

Article

The Response of the Multichannel Detector Complex of the Tien Shan Cosmic Ray Station to an Event of Ground-Level Enhancement and Large Forbush Effects in November 2025 and January 2026

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Abstract

Large episodes of solar activity of the 25th cycle, an extreme Forbush decrease event on 19 January 2026, a series of Forbush effects in November 2025, and an event of ground-level enhancement (GLE 77) on 11 November 2025 have left prominent traces in the monitoring data obtained at a height of 3340 m a.s.l. from the detector facilities of the Tien Shan High-Mountain Cosmic Ray Station. The effects these events have caused on the flux of galactic cosmic rays in the several-GeV energy range, as registered with the standard NM64-type neutron supermonitor, are compared here with their influence on the local neutron and gamma radiation background in the high-mountain environment, which was observed in the counting rate records of the thermal neutron and MeV-order-energy gamma radiation detectors also installed at the station.

Keywords: cosmic rays; solar flare; Forbush effect; ground-level enhancement; environmental radiation background



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1. Introduction

Cosmic rays are a stream of high-energy charged particles coming from interstellar space. Among them, the nuclear component prevails: nearly 90% of cosmic ray particles are protons, about 10% helium nuclei, and approximately 1% heavier nuclei. Sometimes, the flux of cosmic rays sharply intensifies due to particles of solar origin. On intrusion into Earth's atmosphere, primary cosmic rays disintegrate the nuclei of nitrogen and oxygen, initiating a cascade process. Ground-based detector facilities register the flux of secondary particles formed after the passage of cosmic ray particles through the atmosphere.

Highly important information on the processes developing in interplanetary space and the near-Earth environment may be obtained through variation study of the flux of cosmic rays of galactic and solar origin. Particularly informative are the measurement data from neutron monitors, which are standard instruments for registering cosmic ray

variations. Typically, neutron monitors register the evaporation neutrons that originate within a monitor under the influence of high-energy secondary hadrons (mostly neutrons), which, in turn, are the products of nuclear reactions initiated by cosmic ray particles during their collision with air nuclei in the atmosphere. Thus, the counting rate of neutron detectors installed inside a monitor is proportional to the current flux of primary cosmic rays. Neutron monitors are sensitive to the flux of cosmic rays in the energy range of about (0.5–20) GeV, which cannot be investigated as simply or with comparably high statistical accuracy by space-based instruments. Presently, the neutron monitors around the world comprise a global network, and their data are united in the Neutron Monitor Database (NMDB) [1].

The most diversified and actively studied phenomena regarding variations in cosmic rays are Forbush effects, first discovered by Scott Forbush in 1937 as a considerable decrease in cosmic ray intensity measured with the Compton–Bennett meters at the Cheltenham (Maryland) and Huancayo (Peru) stations and explained by him as an impact of a magnetic storm [2]. Presently, a more general naming is accepted for such phenomena, Forbush effect (FE), which is defined as a change in the density and anisotropy of cosmic rays caused by large-scale variations regarding solar wind [3,4].

Large solar wind variations occur due to the active processes on the Sun, which influence interplanetary space. The source of these variations may be sporadic phenomena, such as solar flares and the disappearance of solar filaments, resulting in coronal mass ejection (CME), as well as recurrent coronal holes emitting into space a high-speed flow of solar wind particles. Correspondingly, Forbush effects are divided into sporadic and recurrent ones [5–12].

The opposite of Forbush decrease events are ground-level enhancements (GLEs), which are of special interest in the investigation of cosmic ray variation. These are events when the Sun accelerates charged particles up to extremely high energy that is sufficient for them to reach near-Earth space and interact with the atomic nuclei of Earth's atmosphere such that the secondary particles of these interactions can be registered with on-ground detectors. GLEs occur rather rarely. Since 1942, only 77 events have been detected, i.e., approximately a single event per year. The data on all registered events are stored in the International GLE Database [13]. Most detailed information on GLE events is provided by the worldwide network of neutron monitors.

GLE events are connected with detection of high-energy particles accelerated at solar flares and CMEs [14]. An event would be considered as a GLE if an increase in the counting rate took place at least in two neutron monitors situated at different geographical locations, one of which must be hosted at an altitude near sea level. Also, an increase in proton flux must be practically simultaneously observed by space-borne instruments, which mostly belong to the Geostationary Operational Environmental Satellites (GOES) series [15].

GLEs differ by their magnitude. During the whole era of neutron monitor use, the strongest event, with the maximum integral intensity of about 6000% · h, occurred on 23 February 1956 [16,17]. The last small event, GLE 75 on 8 June 2024, with an increase in neutron monitor counting rate of only 3% · h, was revealed retrospectively such that a statistically meaningful intensity increase was detected merely at high-latitude neutron monitors Dome C, the South Pole, and Peawanuck [18].

Most Forbush effects have a small amplitude below ~3%. Events with an amplitude exceeding 10% are rare. According to the Forbush Effects and Interplanetary Disturbances Database (FEID) created in IZMIRAN, which includes above 9300 events [19], about 30 such FEs were observed between 1957 and 2024. Major FEs are connected with the arrival to Earth of large disturbances in solar wind, which appear under the influence of CME or have mixed solar sources, including big CMEs [5,20,21]. Every such event should be studied

in detail, preferably with maximal available information, including datasets from various experimental facilities that supplement standard neutron monitor data.

An example of such a multichannel approach is an experimental complex of the Tien Shan High-Mountain Cosmic Ray Station, which resides at an altitude of 3340 m above sea level in the mountains of Northern Tien Shan (43.04° N, 76.94° E). Together with a standard neutron supermonitor of the 18NM64 type, there are other instruments installed at the station that are capable of long-term uninterrupted monitoring of radiation background in the local station's environment: gamma ray detectors operating with different energy thresholds of registered radiation, from tens of keV to several MeV, and detectors of the environmental flux of thermal neutrons [21]. A detailed description of the experimental complex of the Tien Shan Cosmic Ray Station may be found elsewhere [22–26].

During autumn–winter 2025–2026, there were two periods of highly intensive solar flares resulting in large Forbush effects, which left noticeable traces in the datasets of the Tien Shan Cosmic Ray Station. These were a series of solar flares in November 2025, which caused a sequence of FEs, an event of ground-level enhancement (GLE 77), and a large solar flare on 18 January 2026, which led to a significant Forbush decrease event on 19 January. The current publication presents various manifestations of these extreme events in the data acquired at the Tien Shan station from various detector facilities.

2. A Highly Intensive Forbush Decrease Event on 19 January 2026

2.1. The Solar, Heliospheric, and Geomagnetic Conditions

The Forbush effect that happened on 19–27 January 2026 was due to disturbances in the interplanetary and near-Earth medium caused by the passage of a coronal mass ejection from an 18 January solar flare.

On 18 January 2026, a long-duration X1.9 solar flare occurred in the active region AR4341 situated near the center of the Sun's disc. The start of the flare in the X-ray range was fixed at 17:27 UT; its maximum was reached at 18:09 UT. The flare of the highest class X initiated a coronal mass ejection, directed mostly eastward. Nevertheless, from the LASCO/C2 and LASCO/C3 coronagraph data of the Solar and Heliosphere Observatory (SOHO) [27], it is seen that the ejection belongs to the halo IV type, which is why it still happened geoeffectively. During the flare, generation of high-energy particles was observed, with a maximum flux of ≥ 10 MeV protons reaching $3.7 \cdot 10^4 \text{ cm}^{-2}\text{s}^{-1}$, as registered on 19 January by the geostationary satellites of the GOES series [28].

Because of the high propagation speed of the ejected matter through interplanetary space of about $1100 \text{ km}\cdot\text{s}^{-1}$, the shock wave achieved Earth's magnetosphere at 21 UT on 19 January, resulting in a geomagnetic storm. According to the Geomagnetic Observatory of the Institute of Ionosphere in Almaty, this extraordinarily intensive magnetic storm continued for nearly two days. An extreme storm of 3 h duration with an index of geomagnetic activity $Kp \geq 9$, two periods of severe storm ($Kp \approx 8$), three episodes of moderate storm ($Kp \approx 6\text{--}7$), and 5 periods of minor storm ($Kp \approx 5$) were detected.

The variation time history of the solar wind and geomagnetic parameters around the date of 19 January 2026 is illustrated by the plots in Figure 1. The data on the speed of solar wind and the strength of the interplanetary magnetic field (IMF) from NASA's Advanced Composition Explorer (ACE) mission presented here were obtained from the website [29]. Information on the state of the geomagnetic field, expressed through the commonly used indices Kp and ap , was obtained from the site [30].

