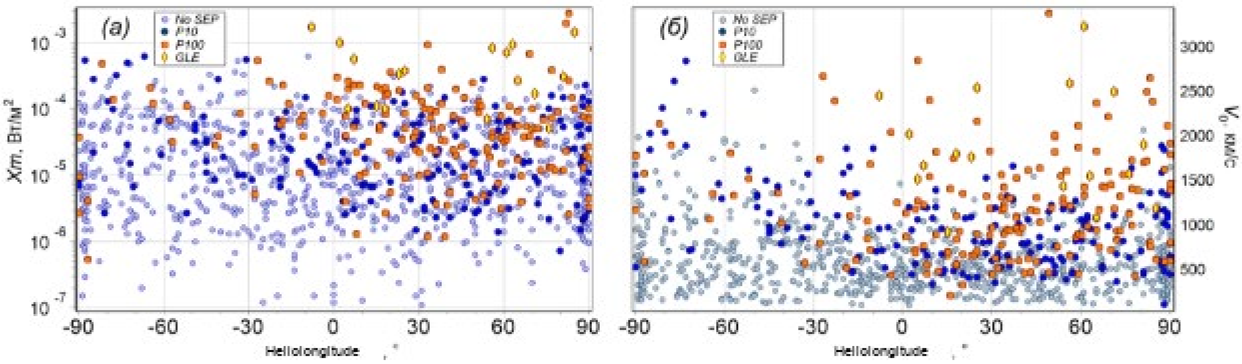

(a)
No SEP
P10
P100
GLE
Xm, Вт/м²
Heliolongitude
(б)
No SEP
P10
P100
GLE
V0, км/с
Heliolongitude

Fig. 1.

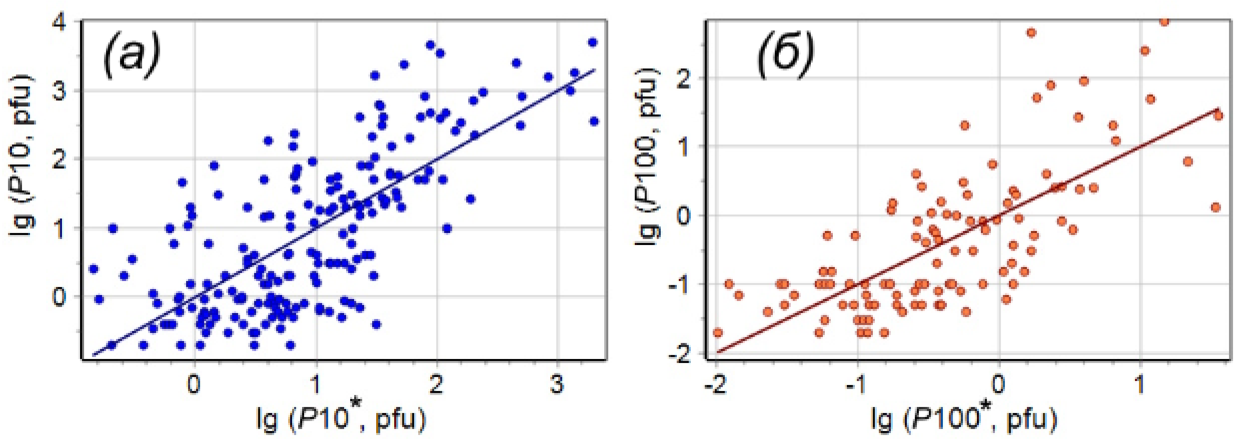

(a)
lg (P10, pfu)
lg (P10*, pfu)
(б)
lg (P100, pfu)
lg (P100*, pfu)

Fig. 2.

