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Results of Detecting Thermal Neutrons at Tien Shan High Altitude Station

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Abstract—The unit for detecting thermal neutrons, which makes it possible to study variations in cosmic rays of the interplanetary and geophysical origin, has been created at the high altitude cosmic ray station (3340 m above sea level) near the Earth's crust fault. It has been established that variations in thermal neutrons are of the same nature as high-energy variations registered with a neutron supermonitor in the absence of seismic activity. The flux of thermal neutrons from the Earth's crust during seismic activity in December 2006 has been registered for the first time. The flux value is higher than the background level by 5–6%. The method for detecting the flux of thermal neutrons from the Earth's crust with the simultaneous registration of high-energy neutrons has been proposed.

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1. INTRODUCTION

At the global network of cosmic ray stations the neutron component has been registered from the middle of the past century with neutron supermonitors based on CHM15 proportional counters, the gas filling of which includes boron trifluoride enriched in the ^{10}B isotope. The counter geometry is 2-m tubes with a diameter of 15 cm. The counters are called "boric" owing to the main reaction proceeding in them. The counting effectiveness depends on the probability of neutron trapping by boron nuclei, which is maximal for thermal neutrons and is high for unscreened boric detectors [Dorman, 1975]. Boric detectors are included in lead in order to increase the count rate due to the local generation of neutrons and in polyethylene in order to reflect thermal neutrons and decelerate fast neutrons. Neutron supermonitors are mainly used to study variations in the galactic cosmic ray intensity and the space outside the Earth's atmosphere. Thermal neutrons were measured episodically using more compact detectors of the CHM 18 type with a helium filling (320 mm in length and 32 mm in diameter). A counter is filled with helium-3 under a pressure of 4 atm. Triton and proton with a total kinetic energy of 746 keV, which is spent on gas ionization, are produced as a result of the nuclear interaction of thermal neutron with a helium-3 nucleus. The effectiveness of these counters in registering thermal neutrons is close to 60%.

At present, the interest in measuring thermal and slow neutrons increases. In the 1990s bursts of the thermal neutron intensity during new and full moons and solar eclipses were registered in the Pamirs. The gravitational impact of the Moon and the Sun on the Earth is extreme during these periods [Volodichev et al., 1977, 2001; Antonova et al., 2007]. It is assumed that the Earth's crust forces out the accumulated reserves of radioactive gases of the radon isotopes. Alpha particles, which actively interact with nuclei of elements in the Earth's crust and air with the origination of neutrons, registered with neutron counters, are produced during the radioactive decay. On the other hand, mechanical impacts on materials are accompanied by the disturbance of bonds between substance molecules, formation of microcracks, and origination of a strong electric field between separable surfaces with emission of different radiations (mechanoemission). The gravitational impact of the Moon and the Sun can cause the origination of microcracks. The detected phenomenon can be used to develop new methods for predicting earthquakes in seismic regions, including Tien Shan.

At the high altitudes station of cosmic rays (3340 m above sea level) near the Earth's crust fault, we created the stationary unit for registering thermal neutrons based on HE2 counters, which was put into operation in November 2006. *The aim of this work is to study the nature of variations in the intensity thermal neutrons,* *registered with the created unit, under different heliogeophysical conditions and to detect the flux of thermal neutrons from the Earth's crust.*