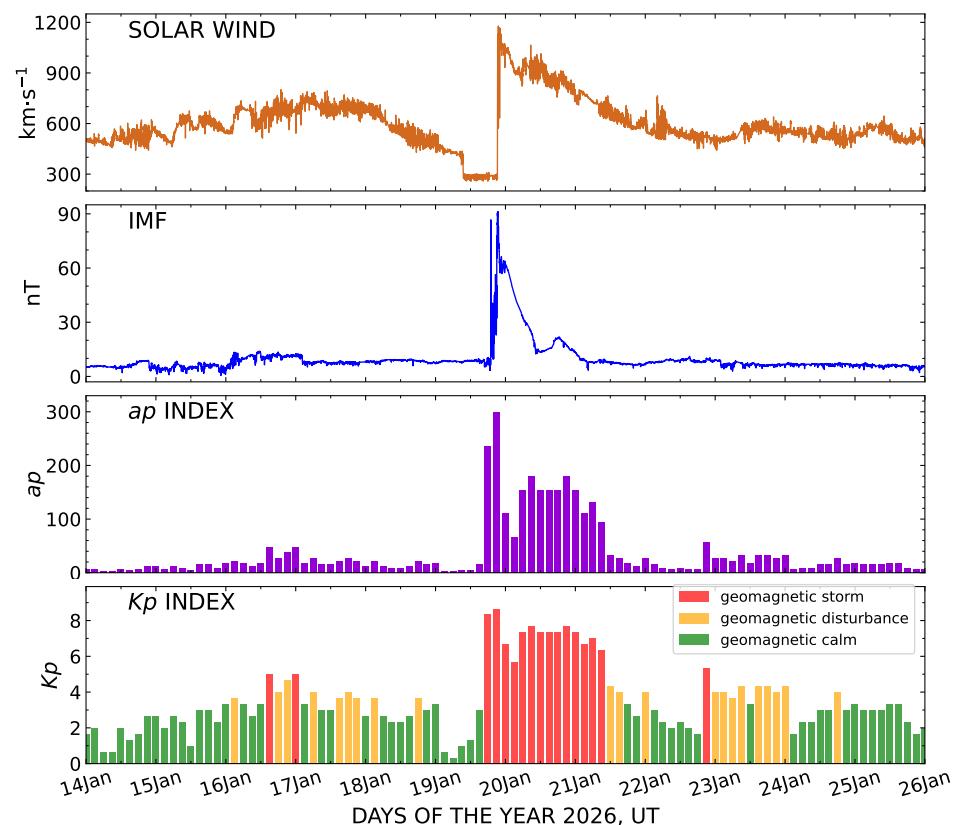


Figure 1. The heliospheric and geomagnetic conditions in January 2026: the speed of solar wind, the module of the strength of the interplanetary magnetic field (IMF), and the ap and Kp indices of the geomagnetic field. The data taken from the sites [29,30].

As noted in [31], a sudden decrease in geomagnetic indices observed in the first half of 19 January 2026 may correspond to a compression of the magnetosphere with development of a ring current afterwards, thereby indicating the moment of arrival into the near-Earth space of the matter of the CME that triggered disturbances in interplanetary space.

2.2. The Impact of the Forbush Effect on the Counting Rate of the Tien Shan Neutron Supermonitor

The Forbush effect of 19 January 2026 was registered by the neutron monitors of the worldwide NMDB network [1], including the NM64-type neutron supermonitor of the Institute of Ionosphere (the NMDB monitor station AATB; 3340 m a.s.l.; cutoff rigidity of 5.9 GV).

The record of the counting rate R registered during the Forbush decrease event at the Tien Shan neutron supermonitor is presented in Figure 2, where it is seen that the drop in intensity of cosmic rays starts at the moment of about 22:25 UT, 19 January 2026. The data of the measurements that proceed with a one-minute periodicity, as is generally accepted in NMDB, are shown in the plot with a thin line; the bold line indicates the same data averaged over one-hour-long periods. All the measurements are corrected for variations in atmospheric pressure, as described in [21].

A period of the neutron supermonitor operation in quiet time just before the beginning of the Forbush effect is stressed in Figure 2 with dashed lines. The measurement data obtained during that interval were used to calculate the values of the mean counting rate of neutron signals $\langle R \rangle$ and its standard deviation σ as in undisturbed conditions. The deviation σ has both statistical and systematic components, being influenced by various small factors (mostly diurnal variation in the intensity of primary cosmic rays in the GeV energy range).

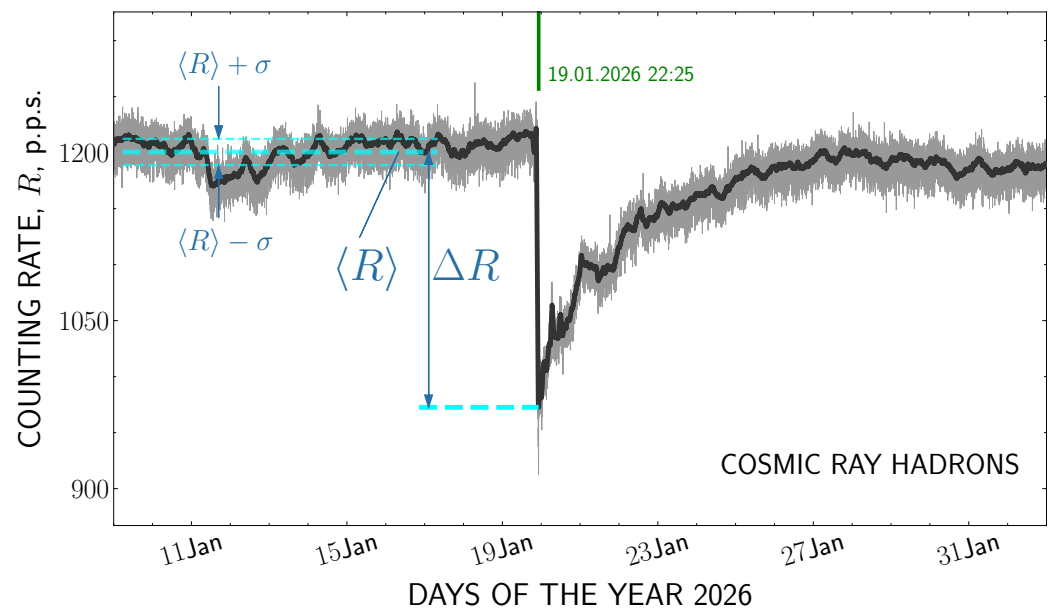


Figure 2. The counting rate of the hadronic component of cosmic rays with the cutoff rigidity of 5.9 GV, as measured at the Tien Shan neutron supermonitor during the big Forbush decrease event in January 2026. Thin curve corresponds to the data of original measurement made with a 1 min time resolution; same data smoothed with hourly resolution are shown with the overlapping bold curve. Definitions of the value of undisturbed mean counting rate $\langle R \rangle$, the levels of its standard deviation $\pm \sigma$, and the ΔR step at the peak of Forbush decrease are indicated in the plot. The counting rate is expressed as a summed per-second number of pulse signals (p.p.s.) that come from all neutron counters of the Tien Shan neutron supermonitor.

According to the numerical data presented in Figure 2, the relative magnitude of the FE, calculated as $\Delta R / \langle R \rangle$, was about 20%. (Here, ΔR is the absolute drop in the counting rate at the peak of the Forbush decrease.) Thus, this event is one of very large FEs, which should be analyzed with the implication of possibly wide bulk of available experimental material.

As such additional information extending the traditional measurement of the integral counting rate in the monitor's neutron detectors, the intensity of the events of multiple neutron production in the monitor may be addressed. Indeed, the Tien Shan neutron supermonitor has the ability to provide the number of events separately when strictly one, two, three, etc., evaporation neutrons originating from an interaction of cosmic ray hadrons inside the monitor were detected during a small time interval, the *gate time*. As numerous investigations of the neutron monitor method have shown, there generally exists a correlation between the number M of neutron signals registered shortly after nuclear interaction caused by a cosmic ray hadron inside the monitor and the energy E_h of that hadron [21–23]. Traditionally, the duration of the gate time for the measurement of neutron multiplicity at the Tien Shan neutron supermonitor was set to 800 μ s. This value is close to the mean lifetime, of ~ 650 μ s, of the evaporation neutrons born inside this facility after a high-energy hadron interaction.

The variations in the counting rate of the events of multiple neutron generation during the Forbush effect of 19 January 2026 are plotted in Figure 3, separately for the events with different multiplicities. All the data presented in these plots are corrected for variations in atmospheric pressure. A synchronous drop in the counting rate reflecting the Forbush effect is distinctly seen in all the distributions.

