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Criteria for Forecasting Proton Events by Real-Time Solar Observations

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Abstract—The sequence for overcoming the threshold values of a number of physical characteristics for proton event forecasting in real time is discussed. Each characteristic adds a new physical meaning that refines the forecast. To take into account all the characteristics, the following continuous patrol observations are necessary: (1) the magnetic field of the active region (ascent of the flux) and the total magnetic field of the Sun, which can predict the onset of flare activity several days prior to main events; (2) soft X-ray radiation in two channels to calculate the temperature (T) and emission measure of plasma, which can show preheating to $T > 10$ MK required to begin proton acceleration (the first few minutes before the start of hard X-ray (HXR) radiation with energies >100 keV); (3) HXR radiation >100 keV or microwave radiation (>3 GHz), which indicates the intensity and duration of operation of the electron accelerator (a few to tens of minutes before the arrival of protons with energies >100 MeV); (4) radio emission at plasma frequencies (<1000 MHz), showing the development of the flare process upward into the corona and leading to a coronal mass ejection (CME) several minutes before the onset of type II and IV radio bursts (the first tens of minutes before the appearance of a CME in the field of view of the coronagraph); (5) the direction and velocity of CME propagation, which determine the conditions to release accelerated protons into the heliosphere. These stages of solar proton flares are illustrated by observations of proton events on August 2–9, 2011. To quantitatively predict the onset time, maximum and magnitude of the proton flux, as well as its fluence, it is necessary to create statistical regression models based on all of the listed characteristics of past solar proton events.

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1. INTRODUCTION

For carrying out and planning space activities, it is necessary to know the expected radiation conditions. In particular, it is desirable to be able to predict solar proton events (SPE)—the onset time, evolution of time profiles, time of maximum, and the duration of the decline of the flux of protons with various energies, as well as their total fluences. Note that the real radiation hazard is posed by SPEs, whose maximum intensity exceeds the depth of galactic cosmic ray (GCR) modulation in the solar activity cycle, since spacecraft must be adapted for flights within the limits of possible GCR variations. However, the level of modern methods for forecasting SPEs does not allow their use in real time. There are still gaps in the understanding of the SPE physics; empirical forecasting models based on statistical analysis of solar and interplanetary phenomena associated with the SPE are mainly used (see (Kuznetsov, 2007; Nymnik, 2007; Balch, 2008; García-Rigo et al., 2016).

The GOES soft X-ray (SXR) satellite patrols provide the longest, most continuous series of data on flare activity in near real time. That is why they are widely used for real-time SPE forecasting and verification of various statistical models for SPE forecasting (Garcia, 2004; Belov et al., 2007; Belov, 2017; Alberti et al., 2017; Kahler et al., 2017; Núñez, 2011, 2015, 2018; Núñez and Paul-Pena, 2020; Ling and Kahler, 2020). A fairly comprehensive overview of the current state of forecast models for 2017 can be found in the work by Swalwell et al. (2017).

Acceleration of protons with $E > 100$ MeV and relativistic electrons in "proton" solar flares occur quite rarely. To determine the acceleration mechanism, and therefore, make a reasonable SPE forecast, it is necessary to relate the observational characteristics of electromagnetic radiation (from radio to gamma radiation) with the physical conditions in solar flares. Hudson (1978) suggested that the characteristics of proton flares depend on the properties of physical processes in a more complex manner than simple proportionality to the total energy; i.e., they demonstrate threshold effects. In this case, the effects become "more striking" for large flares, but the flare processes themselves do not change substantially.

Comparison of fluxes of accelerated electrons and protons based on direct observations in the interplanetary space (IS) (Ramaty et al., 1978) and the results of their interaction in the solar atmosphere (emission of hard X-rays and γ-lines) (Shih et al., 2009) shows two acceleration mechanisms that occur in two phases. In the first phase, predominantly electrons <100 keV are accelerated, and in the second phase, both electrons >100 keV and protons are accelerated. Apparently, the acceleration mechanism is the same and the phases differ by the possibility of observing protons in the solar atmosphere. In the second phase, protons have already overcome the energy threshold for the generation of γ-lines and production of neutrons interacting with nuclei (Struminsky et al., 2020). If we focus on acceleration of protons >100 MeV and electrons >1 MeV are observed in the IS with similar time profiles, then this single mechanism should be long-term stochastic acceleration (Miller et al., 1997). In this case, let us note that without taking into account radiation processes, protons and electrons are accelerated to the same energies in equal times, but the time of their acceleration to the same velocities differs by m_p/m_e times.

To explain the proportional number of high-energy electrons and protons, Gerstein (1979) proposed a mechanism for their collective acceleration ("smoketron"). The past years have shown that the "smoketron" is hardly feasible even in laboratory conditions, although the ideas of accelerating ions through electron rings have been and are widely used (Sarantsev and Perelshtein, 1979), but some of the ideas that formed its basis are worthy of mention. Apparently, Gerstein (1979) was the first to note two fundamental points necessary to begin proton acceleration (second phase of acceleration): heating the plasma to temperatures above 10 MK and maintaining the electrical neutrality of the plasma during the acceleration process.

Since the pioneering works (Garcia, 1994a, b), researchers began to consider not only the power of SXR-radiation, but also the temperature (T) and the emission measure (EM) of SXR plasma. For example, Garcia (2004) suggests to use the flare plasma temperature at the maximum of SXR intensity, since in the range from M1 to X2, flares associated with SPEs (>10 MeV, >10 PFU) are significantly cooler than flares without SPEs (Garcia, 1994a, b). However, the maximum flare plasma temperature shows the lowest correlation coefficient with the maximum SPE amplitude among all considered parameters (Garcia, 2004). It is likely that the low SXR temperature of SPE flares is associated with additional energy removal during the acceleration of fast ($V_{\rm cme}$ > 1000 km/s) and wide CMEs (Ling and Kahler, 2020; Kahler and Ling, 2022).