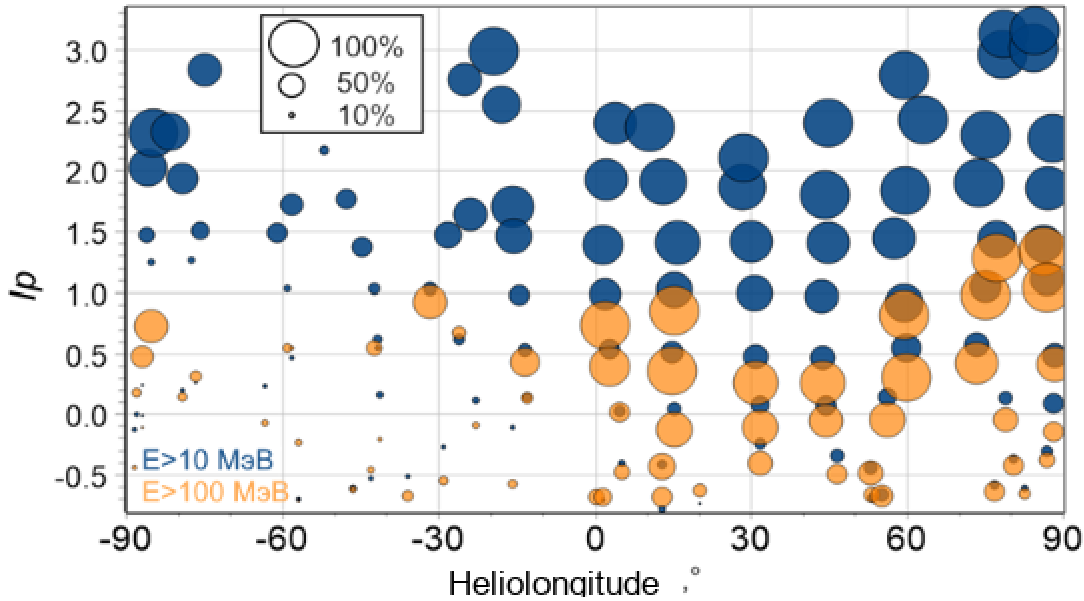

100%
50%
10%
E>10 МэВ
E>100 МэВ
Ip
Heliolongitude , °
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-90
-60
-30
0
30
60
90

Fig. 3.

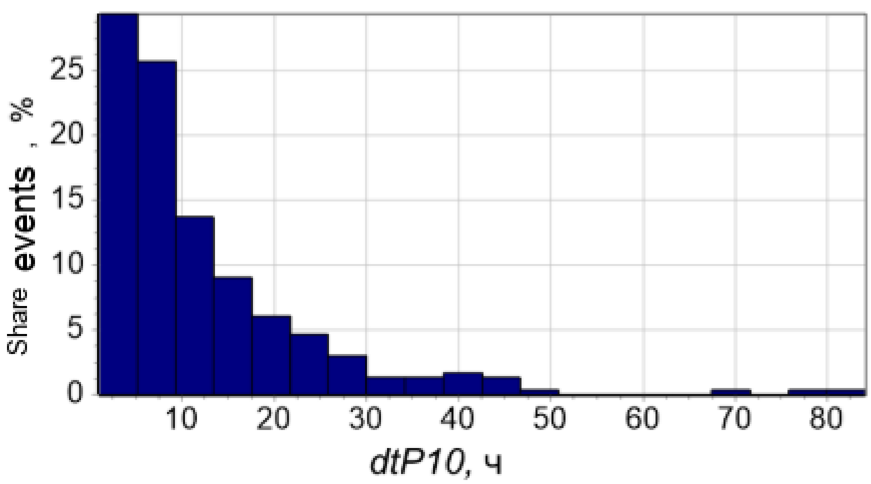

Share events , %
dtP10, ч
0
5
10
15
20
25
10
20
30
40
50
60
70
80

Fig. 4.

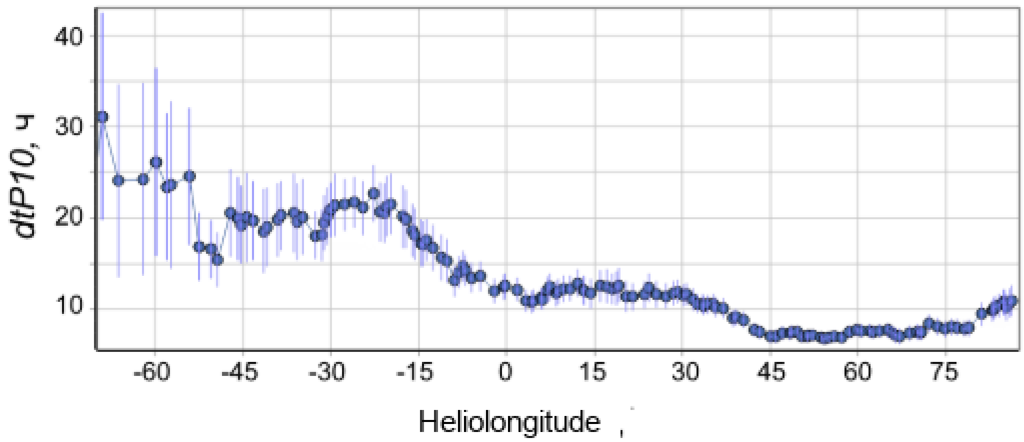

dtP10, ч
Heliolongitude

Fig. 5.