2. EXPERIMENTAL UNIT

A detector of thermal neutrons (DTN) is composed of two modules. Either module includes six He2 proportional counters filled with the mixture of helium-3 gases under a pressure of 2 atm and argon (2 atm). The natural background of counters is not more than 0.2 pulse s^{-1}. The counter length is ~1 m, and the tube diameter is 3 cm. The operating voltage (1600 V) is fed to a thread of counters through high-voltage filters. Counters are grounded through a module case of a sheet aluminum with a thickness of 1 mm. The thermal neutron registration effectiveness is ~60% (the same as the registration effectiveness of CHM18); however, the operation of counters indicated that He2 detectors are much more stable in operation and less subjected to the action of temperature differences. One module (DTN 1) is installed in one room with an 18NM64 neutron supermonitor; the second module (DTN 2), 10 m from the building in a light plywood container at a height of ~30 cm from the ground. The modules are fed separately and are independent. The data bank is formed on a computer hard disk with a 1-min time resolution separately for each channel (counter), which makes it possible to effectively trace instrumental errors. The count rate of the module installed within the building is $\sim 6.8 \times 10^4$ pulse h^{-1}, and that of the external module is $\sim 4.9 \times 10^4$ pulse h^{-1}.

A considerable advantage during an analysis of the thermal neutron detector variations consists in the possibility of comparing these variations with the data of the 18NM64 neutron supermonitor based on CHM15 proportional boric counters, the variations of which are well studied. The 18NM64 neutron supermonitor is installed at Tien Shan at an altitude of 3340 m above sea level and has operated in the continuous time mode from 1973. The data have a high statistical accuracy (the count rate is $\sim 5 \times 10^6$ pulse h^{-1}) and are transmitted to the International Data Center (IDC). The monitor registers neutrons with an energy of about several megaelectronvolts and is mainly sensitive to the sources of interplanetary disturbances when changes in the atmospheric pressure are taken into account. The barometric coefficient, used to correct data, is 0.72% $mbar^{-1}$. Thermal neutrons of the atmospheric origin should also have the same coefficient. The geomagnetic cutoff rigidity is 6.7 GeV. The geographic coordinates are 43.2 N; 76.6 E.

3. COMPARISON OF INTENSITY VARIATIONS OF HIGH-ENERGY (18NM64) AND THERMAL NEUTRONS UNDER DIFFERENT HELIOGEOPHYSICAL CONDITIONS

To analyze the experimental data of thermal neutron detectors, we selected December 2006. By that time, the unit was adjusted and operated stably. In spite of the fact that 2006 belongs to the solar activity minimum, December was unusually reach in outstanding heliogeophysical events: solar flares, coronal mass ejections (CMEs), considerable variations in atmospheric pressure, and seismic activity. The response of these events in the cosmic ray intensity is easily identified in the neutron monitor data; the events are isolated except the last one. We consider the response of these events in the variations in the thermal neutron flux and compare this response to the variations in a standard neutron monitor.

3.1. Atmospheric Pressure Variations

Tien Shan station is located at an altitude of 3340 m above sea level. The average atmospheric pressure is 675 mbar, which one third as low as such a pressure at sea level. The pressure deviations from the average are ±8.5 mbar with a probability of 90%. Figure 1 (from top to bottom) presents the following values in December 2006: the atmospheric pressure, data of the 18NM64 neutron monitor, and intensity of thermal neutrons from DTN2 and DTN1 detectors. The neutron intensity is given in percent with respect to the average monthly value and without correction for atmospheric pressure. It is evident that the intensity variations are similar in all plots, corresponding to the 18NM64, DTN2, and DTN1 detectors, independently of the energy of registered neutrons except December 26. All detectors identically respond to a change in the atmospheric pressure; an increase in the pressure results in a decrease in the count rate of high-energy and thermal neutrons within and outside the building. A decrease in the pressure results in an opposite effect in the neutron intensity. During December 2006, the intensities of thermal and high-energy neutrons varied in the same range (about +/–8%).

We calculated the correlation coefficients between the series of the data of the thermal neutron and neutron supermonitor detectors during December 1–31, 2006. The correlation coefficient is $\mathbf{K = 0.97}$ for the detectors within the building and $\mathbf{K = 0.84}$ for the external module (DTN2). High correlation coefficients and a similar response to a change in the atmospheric pressure make it possible to conclude that registered neutrons are of the atmospheric origin and to use the known formula in order to correct neutron monitor data for pressure and to apply this formula to the data of the thermal neutron detectors.