Nonthermal HXR and microwave radiation provide direct information about electron acceleration. The Neupert effect (1968) indirectly relates thermal (SXR) and nonthermal (HXR and microwave) radiation through plasma heating by accelerated electrons and subsequent "chromospheric" evaporation. At the same time, at the time of observation of HXR and microwave radiation, nothing is known about the acceleration of protons, since they might not yet have reached the threshold energy for γ-line emission (the beginning of the second phase of acceleration). Also, the absence of γ-lines (first phase of acceleration) may be related to the lack of the right instrument at the right time and in the right place (patrol observations). Therefore, to the first approximation nonthermal radiation of electrons may judges acceleration of protons in a flare assuming proportional acceleration of protons from a certain threshold electron energy.

The statistical relationship between SPEs and flare HXR emission is evidenced by the Kiplinger effect, which established that the time evolution of the HXR spectrum E > 30 keV "soft–hard–harder" (SHH) of typical for flares with SPEs. This evolution of the SHH spectrum (the spectrum becomes harder with time) was proposed for automatic forecasting of SPEs (Kiplinger, 1995). Kahler (2012) have carried out a critical analysis of this proposal and considered that flares with SHH evolution of the HXR spectrum and CMEs are components of large eruptive flares, which explains the good relationship of SHH HXR flares with SPEs. The evolution of the SHH HXR spectrum E > 30 keV is a consequence of long-term stochastic acceleration.

Forecasting SPEs using microwave and SXR data has the same probability as using only SXR data, but without false alarms for the considered period and with a slightly increased warning time (Zucca et al., 2017). Microwave patrol observations improve the SPE forecasting scheme compared to that using only SXR data, so having quality microwave observations available in real time seems highly desirable for improving SPE forecasting (Zucca et al., 2017). Information about decimeter type II, III, and IV radio bursts and SXR flares ≥M2 was used to predict SPEs E > 10 MeV (Núñez and Paul-Pena, 2020); for the selected interval the following estimates were obtained: detection probability 70.2%, false alarm announcement 40.2%, waiting time 9 h 52 min.

The technique for forecasting SPEs from radio observations has been under development at IZMIRAN for quite a long time (see (Chertok, 2018) and references therein). It was statistically established that a flare could be a source of SPEs near Earth with a proton flux with E > 10 MeV $J_{10} \geq$ 5–10 PFU (Proton Flux Unit, 1 PFU = 1 (cm^2 with av)$^{-1}$), if the maximum intensity of associated microwave radio bursts at least one of the frequencies in the range 2.7–15.4 GHz exceeds 500 SFU (Solar Flux Unit, 1 SFU = 10^{-22} W m^{-2} Hz^{-1}). Moreover, the duration of the radio burst should be long and also be accompanied by a meter component of radio emission: type II and IV bursts. It is strange that the IZMIRAN methodology does not mention plasma radio emission at frequencies <1415 MHz (decimeter radio waves), which should precede type II and IV bursts at frequencies <180 MHz.

Let us recall that according to existing ideas (Aschwanden, 2006), the place of primary energy release is the frequency generation region of ~500 MHz. Klein et al. (2010) concluded that radio emission at decimeter and longer wavelengths provides a reliable indicator of the penetration of flare-accelerated particles into the upper corona and IS. The absence of such radiation in the flare can be used as evidence that the flare will not be accompanied by SPEs even with sufficiently powerful SXR radiation. However, Zucca et al. (2017) and Chertok (2018) did not consider decimeter radiation to improve SPE forecasting; the studies limited themselves only to microwaves.

Flare events with the detection of solar cosmic rays (SCR), in which protons are accelerated to an energy >100 MeV pose the greatest danger. Proton acceleration with E >100 MeV and relativistic electrons with E > 1 MeV most likely occurs in long-term eruptive flares against the acceleration of CMEs at velocities exceeding the local second cosmic velocity (618 km/s on the surface of the Sun), in the process of multiple reconnection—"magnetic detonation" (Grigorieva et al., 2023: Struminsky et al., 2023). This approach opens up the possibility of forecasting SPEs with proton energies >100 MeV in real time by using several physical thresholds related to energetics of the flare process.

2. THRESHOLD VALUES OF PHYSICAL PARAMETERS

The solar magnetic field is the only available energy source in the corona for the entire set of phenomena associated with a solar flare. Observations show that flares in an active region (AR) occur when a pre-existing magnetic flux interacts with one or more new magnetic fluxes, simultaneously or sequentially popping up in the atmosphere of the Sun. The energy release rate depends on the rate of ascent of the new magnetic flux (magnetic energy).

An increase in flare activity in the AR occurs with the appearance of a new fast magnetic flux; significant solar flare events (SFEs) occur every 0.5–2 days after detection of a sufficiently large magnetic flux (>10^{13} Wb) with its ascent rate >10^9 Wb/s (see (Ishkov, 2023) and references therein). This makes it possible to predict the period of flare energy release on a scale of several days before the first significant SFE occurs. Flares of large and medium magnitudes (according to the classification of SXR radiation, GOES) are always grouped in series, a period of flare energy release lasting 16–80 h, which ends when the supply of magnetic energy stops (the ascent of a new magnetic flux) and the formation of a new stable configuration of the magnetic field of the AR. Sometimes a series of flares may occur in more than one and in several ARs connected to each other by a common magnetic field, i.e., in activity complexes.