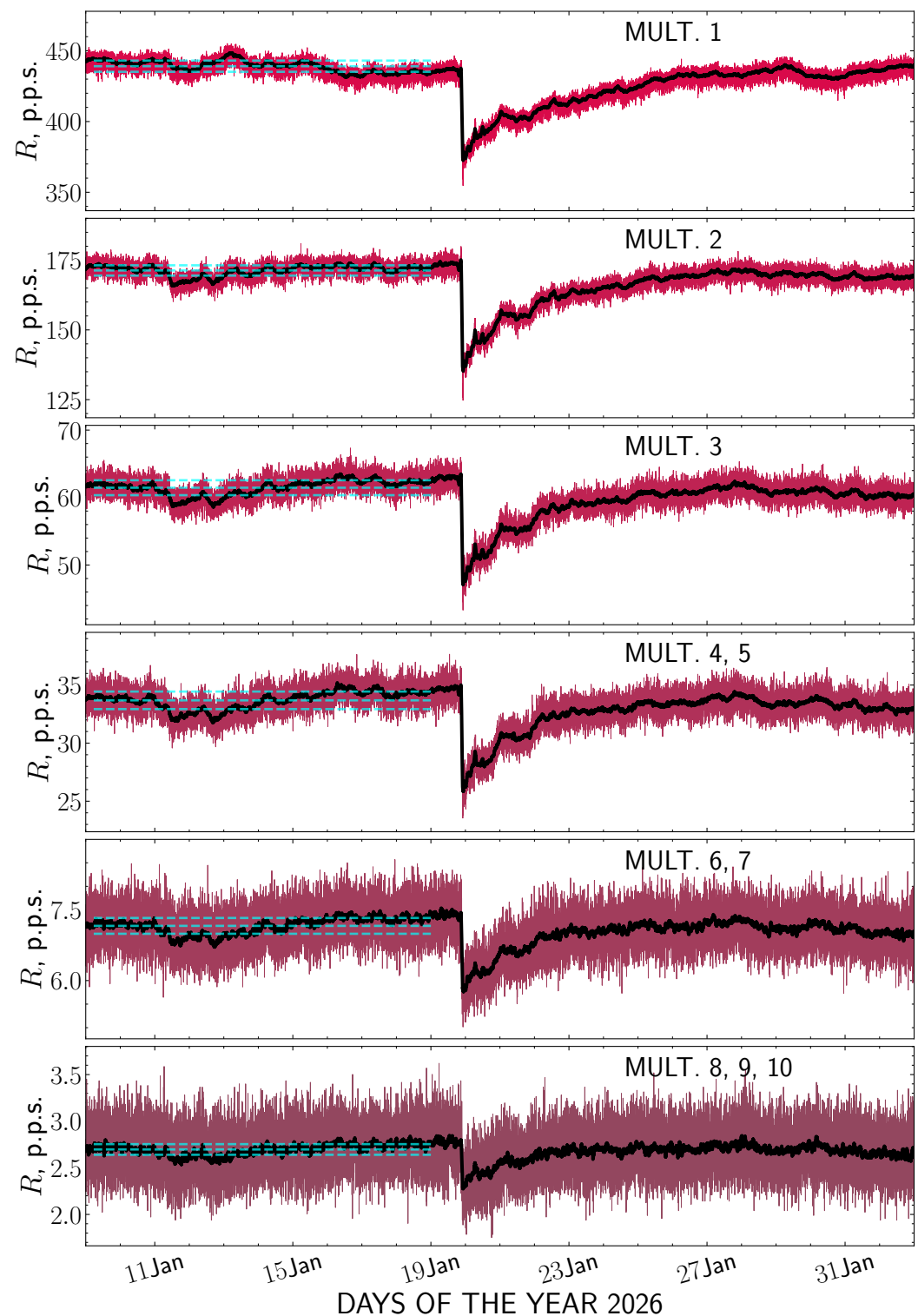


Figure 3. The impact of the Forbush decrease of 19 January 2026 on the counting rate R of the events of multiple neutron generation in the Tien Shan neutron supermonitor. Thin lines correspond to the original one-minute measurements; superimposed bold ones correspond to the same data smoothed with 1 h resolution. Vertical axes are graduated in the units of the counting rate R expressed as a pulse per second (p.p.s.) count. Dashed lines at the beginning of each distribution mark the quiet period before the Forbush event used for calculation of the value of the mean undisturbed counting rate $\langle R \rangle$ and the levels $\pm\sigma$ of its standard deviation.

Table 1 summarizes all the information concerning the effect of the Forbush decrease event on the data about the cosmic ray intensity acquired from the Tien Shan neutron su-

permonitor. The values of the mean counting rate $\langle R \rangle$ and its standard deviation σ shown in the two leading columns of the table were calculated over one-hour-averaged data of the measurements made during the quiet period immediately preceding the Forbush effect; in Figures 2 and 3 the duration of this period is indicated with dashed lines. Absolute magnitude of the Forbush decrease ΔR observed in various informational channels of the neutron supermonitor was calculated at the peak of FE, also using the data with hourly resolution. The estimates of the average energy of cosmic ray hadron E_h that correspond to a particular range of the multiplicity M , which are shown in the first column of the table, were determined in accordance with a formula $E_h \approx 0.5 \cdot M^{1.8}$ GeV, explained in [21].

Table 1. Parameters of the 19 January 2026 Forbush decrease in the data of the Tien Shan neutron supermonitor.

Observable	Mean Counting Rate, $\langle R \rangle$, p.p.s.	Standard Deviation, σ , p.p.s.	Magnitude of Forbush Decrease, ΔR , p.p.s.	Relative Magnitude, $\Delta R/\langle R \rangle$, %	Magnitude in Standard Deviations, $\Delta R/\sigma$
Integral count	1201	11.7	230	19.2	19.7
Single-neutron events, $M = 1$; $E_h \simeq (0.5\text{--}1)$ GeV	439	4.0	66.1	15.1	16.5
$M = 2$; $E_h \simeq 2$ GeV	171	1.8	36.3	21.2	20.2
$M = 3$; $E_h \simeq 3$ GeV	61.5	1.1	14.5	23.5	13.2
$M = 4, 5$; $E_h \simeq (6\text{--}10)$ GeV	33.7	0.76	7.9	23.4	10.4
$M = 6, 7$; $E_h \simeq (13\text{--}17)$ GeV	7.2	0.17	1.42	19.7	8.4
$M = 8, 9, 10$; $E_h \simeq (20\text{--}30)$ GeV	2.7	0.06	0.43	15.9	7.2

According to Table 1, the Forbush effect of 19 January 2026 was seen in the neutron supermonitor as a prominent drop in the counting rate registered in all its channels, both in the integral count of the neutrons produced under the influence of cosmic ray hadrons and among the events divided over various ranges of their multiplicity M . The relative magnitude $\Delta R/\langle R \rangle$ of this decrease was about tens of percent, and its statistical confidence $\Delta R/\sigma$ was rather high, nearly an order of magnitude above the level of standard fluctuation σ . Most distinctively the Forbush effect revealed itself among the counting rate of the events with the multiplicity $M = (2\text{--}5)$, where the relation $\Delta R/\langle R \rangle$ achieves nearly (21–23)%. This multiplicity range corresponds to the secondary cosmic ray hadrons with the energy E_h of about (2–10) GeV. A similar conclusion has been reached from investigation of another large FE considered in [21].

2.3. The Drop in the Local Neutron and Gamma Radiation Background During the Forbush Decrease Event

Besides the neutron supermonitor, the experimental complex of the Tien Shan Cosmic Ray Station includes the detectors of the background flux of thermal neutrons and gamma rays [21].

In January 2026, the neutron detectors, each consisting of a set of proportional gas discharge counters sensitive to the neutrons in the thermal energy range, were operating in the two points situated in the territory of the station and separated with a distance of ~ 180 m. The sum sensitive area of neutron counters constituting each detector equals

1.1 m². One of them, detector #1, is installed at a height of ~2.5 m to measure the neutron flux in the near-surface atmosphere. Another one, detector #2, is placed at the level of the ground in a local depression of the surface.

In contrast to the neutron supermonitor, the detector of the thermal neutron background registers the neutrons that are born in the environment, partially under the influence of cosmic rays, partially as a result of the processes of natural radioactivity, and then they thermalize and diffuse in the soil and near-Earth atmosphere.

There were, also at the Tien Shan Cosmic Ray Station two gamma detectors, one of them installed at the level of the Tien Shan Cosmic Ray Station, 3340 m a.s.l., the other somewhat higher, at an altitude of 3750 m. Both detectors are based on a NaI scintillation crystal with an outer sensitive area of 0.038 m² and equipped with an amplitude discriminator that permits selecting the signals that correspond to different energy ranges of registered gamma radiation between 30 keV and 2 MeV.

Like the Tien Shan neutron supermonitor, registration of the counting rate at all the thermal neutron and gamma radiation detectors proceeds continuously in monitoring mode with a 10 s time gap between subsequent measurements. This permitted to gain detailed data series of the environmental neutron and radiation flux in the time of the Forbush decrease event of 19 January 2026. The data series are presented in Figure 4, both with their original time resolution of 10 s and after averaging over one-hour-long intervals. The thermal neutron data shown in the plots were corrected for the atmospheric pressure in the standard way [21]; the data on gamma ray intensity are left in their original state.

The parameters of the intensity drop in the distributions of Figure 4 that were fixed at the peak of the Forbush decrease are listed in Table 2. The mean values of the counting rate $\langle R \rangle$ and their standard deviations σ shown in the table were calculated over the time distributions averaged with hourly resolution and using their fragment that corresponds to the quiet period in January 2026 before the beginning of the Forbush effect. In Figure 4 this fragment is marked with dashed lines.

Table 2. Parameters of the decrease in the local background of thermal neutrons and gamma radiation at Tien Shan Cosmic Ray Station during the Forbush effect of 19 January 2026.

Detector Facility	Mean Counting Rate, $\langle R \rangle$, p.p.s.	Standard Deviation, σ , p.p.s.	Magnitude of Forbush Decrease, ΔR , p.p.s.	Relative Magnitude, $\Delta R/\langle R \rangle$, %	Magnitude in Standard Deviations, $\Delta R/\sigma$
Detector #1, thermal neutrons	18.3	0.16	3.9	21.3	24.4
Detector #2, thermal neutrons	13.5	0.11	2.8	20.7	25.5
Gamma detector at 3340 m, $E_\gamma \geq 1000$ keV	32.0	0.90	3.6	11.3	4.0
Gamma detector at 3750 m, $E_\gamma \geq 1300$ keV	45.3	1.2	5.3	11.7	4.4

As follows from the table, at the maximum of the extraordinary Forbush effect of 19 January 2026, the relative amplitude of the drop in the intensity of the environmental neutron flux was about 20%, quite comparable with what is shown in Table 1 for the counting rate of the Tien Shan neutron supermonitor. This observation agrees with similarity between the decrease amplitudes found in cosmic rays and neutron background during another large Forbush effect of 1 June 2025 [21] and confirms the possibility of using the

detectors of environmental neutron background of the type applied at the Tien Shan Cosmic Ray Station for regular monitoring of the large effects in cosmic rays connected with the processes of solar activity.