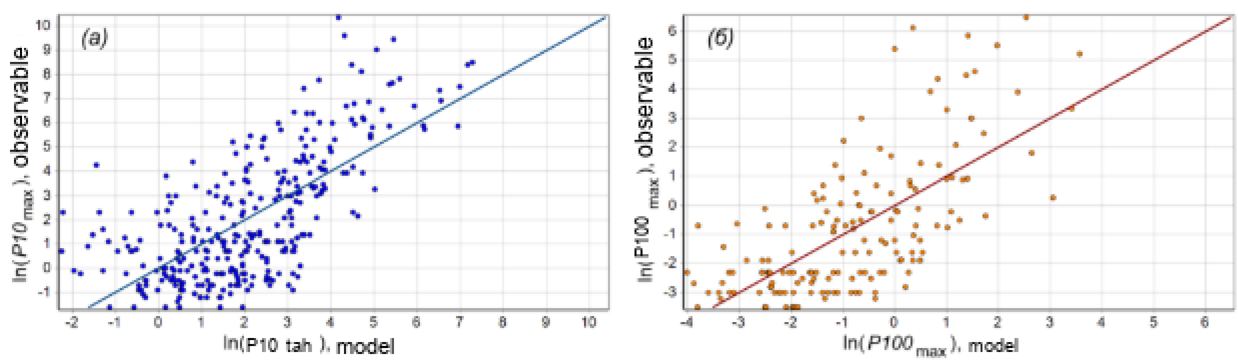
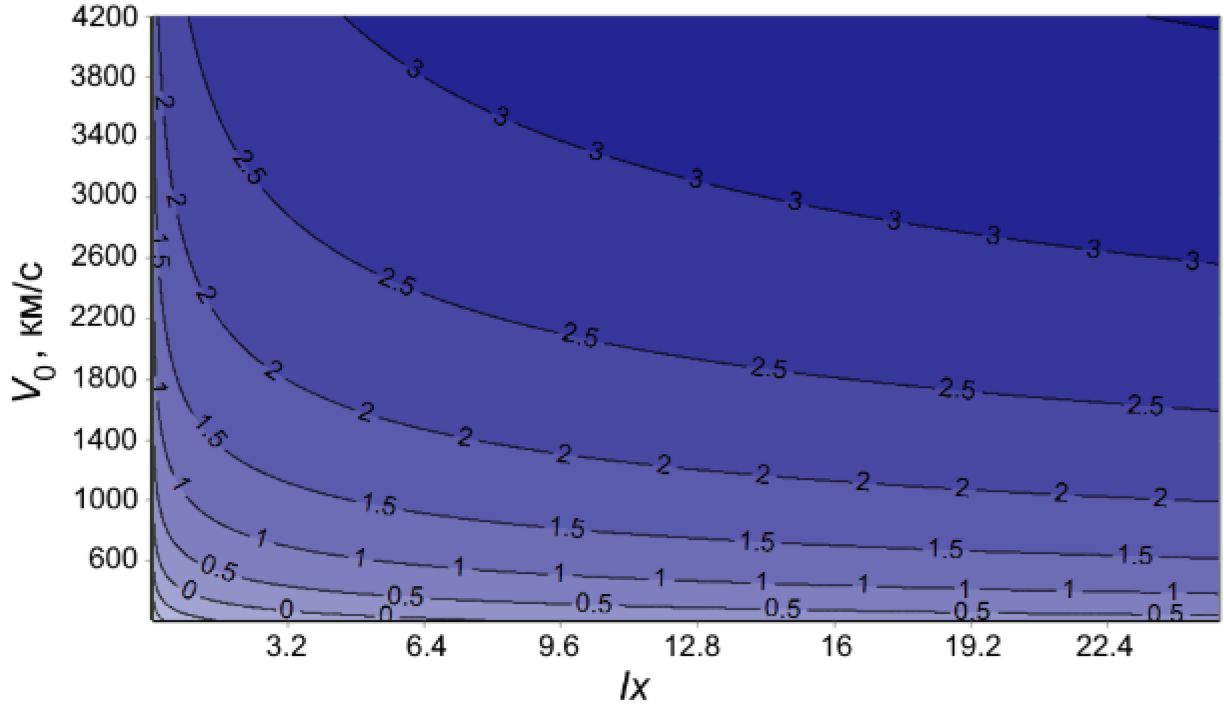

(a)
ln(P10 max), observable
ln(P10 tah), model
(б)
ln(P100 max), observable
ln(P100 max), model

Fig. 6.



4200
3800
3400
3000
2600
2200
1800
1400
1000
600
V0, км/с
3.2
6.4
9.6
12.8
16
19.2
22.4
lx

Fig. 7.