The ARs (or activity complexes) described above are capable creating conditions for long-term stochastic acceleration of electrons and protons, which should not violate the electrical neutrality of the plasma. For this, it is necessary that a number of electrons and protons accelerated to the same velocities be comparable (Struminsky et al., 2020). In this case, a "proton flare" (the appearance of interacting protons with E > 10 MeV) should begin at an electron plasma temperature of ~12 MK (protons with E ~ 2 MeV are equivalent in velocity to electrons with E ~ 1.0 keV). Hot plasma (with T > 12 MK) is necessary to ensure electrical neutrality, which must be maintained throughout the acceleration of protons (observation of HXR and/or microwave radiation)!

Hudson et al. (2021) drew attention to the observational fact that a hot SXR onset (a hot X-ray onset) with a plasma temperature of 10–15 MK precedes the impulsive phase of flares with HXR emission. To substantiate this, Tsap and Melnikov (2023) obtained estimates that showed that effective additional acceleration of electrons is possible only in the case of a relatively rarefied (n < 10^{10} cm^{-3}) and hot (T > 10^7 K) background plasma. The onset of π_0 meson generation will be possible at an electron energy of ~150 keV (protons with E ~ 300 MeV are equivalent in velocity to electrons c E ~ 150 keV), i.e., against the background of microwave (GHz) or HXR radiation E > 100 keV. To achieve such velocities, protons require a time of $m_{p|}/m_e$, at least one time greater than for electrons. Therefore, the key point is the time of acceleration of electrons to energies of ~100 keV, which determines the required duration of observation of HXR radiation with E > 100 keV and/or microwave radiation, as well as the expected moment of arrival of the first accelerated protons to Earth during free propagation.

There are observational data that show the acceleration time of electrons to a kinetic energy of ~100 keV is about ~400 ms (Miller et al., 1997). Delays between HXR bursts at different electron energies (20, 50, 100, 200, and 300 keV) about tens of milliseconds are also observed, which may be due to the acceleration time (see review (Lysenko et al., 2020) and references therein). Therefore, the time required for protons to acquire E ~ 200 MeV will be ~1 min for acceleration of electrons to a kinetic energy of ~100 keV in 40 ms ("fast" acceleration) or ~10 min for acceleration of electrons to ~100 keV in 400 ms ("slow" acceleration). If we take the onset of microwave emission at frequencies 8.8–15.4 GHz as the zero time in solar events (it usually coincides with the appearance of a significant HXR emission signal with E ~ 100 keV), then the expected arrival time of protons with E ~ 200 MeV (V/c = 0.57) into the Earth's orbit will be ~11 and ~21 min, respectively, when propagating without scattering along the Parker spiral to the Earth (1.3 AU, solar wind velocity 300 km/s). Thus, the uncertainty of the characteristic time for acceleration of solar electrons to $E \sim 100$ keV determines the uncertainty of the time of the first arrival of solar protons with $E \sim 200$ MeV to the Earth orbit which is about 10 min. The required time (characteristic size) for accelerating protons with $E > 100$ MeV Apparently the upward development of the flare process associated with the CME acceleration sets the required time (characteristic size) for >100 MeV proton acceleration.

The study of flares without SPEs and CMEs shows (Klein et al., 2010; Grigor'eva and Struminsky, 2021; Struminsky et al., 2021, 2023) that they are distinguished by absence of plasma radiation at frequencies <1415 MHz. The sequential appearance of this radiation at decreasing frequencies and/or its simultaneous presence in a wide frequency range indicates the development of the flare upward and is, in our opinion, a characteristic of accelerating CME—"proton flare" development upward.

Observation of radio emission at plasma frequencies makes it possible to estimate the linear size of the SXR source from its emission measure (EM). Because $\mathrm{EM} \sim n^2L^3$, $L \sim \sqrt[3]{\mathrm{EM}/n^2}$. Assuming that the plasma frequency is $\nu_p = 9000\sqrt{n}$, $\mathrm{EM} \sim \nu_p^4 L^3$. Indeed, CME acceleration occurs against the background of HXR radiation as the emission measure increases. Intense "chromospheric evaporation" should compensate for expansion of the source and decrease of plasma concentration. In this case, we obtain $\mathrm{EM}_{500} > \mathrm{EM}_{1415}$ or $L_{500} > L_{1415}(1515/500)^{4/3}$, for $L_{1415} \approx 15$ Mm, we have $L_{500} \approx 60$ Mm, and $L_{245} > L_{500}(500/245)^{4/3}$ and $L_{245} \approx 155$ Mm (indices indicate the corresponding frequencies in MHz). Thus, the observation of plasma radio emission at frequencies <500 MHz is evidence that the flare has overcome the height threshold of 60 Mm above the photosphere, and at 245 MHz, over 155 Mm.

In addition, note that the heliocentric radius $R = GmM/kT$, found from equality of hydrogen plasma thermal energy at $T > 10$ MK to its potential energy in the gravitational field of the Sun, is comparable to the field of view of the LASCO C2 coronagraph ((1.5–6)R_s). Substituting the constants, we obtain $T = 22/R$ (MK), where R is measured in solar radii. For a heliocentric distance $1.5R_s$, the temperature will be 14.7 MK.

When detecting the first arrival of a solar protons by energy-integral detectors, there is an uncertainty of the first arrival of solar protons with particular energy associated with velocity dispersion. Let us estimate the maximum acceleration time of protons from $E \sim 100$ MeV to ~500 MeV, which will allow protons with $E \sim 500$ MeV ($V/c = 0.75$) to arrive before protons with $E \sim 100$ MeV ($V/c = 0.43$). For protons of $E \sim 500$ MeV ($V/c = 0.75$) propagating without scattering along the Parker spiral to the Earth (1.3 AU, solar wind velocity 300 km/s) the propagation time will be ~15 min, and for protons with $E \sim 100$ MeV it ($V/c = 0.43$) will be ~25 min. Thus, the maximum acceleration time of protons with E from ~100 to ~500 MeV should be less than ~10 min (acceleration rate 0.67 MeV/s), so that protons with an energy >500 MeV will arrive first.