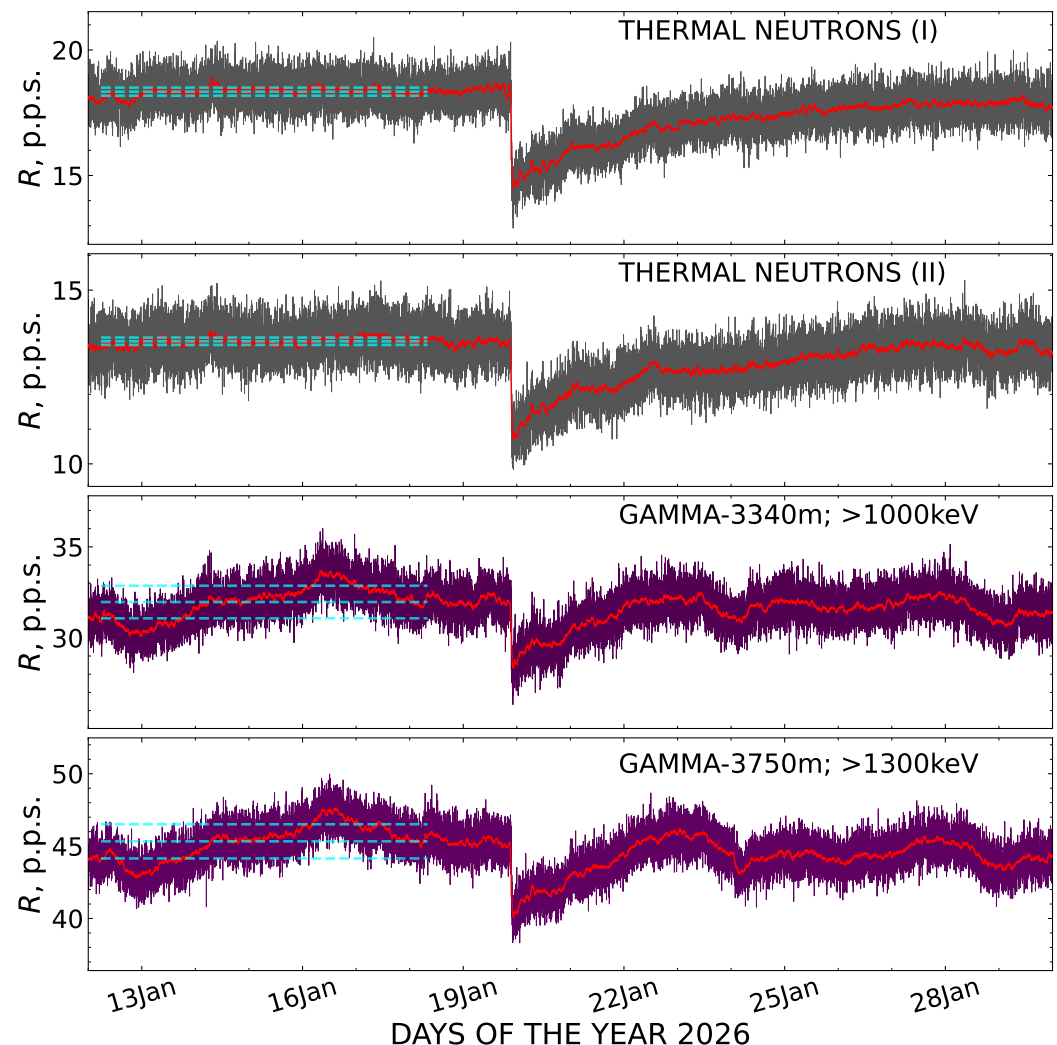


Figure 4. The Forbush decrease in cosmic ray intensity on 19 January 2026, as observed in the data on the counting rate R of the thermal neutron and gamma radiation detectors. The distribution of original 10-second-resolution measurements is indicated with thin lines; the superimposed smooth lines correspond to 1-hour-averaged data. Other designations are the same as in Figure 3.

The relative magnitude of the decrease in the local flux of MeV gamma rays indicated in Table 2 is nearly twice as low as that of the neutron background, which is also in agreement with the mentioned observation of the 1 June 2025 Forbush effect. The noticeably larger fluctuation observed during the quiet time in the radiation intensity, typically $\sigma / \langle R \rangle \simeq 3\%$ for gamma rays against less than one percent for the neutron data, is explained by the essential influence on the radiation background from the diurnal oscillation of local temperature, precipitation, and other meteorological factors. Nevertheless, the effect from the large Forbush effect of 19 January can be quite distinctly seen over the intensity record of MeV gamma rays.

3. The Sequence of Forbush Effects in November 2025

3.1. The Solar, Interplanetary, and Geomagnetic Situation in November 2025

A rather prolonged succession of Forbush effects observed during November 2025 were connected with the disturbances in interplanetary and near-Earth space that appeared

because of solar activity in the active region AR14274. Intensive M- and X-class flares took place in this region from 9 to 14 November. Large Forbush effects of 7–16 November were preceded by a small FE on 4–5 November, caused by the arrival of a high-speed flux of solar wind from a coronal hole.

The complicated structure of FEs from 7 to 16 November was due to propagation through the interplanetary space of several coronal mass ejections after a sequence of solar flares. Thus, an X1.7 flare with succeeding CME occurred in the region AR14274 on 9 November at 07:35 UT, and, on 10 November, 09:19 UT, there was another flare, with a CME as well. On 10 November, weaker CMEs also occurred, which could have interacted with the previous ones. The effect of these CMEs on Earth's magnetosphere resulted in a severe geomagnetic storm that happened on 12–13 November, when the Kp index exceeded 8. As follows from the records of the Geomagnetic Observatory of the Institute of Ionosphere, the storm lasted 42 h, at which time there was a single period of severe storm, five periods of moderate storm, and three periods of minor storm.

A compilation of the variation data on the solar, heliospheric, and geomagnetic parameters in November 2025 taken from the databases [29,30] is shown in Figure 5.

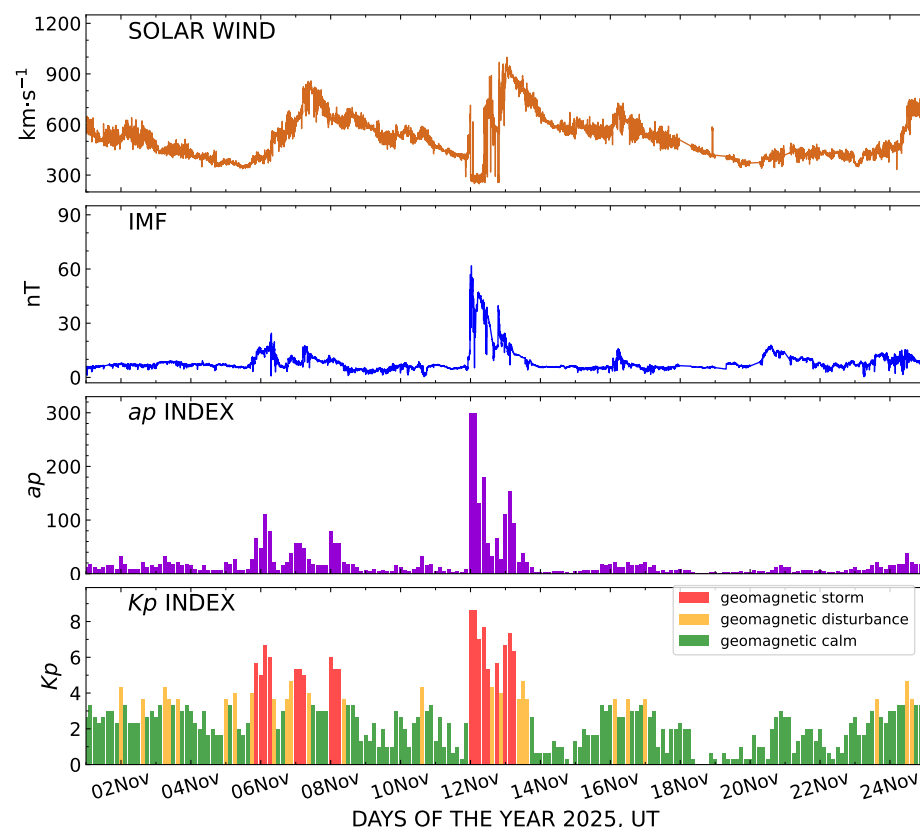


Figure 5. The heliospheric and geomagnetic conditions at the time of serial Forbush effects in November 2025. Designations are the same as in Figure 1. The data were taken from the sites [29,30].

3.2. The Forbush Decrease Events of 5–14 November 2025 as Seen in the Tien Shan Neutron Supermonitor

A sequence of Forbush decrease events observed at the Tien Shan neutron supermonitor in November 2025 is shown in Figure 6 for the integral count data and in Figure 7 for the data on the intensity of the events of multiple neutron generation. As in Section 2.2 above, the original one-minute measurements in all plots are presented with thin lines, while the bold lines indicate the same data averaged over one-hour-long time intervals. All the

values of the counting rate shown in the plots are corrected for variations in atmospheric pressure, as explained in [21].