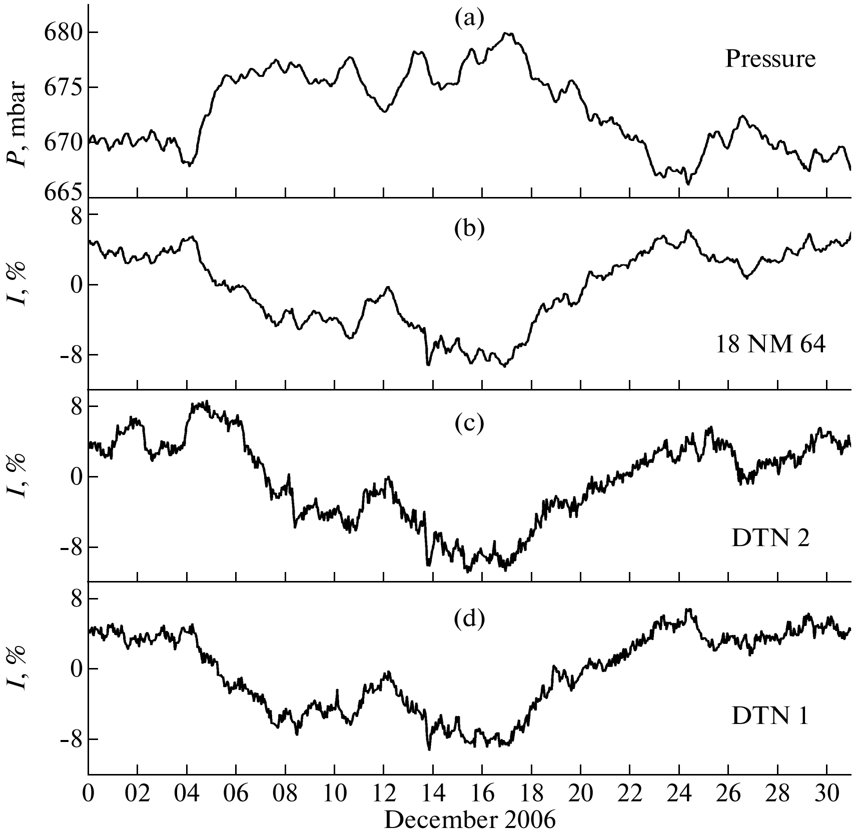

Fig. 1. The hourly values of the (a) atmospheric pressure, (b) 18NM64 neutron monitor, (c) external detector of thermal neutrons (DTN2), and (d) internal detector of thermal neutrons (DTN1). The neutron intensity was not corrected for pressure variations.

3.2. Variations of the Interplanetary Origin

The isolated group of sunspots, which subsequently became the source of powerful flares and CMEs, was registered on the solar disk at the beginning of December. Mainly flared of December 5 and 13 affected the variations in the intensity of galactic cosmic rays registered with ground monitors.

The X9.0/2N flare of December 5, 2006, occurred on the eastern limb (S07E79) at 1035 UT. Neutron monitors did not register an increase in the cosmic ray intensity. However, the flare was accompanied by CME and an IMF disturbance. It is known that ejection of the solar plasma with the frozen-in magnetic field forms a shock wave in the interplanetary space, which acts as a gigantic piston, sweeping out galactic cosmic rays. At that time, ground neutron monitors register a decrease in the cosmic ray intensity (the Forbush effect). Flares on the eastern limb are usually without consequences in the near-Earth space (NES). However, this flare was an exception. The neutron component intensity at Alma-Ata high altitude station started decreasing on December 7. The maximal decrease value was ~3%.

Figure 2 presents the solar wind and IMF velocities according to the GOES-11 satellite data corrected for a change in pressure and the data of the neutron monitor and DTN2 and DTN1 thermal neutron detectors also corrected for pressure variations. The upper plot indicates that the solar wind velocity was 300–350 km/s before CME and considerably increased after CME. A decrease in the neutron component was observed at all detectors. The decrease value at the thermal neutron detectors is not less than at the neutron monitor.