These estimates determine the choice of the zero time for analysis of phenomena associated with solar proton flares, as well as the criteria for "early" (<20 min) and "late" (>20 min) arrival of solar flares into Earth's orbit with respect to the zero time (Grigorieva et al., 2023). In the case of the "fast" mode of acceleration of electrons and protons, the first solar protons with $E > 100$ MeV will be observed near the Earth 10 min after our chosen zero (possibly simultaneously or later than protons with $E > 500$ MeV). In the case of the "slow" mode of acceleration of electrons and protons, the first solar protons with $E > 100$ MeV will be observed near the Earth in 20 min or later.

The CME parameters: the direction of propagation (angle PA) and the velocity of the first appearance in the field of view of the coronagraph and the solid angle determines the conditions for the release of accelerated protons into the IS. To guarantee the release of protons into the IS together with the CME, its velocity in the field of view of LASCO C2 should be >618/1.5 = 412 km/s. The velocity of the first appearance is determined by the acceleration mode of the CME and depends on "chromospheric effects". Since the magnitude of CME acceleration is limited to ~10 km/s^2, the velocity of the first appearance of a CME determines the required minimum duration of its acceleration, ~1 min (Struminsky et al., 2021). The CME parameters can be determined only after detection of two positions in the field of view of the coronagraph. Since the duty cycle of CME observations with the LASCO C2 coronagraph is 12 min, it is impossible to use these data to predict the moment of first arrival of solar protons >100 MeV in real time (Grigorieva et al., 2023). Long-term observation of CME acceleration in the field of view of the LASCO coronagraph may indicate the ongoing energy release and particle acceleration during the posteruptive phase of a flare (Grigorieva and Struminsky, 2022).

Thus, we propose five threshold criteria that must be met sequentially for a proton flare to occur: (1) magnetic flux; (2) the flare SXR plasma temperature. (3) energy and duration of electron acceleration; (4) height of development of the flare process; (5) the velocity and angle of CME propagation. The proposed criteria are discussed below by the example of flares, CMEs, and SPEs observed on August 2–9, 2011.

3. INSTRUMENTS, DATA AND METHODS

The temperature (T) and emission measure (EM) of the flare plasma were calculated from data of two integral SXR channels (1–8 and 0.5–4 Å) of the GOES spacecraft detector (*Geostationary Operational Environmental Satellite*, /satdat.ngdc.noaa.gov/sem/goes/data/) by using the *SolarSoft* package in the single-temperature approximation.

In this study, we only use information about radio emissions presented in YYYYMMDDevents.txt files (https://cdaw.gsfc.nasa.gov/CME_list/NOAA/org_events_text/2011/). These files contain information on the onset, maximum, and end of observed radio emissions at the eight patrol frequencies of the Radio Solar Telescope Network (RSTN). At four frequencies (15.4, 8.8, 4.995, 2.695 GHz), predominantly gyrosynchrotron radiation is recorded; at three (610, 410, 245 MHz) frequencies, plasma radiation is recorded; and at a frequency of 1415 MHz, the contribution of both mechanisms is possible.

The anti-coincidence shield of the spectrometer on the INTEGRAL (ACS SPI) detects HXR with $E >$ 100 keV. These can be as primary photons as well as and secondary photons generated in the body of the detector by protons with $E >$ 100 MeV. The ACS SPI is an efficient but uncalibrated HXR and proton detector that we use to study the relationship between solar flares and proton events. ACS SPI data is available at (https://isdc.unige.ch/~savchenk/spiacs-online/spiacspnlc.pl) with a time resolution of 50 ms. With 1-min smoothing and subtraction of the background, an ACS SPI count rate of less than 10 counts per 50 ms becomes significant. The increase in the ACS SPI count rate during solar radio emission observations is caused by solar HXR emission. We consider the time of the first arrival of solar protons into the Earth's orbit to be the onset of a significant increase in the counting rate against the background or after a burst of solar HXR radiation (e.g., (Struminsky et al., 2020; Grigorieva and Struminsky, 2022).

To monitor the intensity of proton fluxes of lower energies in the IS near the Earth, we use data from the 7.8–25 and 25–53 MeV proton channels of the EPHIN detector (*Electron Proton Helium Instrument* (Müller-Mellin et al., 1995)) on board the SOHO spacecraft, which is located at the Lagrange point $L1$. SOHO EPHIN data were taken from the website (/www2.physik.uni-kiel.de/SOHO/phpeph/EPHIN.htm). When analyzing SPEs, we use estimates of the quasi-maximum proton energy E_{qm} listed in the catalog (https://swx.sinp.msu.ru/apps/sep_events_cat/docs/SPE_24_Summary_List.pdf). Values of E_{qm} give an idea of the power of solar events and provide another unified parameter of SCR events, allowing comparisons with other their characteristics (Logachev et al., 2018).

Data on CME observations are taken from the electronic catalog SOHO LASCO CME CATALOG (/cdaw.gsfc.nasa.gov/CME_list/) (Gopalswamy et al., 2009).

4. SOLAR FLARES AND PROTON EVENTS AUGUST 2–9, 2011. DISCUSSION

To illustrate the method for forecasting of proton events in real time, we chose the period from August 2 to 9, 2011. (beginning of the 24th solar activity cycle), when two ARs, AR11261 (from July 26) and AR11263 (from July 28) showed activity on the solar disk.