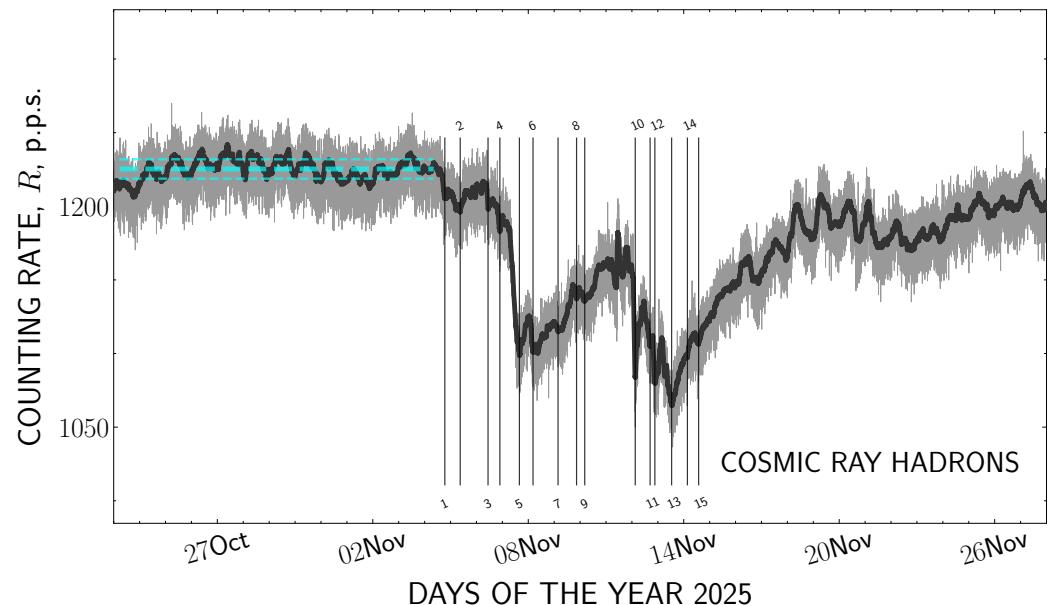


Figure 6. The counting rate of the Tien Shan neutron supermonitor as measured during the period of Forbush effects in November 2025. Vertical lines indicate the moments of the successive Forbush decrease events listed in Table 3; other designations are same as in Figure 2. The counting rate is expressed as a per-second number of pulse signals (p.p.s.) summed over all neutron counters of the Tien Shan neutron supermonitor.

Successive events of Forbush decrease revealed in the integral counting rate of the supermonitor are marked with the numbered vertical lines in Figure 6. These events are also listed in Table 3, together with their corresponding absolute, ΔR , and relative, $\Delta R/\langle R \rangle$ and $\Delta R/\sigma$, magnitudes. The definition of the mean counting rate $\langle R \rangle$, its standard deviation σ , and the amplitude of the drop in the counting rate at the peak of Forbush decrease ΔR are given in Section 2.2 and also illustrated in Figure 2. The quiet period just preceding the time of Forbush effects, the measurements of which were used for calculation of the $\langle R \rangle$ and σ values, is indicated with dashed lines in all plots of Figures 6 and 7. For the calculation, the hourly averaged distributions of the counting rate were used. Numerical values of $\langle R \rangle$ and σ detected in all informational channels of the neutron supermonitor before the period of Forbush effects are listed in Table 4.

The Forbush effects that happened on 11 November are not mentioned in Table 3 since the GLE event that occurred on that date will be considered in detail in the next section.

As follows from Table 3, the prolonged sequence of Forbush decrease events started with several insignificant effects on 4–6 November, when the relative magnitude of the decrease in intensity of cosmic rays $\Delta R/\langle R \rangle$ did not exceed (2–5)%. Since 7 November, the magnitude of Forbush decrease did rise and reached its maximum of (12–13)% around 12–13 November, with arrival to Earth of the matter from the CMEs on 9 and 10 November. It is seen in Figure 6 that successive decrease events were distinctively differentiated from each other against a generally $\sim 10\%$ reduced background of the counting rate, which has restored its normal behavior with regular diurnal variation only around 18–19 November.

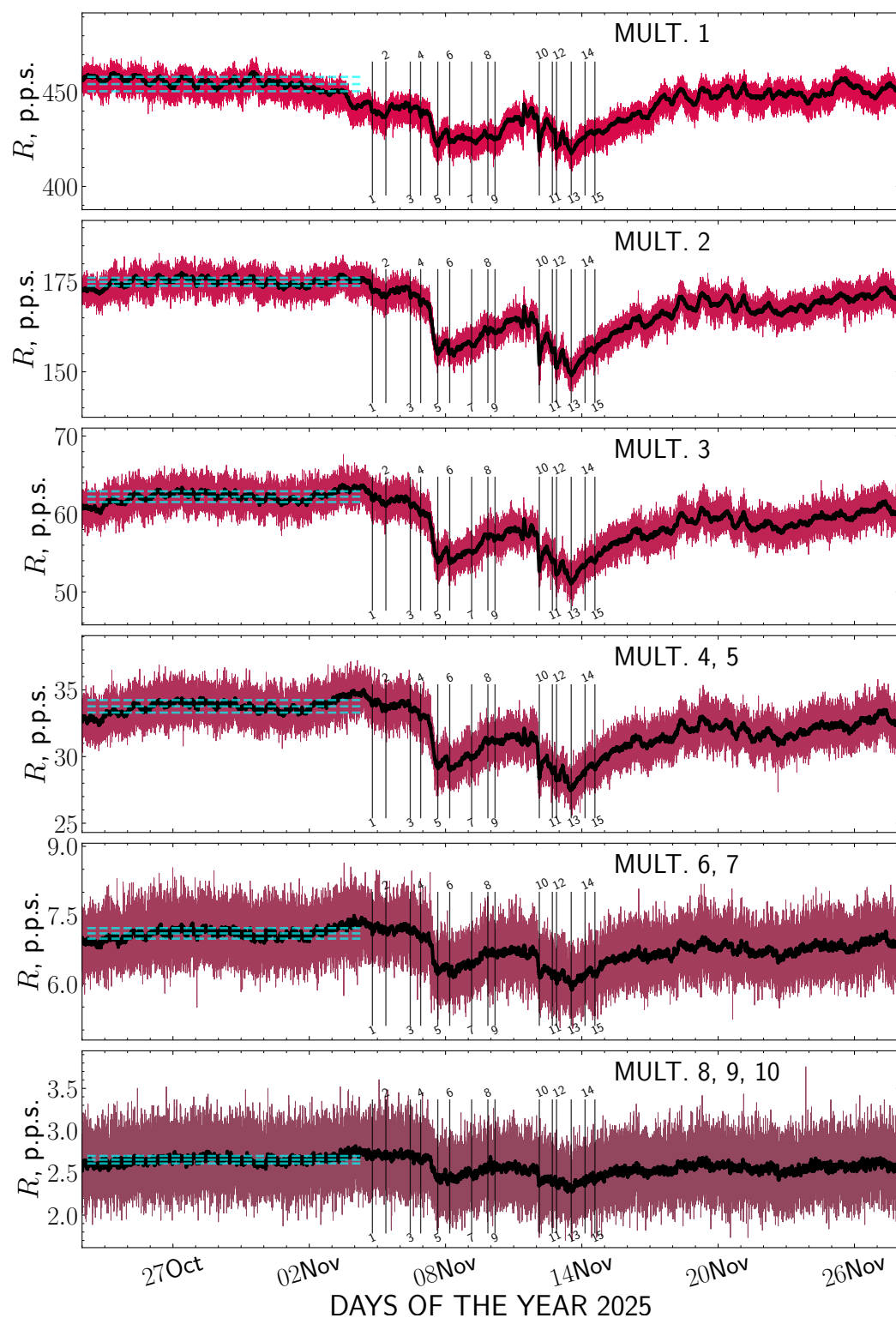


Figure 7. The Forbush decrease events of November 2025 as seen in the signal of multiple neutron generation in the Tien Shan neutron supermonitor. The straight vertical lines mark the moments of Forbush events listed in Table 3; other designations are the same as in Figure 3. Vertical axes are graduated in the units of the counting rate R expressed as pulse per second (p.p.s.) counts.

Table 3. The list of the Forbush decrease events as registered in the counting rate of the Tien Shan neutron supermonitor in November 2025.

Number of Forbush Decrease Event in Figure 6	Peak Moment of Intensity Drop, UT	Magnitude of Forbush Decrease, ΔR , p.p.s.	Relative Magnitude, $\Delta R/\langle R \rangle$, %	Magnitude in Standard Deviations, $\Delta R/\sigma$
1	4 November 2025 18:43	20.3	1.7	3.1
2	5 November 2025 08:57	29.3	2.4	4.4
3	6 November 2025 10:44	27.4	2.2	4.2
4	6 November 2025 21:42	42.7	3.5	6.5
5	7 November 2025 15:47	127	10.4	19.2
6	8 November 2025 04:24	125	10.2	18.9
7	9 November 2025 03:35	111	9.1	16.8
8	9 November 2025 20:44	88.0	7.2	13.3
9	10 November 2025 04:18	89.9	7.3	13.6
10	12 November 2025 03:05	142	11.6	21.5
11	12 November 2025 16:51	121	9.9	18.3
12	12 November 2025 21:15	146	11.9	22.1
13	13 November 2025 12:47	161	13.1	24.4
14	14 November 2025 03:24	128	10.4	19.4
15	14 November 2025 13:48	119	9.7	18.0

Table 4. The levels of the mean counting rate in informational channels of the Tien Shan neutron supermonitor fixed in quiet time before the beginning of the period of disturbances of 4–19 November 2025.

Observable	Mean Counting Rate, $\langle R \rangle$, p.p.s.	Standard Deviation, σ , p.p.s.
Integral count	1225	6.6
Single-neutron events, $M = 1$	454	3.8
$M = 2$	175	1.1
$M = 3$	62.2	0.69
$M = 4, 5$	33.8	0.47
$M = 6, 7$	7.1	0.11
$M = 8, 9, 10$	2.7	0.04

Strict moments of Forbush effects in November 2025, as determined by the integral counting rate in the neutron supermonitor, are labeled with vertical lines over time series of the intensity of the events of multiple neutron production in Figure 7. In the case of a noticeable dip with a magnitude exceeding 3σ level being revealed in a distribution in Figure 7 within a ± 1 h neighborhood of an FE, the effect in the counting rate is considered as connected with this Forbush decrease, and its numerical characteristics ΔR and $\Delta R/\langle R \rangle$

are listed in corresponding rows of Table 5. According to the table, the effect of all Forbush decreases on the events of multiple neutron production reaches its maximum magnitude in the neutron multiplicity range of about $M \simeq (3-5)$, which corresponds to the energy of the order of several GeV for the secondary hadrons that originate from interactions of cosmic rays in the atmosphere and come into the neutron supermonitor from outside.