The X3.4/4b flare with coordinates of S06W24, which occurred at 0240 on December 13 in region 930, was the most pronounced and geoeffective event in December. All high-latitude neutron monitors registered an increase in intensity. At Tien Shan station, an increase was not more than the noise level owing to a high geomagnetic cutoff rigidity. The optical characteristics and X rays of the flare that occurred on December 13 were smaller than those of the flare of December 5, but this flare took place in the western part of the solar disk and was also accompanied by full halo CME. A shock wave approached the Earth on December 14. At that time, the GOES spacecraft registered high values of the solar wind velocity (~1000 km/s, Fig. 2a) and a considerable increase (abrupt) in the IMF values (Fig. 2b). Figure 2c–2e) show an identical response to a disturbance in the

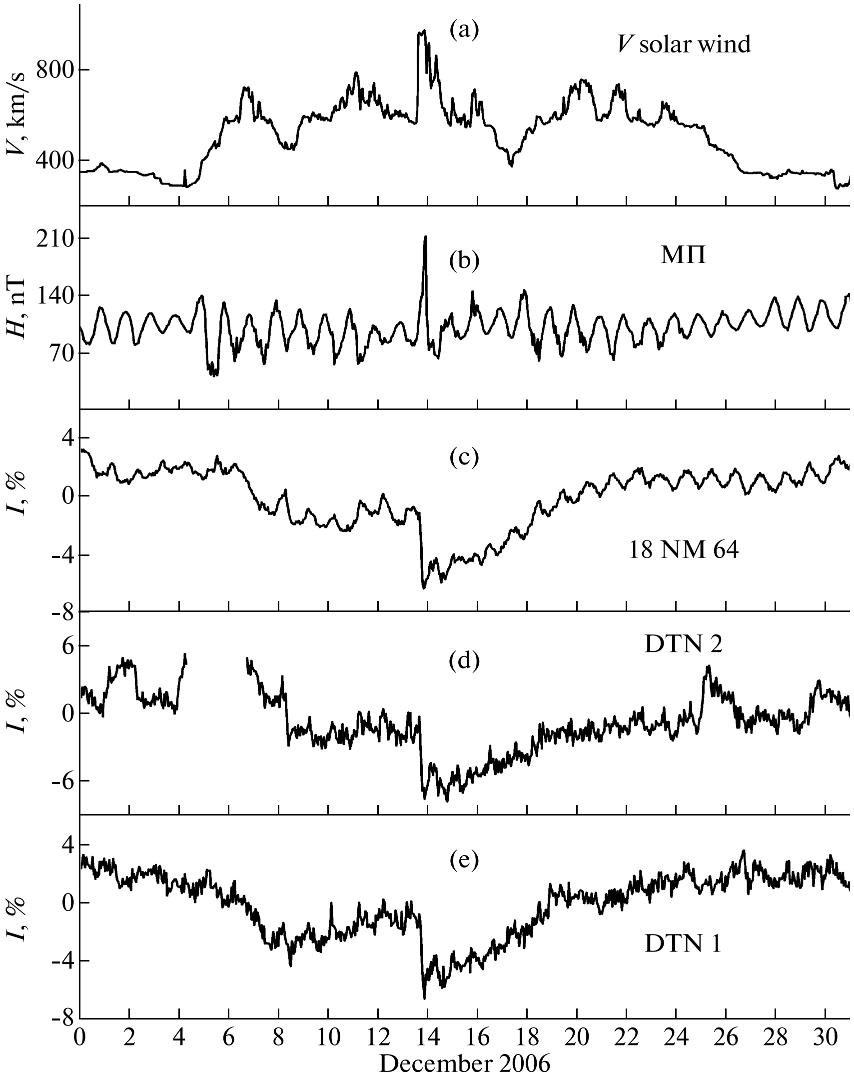

Fig. 2. The hourly values of the (a) solar wind velocity, (b) IMF, (c) 18NM64 neutron monitor, (d) external detector of thermal neutrons (DTN2), and (e) internal detector of thermal neutrons (DTN1). The neutron intensity was corrected for pressure variations.