Apparently, these ARs were connected by a common magnetic field and were part of an activity complex that became the source of a series of flares from July 30 to August 9, 2011. The first significant (magnitude M or more) event during this period was flare M9.3 July 30, 2012 with coordinates (N14E35) in AR11261, in which the SXR plasma was heated to 20 MK. It was an impulsive (8 min duration of GOES SXR emission) and confined flare, in which there was no radio emission at frequencies <1415 MHz, type II and IV radio bursts. The first significant event in AR11263 appears to have been M1.7 flare August 3, 2011 with coordinates (N15E08), to which the SXR plasma heated up to 19 MK. It was also an impulsive (6 min duration SXR GOES) and confined flare, in which there were no radio emission at frequencies <1415 MHz, type II and IV bursts.

Since the objective of this study is not to analyze the configuration and dynamics of the magnetic field, we assume that since the M9.3 flare on July 30, 2012, the conditions proposed by Ishkov (2023) for the ascent of a new magnetic flux in AO11261 had been realized (since the M1.7 flare on August 3, 2011 in AO11263). Therefore, in a few days, we are right to expect continued flare activity.

Indeed, from August 2 to 9, 2011, two SPEs were recorded, in which the flux of protons with energies >10 MeV exceeds >10 PFU, according to the catalog (https://umbra.nascom.nasa.gov/SEP/), and four SPEs with a proton flux >1 PFU >10 MeV, according to the catalog (https://swx.sinp.msu.ru/apps/sep_events_cat/docs/SPE_24_Summary_List.pdf). Figure 1 shows the time profiles of proton fluxes in differential energy channels 7.8–25 and 25–53 MeV of the SOHO/EPHIN detector and the temperature of the SXR plasma for the entire period under study. Tables 1–3 present the characteristics of flares whose SXR temperatures exceeded the threshold of 12 MK (horizontal arrow). These flares could have become proton flares; they are indicated by numerals in Figs. 2a, 2b, and 2d. Information was taken from solar activity reports compiled by the NOAA Space Weather Forecasting Center (https://cdaw.gsfc.nasa.gov/CME_list/NOAA/org_events_text/2011/) and the LASCO catalog (/cdaw.gsfc.nasa.gov/CME_list/).

Figure 1 shows, in the time profiles of proton intensity (SOHO/EPHIN), five increases associated with parent solar flares, and the largest, sixth increase (maximum proton flux for this period) was near the time of SC (sudden commencement of a magnetic storm) on August 5 (Fig. 2b). The increase on August 5

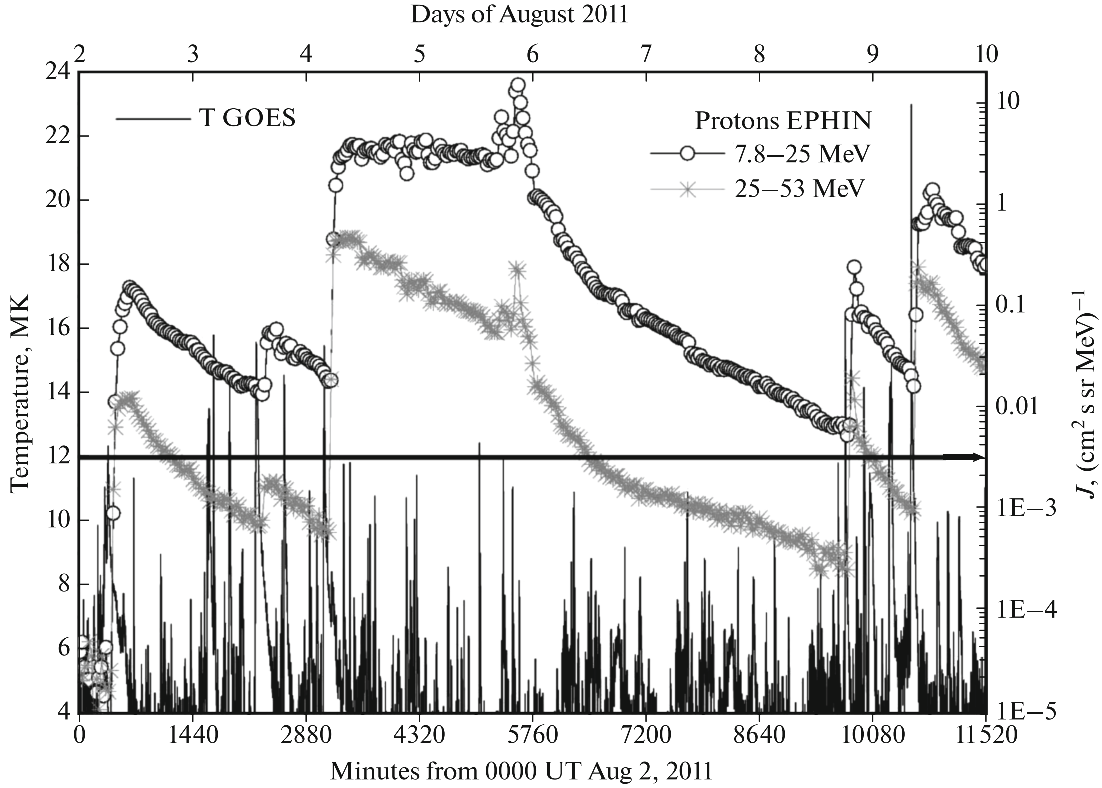

Fig. 1. Period from August 2 to 9, 2011 (upper horizontal scale is days of August; lower, minutes from 0000 UT on August 2, 2011). Flare plasma temperature calculated from GOES SXR detector data, black curve. Black arrow shows flare plasma threshold temperature of 12 MK for proton acceleration. Proton intensity in differential channels of EPHIN/SOHO detector is 7.8–25 MeV (black open circles) and 25–53 MeV (gray stars).