Table 5. Parameters of the drops in intensity of the events of multiple neutron generation in the Tien Shan neutron supermonitor caused by the Forbush effects in November 2025.

Number of Forbush Decrease Event in Figure 6	Neutron Multiplicity/Hadron Energy											
	1 (0.5–1) GeV		2 2 GeV		3 3 GeV		4, 5 (6–10) GeV		6, 7 (13–17) GeV		8, 9, 10 (20–30) GeV	
	ΔR , p.p.s.	$\frac{\Delta R}{\langle R \rangle}$, %	ΔR , p.p.s.	$\frac{\Delta R}{\langle R \rangle}$, %	ΔR , p.p.s.	$\frac{\Delta R}{\langle R \rangle}$, %	ΔR , p.p.s.	$\frac{\Delta R}{\langle R \rangle}$, %	ΔR , p.p.s.	$\frac{\Delta R}{\langle R \rangle}$, %	ΔR , p.p.s.	$\frac{\Delta R}{\langle R \rangle}$, %
1	–	–	2.9	1.6	–	–	–	–	0.03	0.4	–	–
2	–	–	4.4	2.5	1.2	1.9	0.39	1.2	–	–	–	–
3	14.8	3.3	4.4	2.5	1.4	2.2	0.36	1.1	–	–	–	–
4	17.5	3.9	6.7	3.8	2.4	3.9	1.0	3.0	–	–	–	–
5	34.0	7.5	20.1	11.5	8.5	13.7	4.7	13.9	0.90	12.8	–	–
6	31.1	6.9	20.6	11.8	8.6	13.8	4.8	14.2	0.93	13.1	–	–
7	–	–	18.0	10.3	–	–	4.0	11.8	–	–	–	–
8	28.5	6.3	14.5	8.3	5.4	8.7	2.8	8.3	–	–	–	–
9	29.6	6.5	14.4	8.2	5.7	9.2	2.8	8.3	–	–	–	–
10	35.5	7.8	22.8	13.0	9.6	15.4	5.5	16.3	0.97	13.7	0.31	11.5
11	–	–	19.6	11.2	8.4	13.5	5.1	15.1	–	–	–	–
12	34.1	7.5	23.9	13.7	10.1	16.2	5.6	16.6	1.1	15.5	–	–
13	36.9	8.1	26.1	14.9	11.2	18.0	5.2	15.4	1.2	13.9	–	–
14	–	–	–	–	–	–	5.2	15.4	–	–	–	–
15	26.8	5.9	19.6	11.2	8.5	13.7	4.8	14.2	–	–	–	–

3.3. The Flux of Thermal Neutrons and Hard Gamma Radiation at the Tien Shan Cosmic Ray Station During the Period of Forbush Decrease Events

During November 2025, the intensity of local neutron and radiation background at the Tien Shan Cosmic Ray Station was continuously measured with the detectors of thermal neutrons and gamma rays mentioned in Section 2.3. The resulting time series of these data are presented in Figure 8, together with the superimposed time markers of the events of Forbush decrease, as detected by the Tien Shan neutron supermonitor. In Table 6, the mean values of the counting rate in all detectors $\Delta R / \langle R \rangle$ and their standard deviations σ are presented, which were calculated over the quiet time preceding the period of Forbush effects. In the plots of Figure 8 this time is indicated with dashed lines.

Table 6. The levels of the mean counting rate in the thermal neutron and gamma radiation detectors of the Tien Shan Cosmic Ray Station before the beginning of the period of Forbush effects in November 2025.

Detector Facility	Mean Counting Rate, $\langle R \rangle$, p.p.s.	Standard Deviation σ , p.p.s.
Thermal neutron detector #1	19.5	0.15
Thermal neutron detector #2	14.7	0.11
Gamma detector at 3340 m	31.2	0.53
Gamma detector at 3750 m	46.2	0.67

To reveal the possible influence of the Forbush decrease events on the environmental radiation flux, a search for characteristic downturn features was made in the time series of Figure 8, using for the purpose one-hour-averaged distributions of the counting rate that are shown in the plots with bold lines. The search for response to each Forbush effect was made in a ± 1 h time neighborhood around the corresponding decrease in the neutron supermonitor counts; the parameters of the dips found in the intensity of the neutron and gamma radiation background are listed in Table 7.

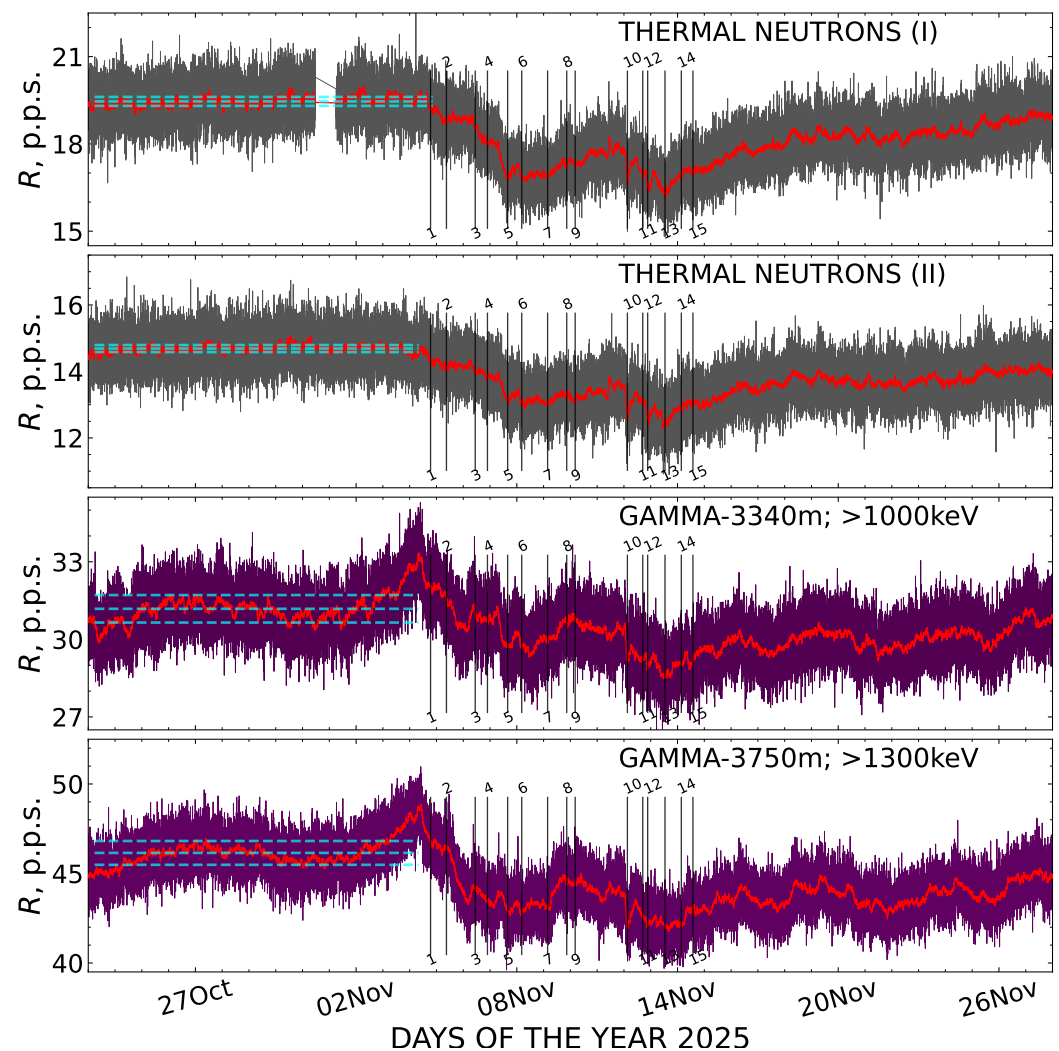


Figure 8. The counting rate in the thermal neutron and gamma radiation detectors of the Tien Shan Cosmic Ray Station as registered during the period of Forbush events in November 2025. The straight vertical lines mark the moments of subsequent Forbush decrease events revealed in the neutron supermonitor data and numbered in accordance with Table 3; other designations are the same as in Figure 3. The units along vertical axes are the values of the counting rate R expressed as pulse per second (p.p.s.) counts.

As follows from these data, at the times of most prominent events, the Forbush effects with the numbers 5, 6, 10, 12, and 13 in Figure 6/Table 3, the relative magnitude $\Delta R / \langle R \rangle$ of the drop in the counts of the thermal neutron detectors #1 and #2 was about (12–17)%. Thus, the influence of Forbush decrease on the local neutron background was of the same order or even exceeded the effect measured by the neutron supermonitor in cosmic ray hadrons, whose magnitude was about (10–13)% (see Table 3). As just mentioned in Section 2.3, regular measurement of the flux of thermal neutrons in the environment may indeed be considered as an effective means for monitoring large disturbances in the heliosphere connected with processes of solar activity.