interplanetary space in the form of an abrupt decrease in intensity (~6%) on December 14 at all presented detectors, registered neutrons with different energies. The value of the Forbush effect in the thermal neutron intensity was not less than in the neutron supermonitor data. In the external module, this effect was even larger (~7%) apparently because an additional beam of neutrons was registered in the low-energy spectral region. A slow recovery of intensity takes place also synchronously at all detectors.

We calculated the correlation coefficients between the series of data of thermal neutron and neutron supermonitor detectors for the period December 1–24, 2007, including CME events. The correlation coefficients (*K*) for the detectors within and the building and for the external module (DTN2) are 0.98 and 0.89, respectively. So high correlation coefficients indicate that the modulation sources of the intensity of thermal neutrons and the intensity registered with the neutron supermonitor were identical during that period.

The result confirms our conclusion that thermal neutrons, registered with the DTN1 and DTN2 detectors, were generated mainly in the atmosphere rather than in the Earth's crust. However, we should note that the correlation coefficients with the neutron monitor of the thermal neutron external detector (DTN2), calculated for different periods were always lower than the coefficients calculated for DTN1, located in the building (table). This is possibly related to the fact that the external module registered some thermal neutrons of the other nature. We pay attention to a burst of

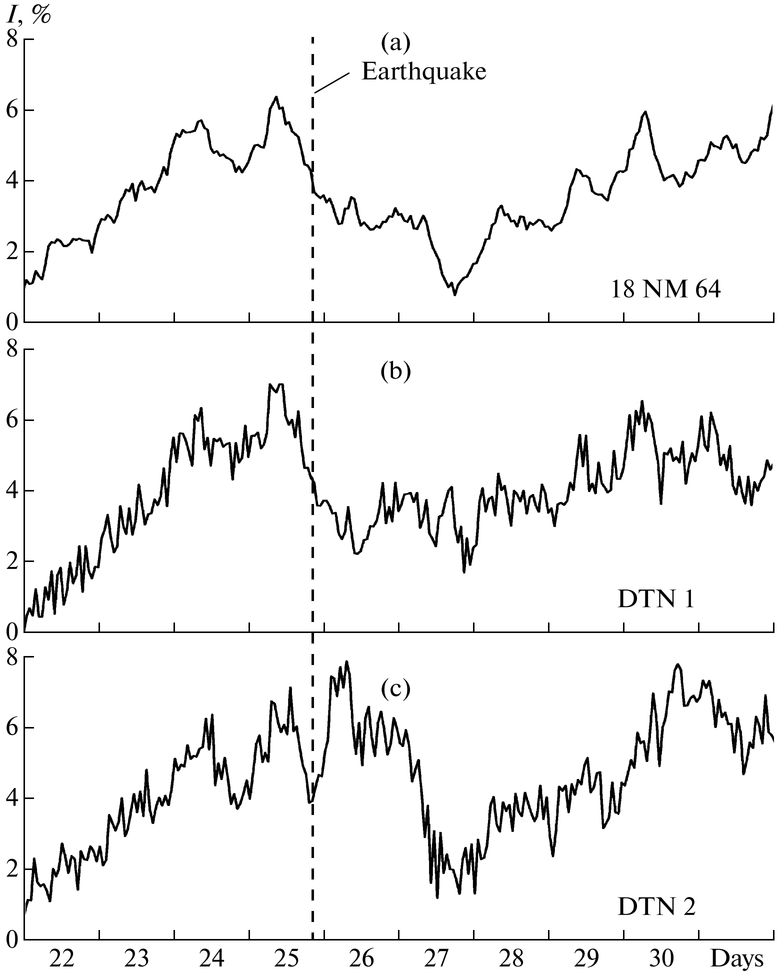

Fig. 3. The hourly values of the detectors not corrected for atmospheric pressure before and after the earthquake: (a) 18NM64 neutron monitor, (b) external detector of thermal neutrons (DTN2), and (c) internal detector of thermal neutrons (DTN1).

intensity on December 25 at the external detector (Fig. 2), which will be considered in detail in the next section.