Table 1. Characteristics of flares with $T > 12$ MK for August 2–3, 2011 (see Fig. 2a)

A	B	C	D	E	F	G	H	I	J
1	**02/08 M1.4 12.3 MK**	**1261 N14W15**	**0519 0619 0648**	**0608 0608 0609**	**0559 0609 U0649**	**x – no p +**	**0636 712 296**	**0617 //// 0628**	**0612 //// 0946**
2A	03/08 M1.1 13.5 MK	1261 N17W24	0308 0337 0351	No	No	No	No	No	No
2B	03/08 M1.7 15.7 MK	1263 N15E08	0429 0432 0435	0431 0431 0431	No	No	No	No	No
3	03/08 C1.1 8.3 MK	1261 N15W27	0642 0646 0649	No	No	No	No	No	No
4	03/08 C8.7 14.4 MK	1261 N15W29	0738 0758 0806	No	No	No	No	No	No
5	**03/08 M6.0 15.6 MK**	**1261 N16W30**	**1317 1348 1410**	**1327* 1328 1335**	**1331 1334 1335**	**No**	**1400 610 316**	**1352 //// 1344**	**1330 //// A2359**
6	03/08 C8.5 14.5 MK	1261 N13W36	1923 1930 1942	No	1933 1933 1933	No	No	No	No

Table 2. Characteristics of flares with $T > 12$ MK for August 4–5, 2011 (see Fig. 2b)

A	B	C	D	E	F	G	H	I	J
1	**04/08** **M9.3** **15.5 MK**	**1261** **N19W36**	**0341** **0357** **0404**	**0349 0353** **0402**	**0351** **0356** **0423**	**X +** **p +**	**0412** **1315** **296**	**0354** **////** **0403**	**0400** **////** **1750**
2	05/08 C2.0 12.4 MK	1263 N19W24	1238 1245 1257	No	No	No P mod	No	No	No

Table 3. Flare Characteristics $T > 12$ MK for August 8–9, 2011 (see Fig. 2d)

A	B	C	D	E	F	G	H	I	J
1	**08/08** **M3.5** **16.3 MK**	**1263** **N16W61**	**1800** **1810** **1818**	**1803** **1803 1805**	**1803** **1804** **1826**	**No**	**1812** **1343** **276**	**1803** **////** **1816**	**No**
2A	08/08 C7.7 **14.2 MK**	1263	2200 2209 2220	No	No	No	No	No	No
2**B**	08/08 C5.3 11.5 MK	1263	2302 2322 2359	No	No	No	**2312** **1070** **275**	No	No
3	09/08 M2.5 15.5 MK	1263 N18W68	0319 0354 0408	No	No	No–	0348 1146 275	No	No
4	**09/08** **X6.9** **23 MK**	**1263** **N17W69**	**0748** **0805** **0808**	**0801** **0803 0807**	**0800** **0802** **0809**	**x +** **p +**	**0812** **1610** **280**	**0801** **////** **0816**	No

A, flare number on different panels of Fig. 2, letters separate merging flares; B, date, X-ray score and maximum temperature; C, number of active area and coordinates; D, SXR flare GOES time UT (onset, maximum, end); E, microwave radiation 15.4 GHz, time UT (RSTN, onset, maximum, end); *, case is highlighted when there is no information about 15.4 GHz; F, plasma radiation 245 MHz, time UT (RSTN, onset, maximum, end); G, ACS SPI detection of solar HXR radiation and solar protons >100 MeV; H, time UT of first appearance of CME in LASCO field of view and average velocity km/s, angle PA; H, type II radio emission (onset and end UT); I, type IV radio emission (onset and end UT). Cases of increase in EPHIN proton signal are in boldface.

is apparently associated with the modulation of an already existing proton flux in the IS near propagating shock waves (storm particles); it is an analog of "rogue events" (Kallenrode and Cliver, 2001), but with much lower intensity.

Of the flares on August 2–3, 2011, only two, (1) and (5), produced obvious proton enhancements (see Table 1, Fig. 2a), which showed $T > 12$ MK, development in plasma with characteristic frequencies <245 MHz, and CME velocity close to 618 km/s. Despite the clearly defined flare source (5) in the catalog (https://swx.sinp.msu.ru/apps/sep_events_cat/docs/SPE_24_Summary_List.pdf), event (5) is marked as the second maximum of event (1) with a maximum intensity of 0.55 PFU and a quasi-maximal energy of 70 MeV, as not exceeding the threshold of 1 PFU. Flares (2a), (2b), (3), and (4) were confined, they did not develop upward into the corona, and SPEs and CMEs not accompanied them.

Zuccarello et al. (2014) considered the evolution of a magnetic field in AR 11261 from 0200 UT on August 3 to 0400 UT on August 4, which led to the eruption of a filament and flare (1) in Table 2. According to the authors, the key events were: (2) large and small filaments becoming visible, (3) activation of a small filament, and (5) eruption of a small filament (see Table 1, Fig. 3a). For unknown reasons, the event (1) on August 2 was not considered by Zuccarello et al. (2014). In our concept of the development of eruptive flares, eruption of a magnetic flux rope is not a necessary condition.