Relative magnitude of the effect caused by the Forbush events on the intensity of MeV gamma ray background in Table 7 is 1.5–2.5 times less than the magnitude of the effect in neutron component. This observation agrees, again, with corresponding conclusion made at the end of Section 2.3 concerning relative significance of the impact of Forbush effect on intensity of the neutron and gamma radiation background in the environment.

Table 7. Parameters of the temporary drops in the counting rate of thermal neutron and gamma radiation detectors connected with the sequence of Forbush decrease events in November 2025.

Number of Forbush Decrease Event in Figure 6	Detector #1, Thermal Neutrons			Detector #2, Thermal Neutrons			Gamma Detector at 3340 m, ≥1000 keV γ -Rays			Gamma Detector at 3750 m, ≥1300 keV γ -Rays		
	ΔR , p.p.s.	$\frac{\Delta R}{\langle R \rangle}$, %	$\frac{\Delta R}{\sigma}$	ΔR , p.p.s.	$\frac{\Delta R}{\langle R \rangle}$, %	$\frac{\Delta R}{\sigma}$	ΔR , p.p.s.	$\frac{\Delta R}{\langle R \rangle}$, %	$\frac{\Delta R}{\sigma}$	ΔR , p.p.s.	$\frac{\Delta R}{\langle R \rangle}$, %	$\frac{\Delta R}{\sigma}$
1	—	—	—	—	—	—	—	—	—	—	—	—
2	—	—	—	0.70	4.8	6.4	—	—	—	—	—	—
3	—	—	—	0.82	5.6	7.5	—	—	—	—	—	—
4	—	—	—	—	—	—	—	—	—	—	—	—
5	2.7	13.8	18.0	1.7	11.6	15.5	1.5	4.8	2.8	3.5	7.6	5.2
6	2.7	13.8	18.0	1.8	12.2	16.4	1.5	4.8	2.8	3.5	7.6	5.2
7	—	—	—	—	—	—	—	—	—	—	—	—
8	2.3	11.8	15.3	1.5	10.2	13.6	—	—	—	1.8	3.9	2.7
9	2.3	11.8	15.3	—	—	—	—	—	—	—	—	—
10	2.9	14.9	19.3	2.1	14.3	19.1	2.1	6.7	4.0	4.2	9.1	6.3
11	2.7	13.8	18.0	—	—	—	—	—	—	—	—	—
12	3.1	15.9	20.7	2.3	15.6	20.9	2.4	7.7	4.5	4.2	9.1	6.3
13	3.3	16.9	22.0	2.4	16.3	21.8	2.7	8.6	5.1	—	—	—
14	—	—	—	—	—	—	—	—	—	—	—	—
15	2.5	12.8	16.7	—	—	—	—	—	—	—	—	—

4. The Ground-Level Enhancement Event of 11 November 2025

During the series of Forbush effects in November 2025, an event of ground-level enhancement (GLE 77) was detected that had a maximum integral intensity of $802\% \cdot h$, thereby making it one of the strongest GLEs seen in the last 20 years [32,33]. Generation of the particles that resulted in the GLE 77 event took place in a X5.1 solar flare, which started on 11 November at 09:49 UT and reached its maximum at 10:04 UT. Before the flare, a small event of solar filament disappearance was observed, which could trigger the flare effect. After the flare, a CME with a very large speed of about $1700 \text{ km} \cdot \text{s}^{-1}$ was detected by the LASCO coronagraph of the SOHO observatory [27].

The GLE 77 event was observed worldwide at the neutron monitors of the NMDB network. A complete review of experimental information concerning the event may be found in publication [33]. In particular, for the effect this event induced on the Tien Shan neutron supermonitor (the NMDB station AATB), this article provides a sufficiently noticeable value of integral intensity of $5.8\% \cdot h$.

Here, we present some additional data on the GLE 77 event that were acquired with the detectors of the Tien Shan Cosmic Ray Station.

4.1. The Effect of GLE on the Hadronic Component of Cosmic Rays

Time series of the counting rate registered around the moment of the GLE event of 11 November in various informational channels of the Tien Shan neutron supermonitor are shown in Figure 9. All the data presented here are corrected for variations in atmospheric pressure [21]. According to the plots, the intensity of GeV cosmic rays started to rise at 10:10 UT, and its level remained enhanced for about 3 h afterwards.

The numerical characteristics of the intensity increase in the neutron supermonitor are listed in Table 8. These parameters were calculated using one-hour-averaged distributions of the counting rate, which are shown with bold lines in Figure 9. Absolute magnitude of an intensity increase ΔR for each informational channel of the supermonitor was fixed at the moment of maximum divergence of its counting rate from the mean level $\langle R \rangle$; the values of $\langle R \rangle$ and its standard deviation σ were determined over a fragment of corresponding time distribution just preceding the onset of the intensity rise connected with GLE. In the plots of Figure 9 this fragment is indicated with horizontal dashed lines.

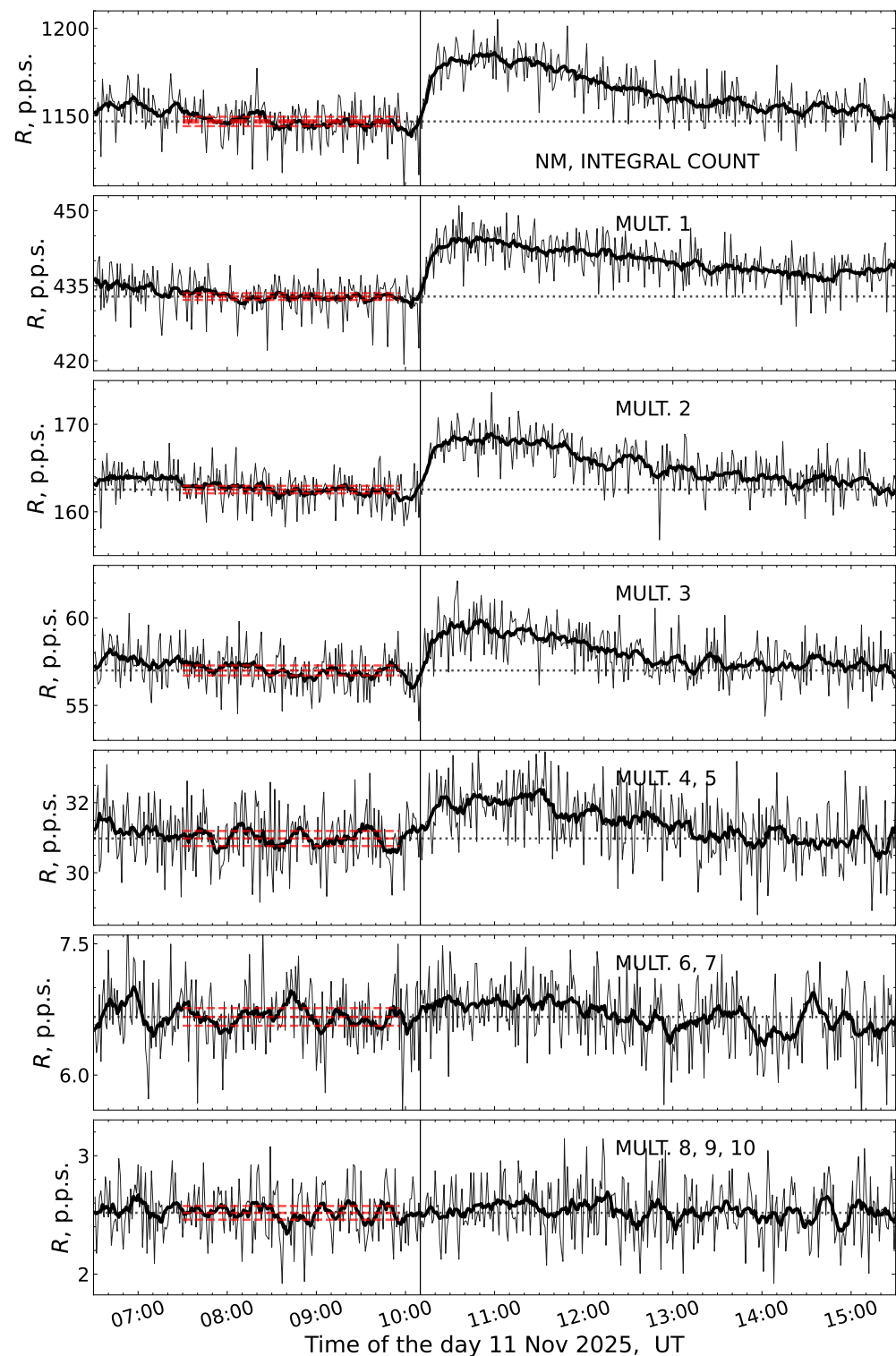


Figure 9. Variations in the counting rate of the Tien Shan neutron supermonitor at the GLE event of 11 November 2025 according to the original 1 min resolution measurements (thin lines) and with hourly averaging (bold curves). The horizontal dotted lines indicate the level of the mean counting rate $\langle R \rangle$ in each channel just before the GLE event; dashed lines stress the time period this level and its standard deviation $\pm\sigma$ were calculated over. Vertical lines mark the onset of the GLE event in the neutron supermonitor at 10:10 UT. The units along ordinate axes are the values of the counting rate R expressed as pulse per second (p.p.s.) counts.

Table 8. Parameters of the effect from GLE77 event in the data of the Tien Shan Cosmic Ray Station detectors.