3.3. Analysis of the Measurements during Seismic Activity

At 0201 LT on December 26, 2006, or at 2001 according to the Greenwich Time (UT), the earthquake occurred at a distance of 146 km southwestward from Alma-Ata. Its epicenter was located in Kyrgyzstan. According to the data of the Kazakh Center of seismic data, the earthquake parameters are as follows: the time at the center is 2001, the latitude is 42.10 N, the longitude is 76.03 E, the magnitude is 5.95, and the energy class is $K = 14.2$. In Alma-Ata the earthquake intensity was 4–5.

We consider in more detail the variations in the intensity of high-energy and thermal neutrons (not corrected for pressure) in the last decade of December (Fig. 3). A dashed line in the plots marks the earthquake time. At all detectors, including the neutron supermonitor, the intensity variations before the earthquake instant are absolutely similar independently of the neutron energy, which is confirmed by very high correlation coefficients on December 20–24, 2006 (table). This coefficient is 0.98 and 0.97 for DTN1–18NM64 and DTN2–18NM64, respectively.

Correlation coefficients between the detectors of thermal neutrons and the standard neutron monitor

Detectors	Correlation coefficients, K				
	K_1	K_2	K_3	K_4	K_5
DTN1-18NM64	0.97	0.98	0.98	0.74	0.90
DTN2-18NM64	0.84	0.89	0.97	0.57	0.87

Note: K_1 (from December 1 to December 31, 2006); K_2 (from December 1 to December 24, 2006); K_3 (from December 20 to December 24, 2006; K_4 (from December 25 to December 31, 2006); K_5 (from December 31 to January 4, 2007).

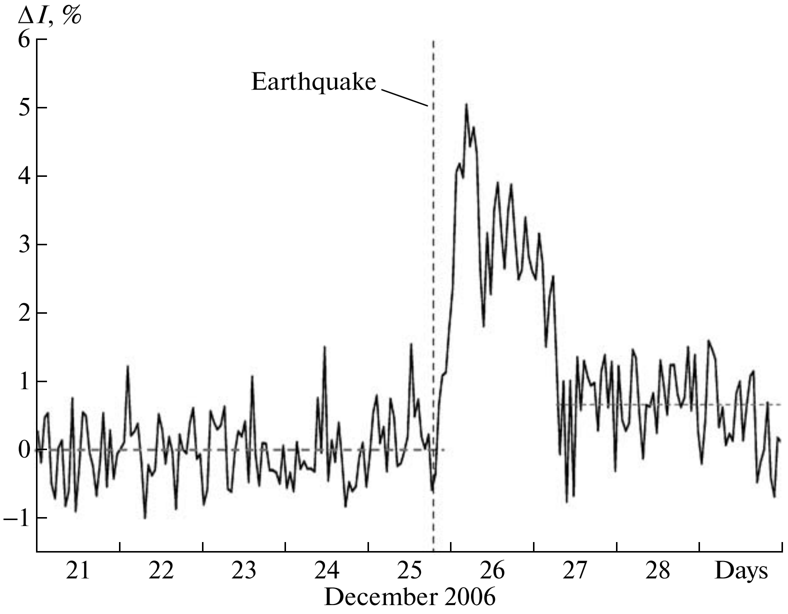

Fig. 4. Additional flux of thermal neutrons from the Earth's crust at the Tien Shan detector during seismic activity in December 2006.