From the flares of August 4–5, 2011 (Table 2, Fig. 2b), the obvious proton increase is associated only with flare (1), which showed $T > 12$ MK, development in plasma with characteristic frequencies <245 MHz, and a CME velocity >1300 km/s. In this flare, protons with energies above the threshold energy of π_0 meson generation were accelerated. Altyntsev et al. (2019) consider the very beginning of the impulsive phase, in which they estimated the acceleration time of electrons (on the order of tens of milliseconds) in individual pulses and consider this an argument against stochastic acceleration. However, the arrival time of the

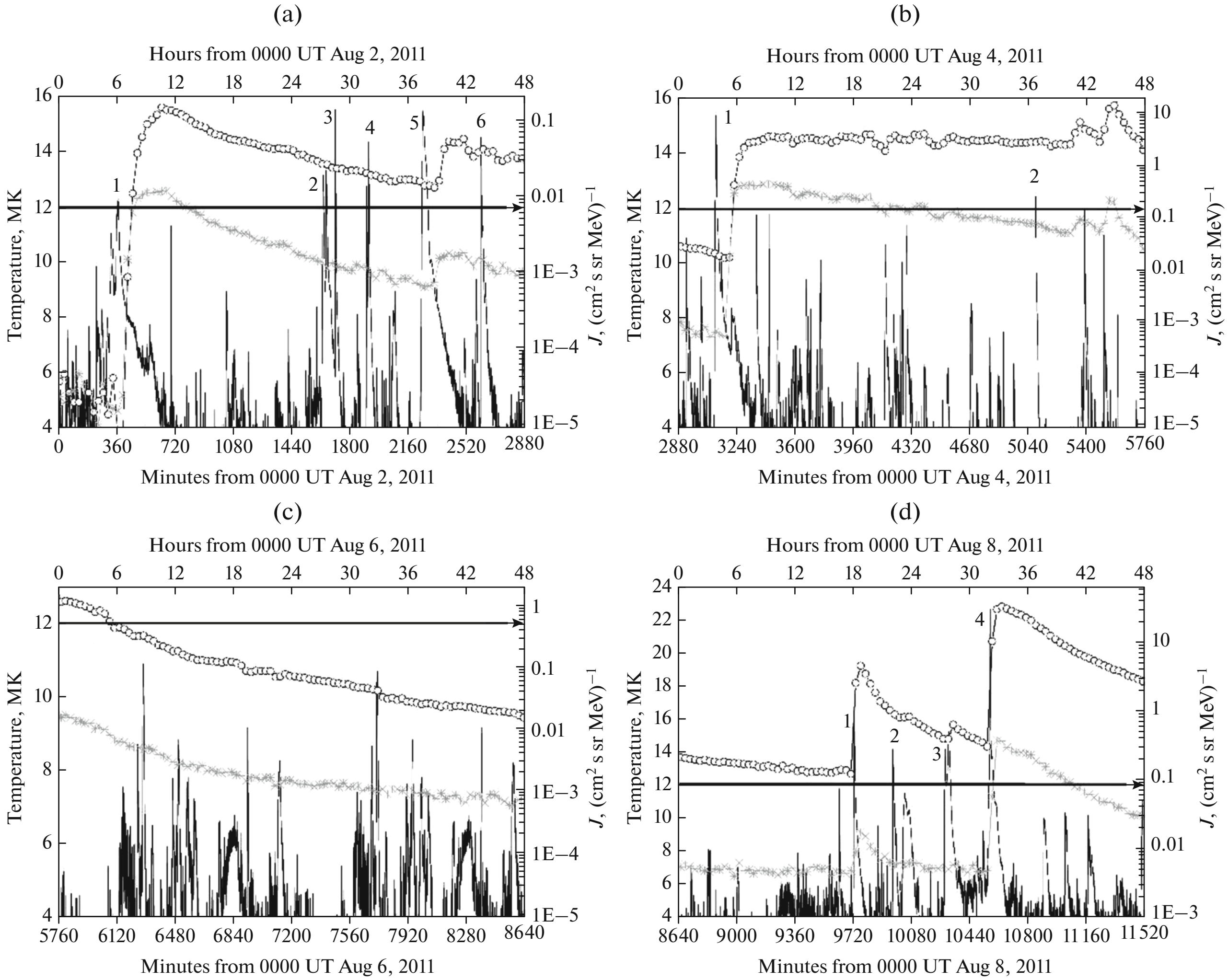

Fig. 2. See Fig. 1 for notation. Period from August 2 to 9, 2011, is divided into 2-day segments: (a) August 2–3, (b) 4–5, (c) 6–7, and (d) 8–9. Upper horizontal scale is hours; lower, minutes. Numerals in each panel correspond to flare numbers in Tables 1–3.

first protons—later than 20 min with respect to the chosen zero—indicates stochastic "slow" acceleration. Flare (2) on August 5 (Table 2, Fig. 2b) does not meet the criteria: duration $T > 12$ MK, plasma and microwave (HXR) radiation, and, as expected, no SPEs and CMEs.

None of the flares on August 6–7, 2011 (Fig. 2c) overcame the temperature threshold of 12 MK. On these days, CMEs with velocities greater than the local second escape velocity (on the solar surface, 618 km/s) were not observed, and proton fluxes recorded in the SOHO/EPHIN channels, decreased monotonically.

Four flares on August 8–9, 2011 (Fig. 2e, Table 3), which occurred in AO11263, were accompanied by CMEs. Events (1) and (4) are marked as proton events in the catalog (https://swx.sinp.msu.ru/apps/sep_events_cat/docs/SPE_24_Summary_List.pdf) with quasi-maximal energies 100 and 650 MeV, respectively. They satisfy the criteria for plasma and nonthermal radiation. Only in flare (4) were protons with energies above the π_0-meson generation threshold accelerated; after this, there was a proton increase in the ACS SPI counting rate. Flares (2a), (2b), and (3) (Fig. 2e, Table 3) do not meet the criteria for plasma and non-thermal radiation for proton acceleration >100 MeV. We do not know which of the two flares, either (2a) not accompanied by a CME, or (2b) with an SXR plasma temperature <12 MK, contributed to the proton flux 7.8–25 MeV detected by SOHO/EPHIN.