Detector Facility	Mean Counting Rate, $\langle R \rangle$, p.p.s.	Standard Deviation, σ , p.p.s.	Peak Magnitude of the Effect, ΔR , p.p.s.	Relative Magnitude, $\Delta R/\langle R \rangle$, %	Magnitude in Standard Deviations, $\Delta R/\sigma$
NM64 supermonitor, integral count	1147	2.7	39.4	3.4	14.7
NM64 supermonitor, $M = 1$ ($E_h \simeq (0.5\text{--}1)$ GeV)	433	0.67	11.9	2.8	17.7
NM64 supermonitor, $M = 2$ ($E_h \simeq 2$ GeV)	163	0.42	6.4	3.9	15.1
NM64 supermonitor, $M = 3$ ($E_h \simeq 3$ GeV)	57	0.29	2.9	5.1	10.0
NM64 supermonitor, $M = 4, 5$ ($E_h \simeq (6\text{--}10)$ GeV)	31	0.22	1.4	4.5	6.5
Neutron detector #1	17.6	0.12	0.91	5.2	7.6
Neutron detector #2	13.2	0.13	0.78	5.9	5.9

As follows from Table 8, the GLE event of 11 November 2025 had a moderate effect on the integral counting rate in the neutron supermonitor such that the peak relative magnitude $\Delta R/\langle R \rangle$ was only about 3.4%, which results from the middle-latitude disposition of the Tien Shan supermonitor. However, statistically, this effect is quite reliable since its magnitude ΔR exceeds by more than 14 times the typical level of standard deviation σ .

A somewhat more distinctive reaction of the supermonitor to the GLE event may be found if we consider the intensity of the events of multiple neutron generation in different ranges of their multiplicity M (see Section 2.2). Thus, the value of relative magnitude $\Delta R/\langle R \rangle$ grows up to $\sim 5\%$ for the events with $M = (3\text{--}5)$, which correspond to the mean energy of registered cosmic ray hadrons of $E_h \simeq (3\text{--}10)$ GeV. Nevertheless, statistical confidence of the effect revealed in such a way is worse, and the relation $\Delta R/\sigma$ occurs around (7–10) only as a consequence of essentially lower mean counting rate in the larger-multiplicity channels. In the multiplicity ranges of $M \geq 6$ statistical confidence degrades below 3σ , so corresponding rows were omitted in Table 8.

4.2. Behavior of the Local Neutron and Radiation Background in the GLE Time

Figure 10 presents the variation time series of the counting rate in the thermal neutron and MeV gamma radiation detectors registered during the day of 11 November 2025. The measurements of the thermal neutron intensity shown here are corrected for variations in the atmospheric pressure. The data on the intensity of gamma radiation are left in their original state.

The starting moment of the GLE event at 10:10 UT, as fixed by the Tien Shan neutron supermonitor, is indicated in the plots of Figure 10 with a straight vertical line. It is seen in the upper two panels of the figure that, after this moment, a systematic excess of counting rate

appears in the neutron detectors such that the surplus abundance of neutron counts above the average level that preceded the GLE remains about (2.5–3)h, which is in agreement with the behavior of the intensity of cosmic rays registered by the supermonitor. This observation permits stating the detection of a noticeable effect from the side of GLE 77 on the local neutron flux in the environment of the Tien Shan Cosmic Ray Station. According to the numerical values presented in the two bottom rows of Table 8, the relative magnitude of this effect $\Delta R / \langle R \rangle$ is about (5–6)%, similar to the mostly sensitive informational channels of the neutron supermonitor.

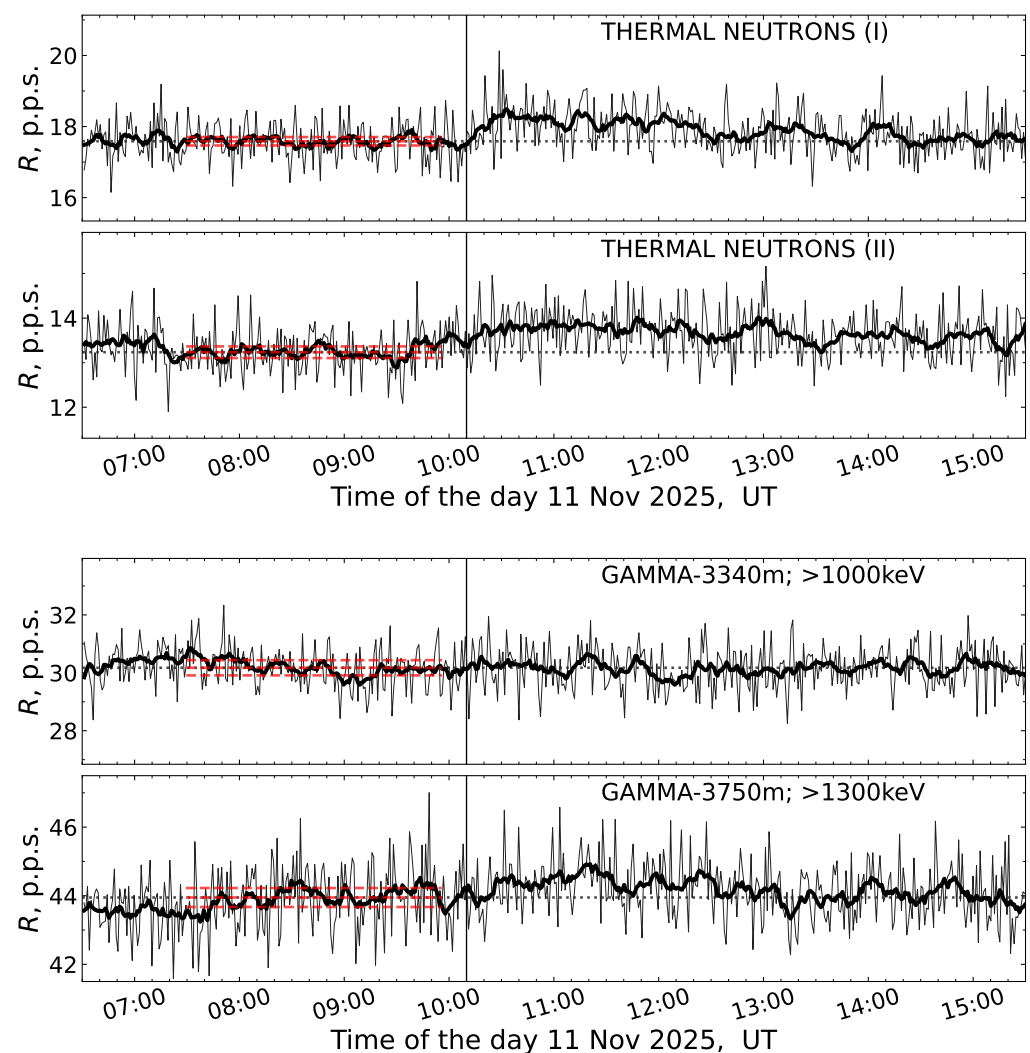


Figure 10. Variations in the environmental flux of thermal neutrons and MeV gamma rays at the Tien Shan Cosmic Ray Station in the time of the GLE event of 11 November 2025. Designations are the same as in Figure 9.

As for the gamma radiation background in the MeV energy range, the two lower plots in Figure 10 evidence that any statistically significant increase in the counting rate in gamma detectors was absent during the whole period of the GLE event such that the fluctuation in radiation intensity remained inside the $\pm 3\sigma$ corridor drawn around its mean level that was typical for the preceding time. A search for any response to the GLE among the monitoring records of gamma radiation with lower energy thresholds, starting from 30 keV, also did not yield a positive result. Thus, it may be concluded that the GLE event of 11 November did not leave any noticeable traces in the environmental gamma radiation background of the Tien Shan Cosmic Ray Station.

5. Conclusions

Above, we present detailed characteristics of the effects that major heliospheric disturbances from the powerful solar flares in November 2025 and January 2026 have left in the time series of the intensity of GeV cosmic rays and environmental radiation background registered by a set of detectors with a middle-latitude high-mountain disposition. It is shown that, with such a detector location, the traces from the large Forbush decrease events of 19 January 2026 and 4–14 November 2025 not only can be found in the data of a standard neutron supermonitor but also rather distinctively reveal themselves among the intensity measurements of the local background of thermal neutrons and the hard gamma radiation that was registered with an MeV-order threshold. In the case of thermal neutron detectors, the relative magnitude of the detected effect is quite comparable to that registered by the neutron supermonitor. The response to the same Forbush decrease events found in the flux of MeV gamma rays has nearly twice as low an amplitude.

Even though ground-level enhancements generally rarely occur during Forbush effects, such an event, GLE 77, was detected on 11 November 2025, demonstrating a 3.4% increase in the integral counting rate of the Tien Shan neutron supermonitor. The GLE event has also influenced the flux of thermal neutrons in the local environment, causing an even higher, up to (5–6)%, increase in its intensity, although with lower statistical confidence.

Most clearly, the surplus flux of solar cosmic rays at the GLE 77 time revealed itself among the time series of the supermonitor events with neutron multiplicity $M = (3–5)$, corresponding to an energy of about (3–10) GeV for the secondary cosmic ray hadrons that come into the supermonitor from outside. For these events, the relative magnitude of the rise in the counting rate reached values of (4–5)%. A similar conclusion regarding the higher sensitivity of the events with said multiplicity to sporadic non-stationary effects in cosmic rays, which are identified among undisturbed counts in the neutron supermonitor, can also be reached from the observations of the mentioned Forbush decrease events.

Thus, purposeful registration of the events that belong to a specific multiplicity range of registered neutrons may be an effective means to reveal low-amplitude disturbances at a middle-latitude neutron monitor-like installation, both of FE and GLE types, even if they are not sufficiently manifest in the integral counting rate. This provides additional information for determining the geomagnetic cutoff threshold of the particles observed during such events.

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Conflicts of Interest: The authors declare no conflicts of interest.

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