In all three detectors, the intensity decreases due to an increase in the atmospheric pressure on December 25. During that period, IMF was absolutely quiet (Fig. 2). The solar wind velocity decreased to the minimal values at the end of the month. The intensity at the neutron monitor continued decreasing up to December 27. The situation is absolutely different in the lower plot, where the data of the external detector of thermal neutrons are presented: the intensity started increasing exactly at the earthquake instant. Taking into account that the intensity continued decreasing by 2% more (beginning from the earthquake instant) until the middle of December 26 at a similar DTN1 detector, an increase in the intensity at the external detector of thermal neutrons (DTN2) corresponds to 5–6%.

After the earthquake, the correlation between the data of the external detector and the neutron monitor was disturbed from December 25 to December 31 ($K = 0.57$, table). We should note that the intensity variations after the earthquake also differed from the variations at the neutron supermonitor at the internal detector of thermal neutrons. The correlation coefficient between the DTN1 internal detector and the neutron monitor became slightly lower (0.74) than before the earthquake. At the beginning of January, 2007, the correlation coefficients between the thermal detectors and the neutron supermonitor increased again.

An exact coincidence of the earthquake time with an increase in the flux of thermal neutrons at the external detector, a disturbance of correlation with the neutron monitor data, and an increase in phase with the atmospheric pressure in the absence of disturbances in the interplanetary medium indicate that the source of the additional neutron flux at the DTN2 detector during the earthquake fundamentally differed from the sources of the variations considered above. We assumed that the additional flux of thermal neutrons was caused by the Earth's crust. The earthquake of December 25, 2006, probably caused a considerable escape of radon due to deformations of faults in the Earth's crust or the formation of microcracks. Both factors could result in the generation of the additional flux of thermal neutrons from the Earth's crust.

3.4. Separation of the Flux of Thermal Neutrons from The Earth's Crust from the Variations of Neutrons Produced in the Atmosphere

We indicated above that the variations in the data of the neutron monitor and thermal neutron detectors are of the same order and have the same modulation sources except the period of seismic activity at Tien Shan station. We have the unique possibility of separating the flux of thermal neutrons from the Earth's crust from the variations in neutrons produced in the atmosphere. Taking into account that the probability of registering thermal neutrons with the neutron monitor is extremely low (lower than 0.01) and the variations of the atmospheric and interplanetary origin are similar at all detectors, we subtract the data of the neutron monitor from those of the DTN2 thermal neutron detector. Thus, we eliminate the general variations. Figure 4 presents the result of this procedure with the data not corrected for atmospheric pressure. Note that the result is the same when we use the data corrected for atmospheric pressure or uncorrected data. The plots repeat one another even in fine details. The LF intensity trends and the daily variations in neutrons, which are observed in Fig 2, are absent in Fig. 4, but an increase in the flux of thermal neutrons during the first hours after the earthquake by more than 5% is evident. An additional flux of neutrons was received during ~1.5 days.

We propose to use the method for detecting the flux of thermal neutrons from the Earth's crust, using the simultaneous registration of high-energy neutrons for the purpose of probable registration of seismic activity. However, this method requires further development. We plan to continue developing the method in subsequent studies.

4. CONCLUSIONS

(1) The unit for detecting thermal neutrons, which makes it possible to study variations cosmic rays of the interplanetary and geophysical origin, was created at an altitude of 3340 m above sea level at Tien Shan cosmic ray station in the seismic region.

(2) We established that the variations in thermal neutrons are of the same origin as the high-energy variations registered with a neutron supermonitor in the absence of seismic activity.

(3) We confirmed the conclusion that it is possible to register the flux of thermal neutrons from the Earth's crust. For the first time, we registered the flux of thermal neutrons from the Earth's crust at the Tien Shan detector during seismic activity in December 2006. We assume that this flux is caused by the escape of radon and disturbance of the Earth's crust structure with the formation of microcracks during earthquakes.

(4) We proposed the method for detecting the flux of thermal neutrons from the Earth's crust, using the simultaneous registration of high-energy neutrons.

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