Figure 3 shows the ACS SPI count rate curves for 50 ms (smoothed 1 min averages, background subtracted) with respect to moments of the specified zero time UT on August 2 (light gray curve), August 4 (gray curve), August 5 (thin black curve), and August 9 (black curve) 2011. Proton increases on August 2 and 4 with quasi-maximal energies of 120 and 500 MeV were observed later than 20 min and correspond to "slow" electron acceleration. The proton increase on August 9

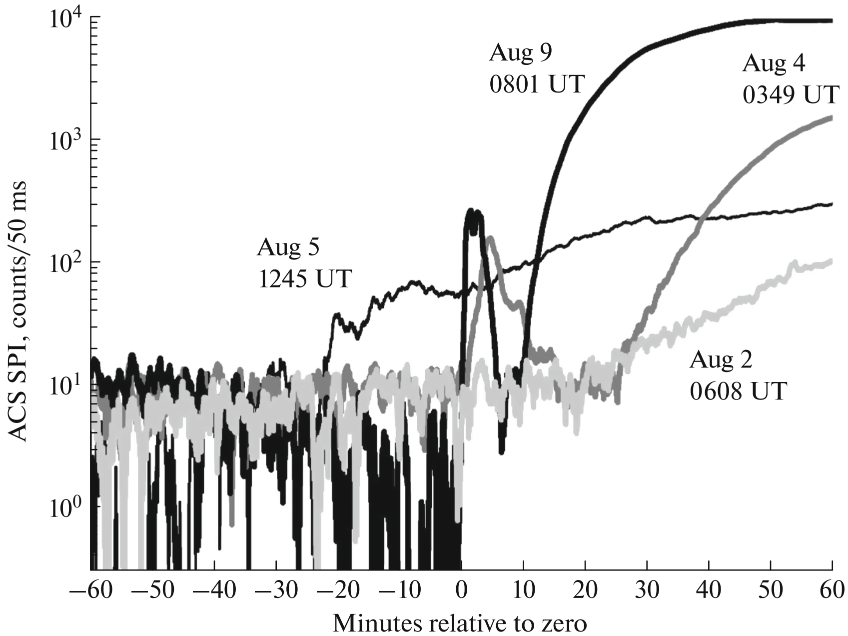

Fig. 3. ACS SPI count rate for 50 ms (smoothed 1 min averages, background subtracted) with respect to specified zero UT time in events 2 (light-gray curve, proton signal after 25 min), 4 (gray curve, HXR 0–15 min, solar protons after 25 min), 5 (thin black curve, modulation of GCR and SCR flux after –25 min), and 9 (black curve, HXR 0–7 min, solar protons after 10 min) August 2011.

with a quasi-maximal energy of 650 MeV is early (less than 20 min) and corresponds to "fast" acceleration (Grigorieva et al., 2023); it showed the greatest increase in the ACS SPI counting rate in the first hour after zero. The event on August 9, 2011, did not produce a ground level event (GLE), since there was insufficient time for acceleration of the required number of protons with energies above the atmospheric cutoff threshold (Grigorieva and Struminsky, 2022).

Thus, a detailed examination of five parent flares favorably located for observing SPEs (which made a visible contribution to the proton fluxes recorded by SOHO/EPHIN) shows that all of them were distinguished by three observational features:

(1) the flare plasma temperature T, calculated from data of two channels of the GOES soft X-ray detector, was >12 MK for 2 min or more;

(2) the plasma density corresponded to plasma frequencies <610 MHz (RSTN);

(3) acceleration of the CME (SOHO_LASCO) to velocities greater than the local second cosmic velocity (618 km/s at the solar surface).

A distinctive feature of flares in which protons with energies $E > 300$ MeV were accelerated (SPE observations (https://swx.sinp.msu.ru/apps/sep_events_cat/docs/SPE_24_Summary_List.pdf) and γ-radiation with energies $E > 100$ MeV (FermiLAT, (Ajello et al., 2021)); there was a fourth feature: (4) generation of HXR radiation with $E > 100$ keV for > 5 min, which was reliably recorded by the RHESSI and ACS SPI detectors. It is these two events on August 4 and 9, 2011, that meet the SPE 10 PFU criterion, according to the catalog (https://umbra.nascom.nasa.gov/SEP/).

By our opinion, these four features together are necessary and sufficient observational conditions for real-time forecasting of the most hazardous proton flares and subsequent SPEs. To predict quantitatively the onset time, maximum and magnitude of the proton flux, as well as its fluence, statistical regression models are needed based on all of the listed characteristics of past SPEs, which remain to be done.

5. CONCLUSIONS

Necessary and sufficient observational features for real-time forecasting of the most hazardous proton flares and subsequent SPEs are considered.

To implement the proposed method, patrol observations of the following are required:

(1) the magnetic field of active regions (ascent of the flow) and total magnetic field of the Sun, which will make it possible to forecast the onset of flare activity several days before the main events (ground- and space-based magnetographs for continuous observation of the Sun 24 h/day);

(2) soft X-ray radiation in two channels to calculate the temperature and plasma emission measures, which will show overcoming of the threshold for the SXR plasma temperature necessary for the onset of proton acceleration (several tens of minutes before the onset of HXR radiation);

(3) radio emission at plasma frequencies (<1000 MHz), which will show the development of the flare process in height, leading to a CME, a few minutes before the onset type II and IV radio emission;

(4) hard X-ray radiation >100 keV and/or microwave radiation (GHz), which will show the intensity and duration of operation of the electron accelerator (a few and tens of minutes before the onset of proton growth in Earth's orbit);

(5) kinematic parameters of CMEs, which determine the conditions for the release of accelerated protons into the heliosphere (a few hours until the maximum intensity of protons on Earth).

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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