Comparison of Two Methods of Showing up of Solar Neutrons

R. U. Beisembaev, E. A. Dryn, and O. N. Kryakunova

Abstract — **The moments of the commencement of bursts of solar X-radiation of a class higher than M1 registered by GOES satellite were laid upon the time series of the experimental data registered by the high altitude neutron monitor Alma-Ata for the period of 1976-2005. Searches of direct solar neutrons were realized about the moments of the commencement of bursts of solar X-radiation by two methods: 1) entropy criterion; 2) epoch-lay method. Comparative analysis of the results found by these methods were carried out.**

SEARCH of the neutrons that came directly from the Sun was realized in the works [1]–[5]. That search was carried out on the assumption that solar neutrons would be able to disturb the uniform character of the flux of secondary particles generated in the atmosphere by galactic cosmic rays. In that works neutron monitor "Alma-Ata B" readings for the 1976-2003 in the periods of time in the neighborhood of moments of the start of of X-ray solar radiation flares with the class higher than M1 registered by the GOES satellite were analysed.

To find out the disturbances of uniformity the entropy criterion was applied. Works [1]–[3] showed that entropy criterion revealed the disturbances of uniformity of 0.3 % value relatively of average intensity of particle flux. In the works [4], [5] close to the moment of the start of X-ray flare, we discovered in the data of the neutron monitor disturbance of uniformity on the level exceeding 3 standard deviations. But in these works we could not directly isolate the excess of particles that caused this irregularity. We considered time series of the monitor observations all year around in the periods ±4 hours with respect to the moment of the start of X-ray solar radiation flares.

So, there were many cases when the Sun was low above the horizon of Almaty with big zenith angles in the events we chose. Particles that invade the atmosphere with big zenith angles are mainly absorbed having not been able to penetrate the big depth of the atmosphere to reach the level of observation. The conditions favorable for registration of solar neutrons occur on the latitude of Almaty only in spring and summer in the period of time close to the noon, when the Sun is located high above the horizon.

In this work we used the experimental material received at the high-altitude neutron monitor "Alma-Ata B" for the period of 1976-2005. The moments of the start of X-ray solar radiation flares with the class higher than M1 registered at GOES Satellite were superimposed on the time series of the results of registration of the fluxes of particles by the monitor. We chose flares occurred from April till August for the periods ±2 hours relative to the noontime of Almaty. Our sample contained 232 such events, each of that was a four-hour time series of observations of high-altitude neutron monitor "Alma-Ata B" taken in such a manner that the moment of the start of an X-ray solar radiation flare would be in the middle of such four-hour series. Thus, we selected the monitor readings for the periods of time when the quantity of the matter of the atmosphere in the line of the Sun did not exceed 1000 gram/cm^2.

In each hour-hour time series of observations of the neutron monitor we considered areas "1" and "2" (Figure 1) with the duration of up to 50 minutes. The beginning of area "1" was chosen two hours before the start of a flare, and the beginning of area "2" was located in different moments of time, both before and after the flare. These areas were split into n=5 intervals and distribution of the intensity of the flux of particles by intervals of area "2" was compared with the distribution of the intensity by intervals of area "1".

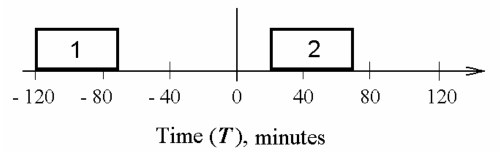

Figure 1. Areas compared according to the entropy criterion.

In areas "1" and "2", a random variable

$$\tilde{H} = -\sum_{k=1}^{n} \tilde{p}_k \ln \tilde{p}_k \ , \qquad (1)$$

that serves for the estimation of entropy

$$H = -\sum_{k=1}^{n} p_k \ln p_k \ . \qquad (2)$$

was determined for each event.

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To calculate the entropy estimation instead of the probability of entry into k^{th} interval – p_k, probability estimation $\widetilde{p}_k = \dfrac{N_k}{N_0}$ is used. Here N_0 is the total number of particles in the area, and N_k is the number of particles that entered the k^{th} interval ($k = 1, 2, \ldots, n$).

Having determined the value $\widetilde{H}$ for all $N = 232$ events, we found for yeas area the average entropy

$$\langle \widetilde{H} \rangle = -\sum_{i=1}^{N} \widetilde{H}_i \,, \tag{3}$$

which was called by us as entropy criterion. Among possible distribution of random values possessing n values, entropy reaches its maximal value $H_0 = \ln n$ only with uniform distribution. In case of uniformity disturbance of distribution, the value of the entropy criterion $\langle \widetilde{H} \rangle$ will be less than H_0, and the more such disturbance is, the less $\langle \widetilde{H} \rangle$ value will be.

To compare values of the entropy criterion $\langle \widetilde{H}_1 \rangle$ and $\langle \widetilde{H}_2 \rangle$, calculated in areas "1" and "2", correspondingly, we used the Student criterion

$$G = \frac{\langle \widetilde{H}_1 \rangle - \langle \widetilde{H}_2 \rangle}{\sqrt{S_1^2 + S_2^2}} \,. \tag{4}$$

Here S_1^2 and S_2^2 are dispersion estimations of the entropy criterion values for areas "1" and "2" correspondingly.

The average $\langle \widetilde{H}_1 \rangle$ and $\langle \widetilde{H}_2 \rangle$ and estimations of dispersions S_1^2 and S_2^2 were determined on 232 events, so the number of degrees of freedom of Student criterion G is big, and the behavior of this criterion is described well by normal distribution. This implies that the value of G criterion can be considered as the number of standard deviations of $\langle \widetilde{H}_2 \rangle$ value from $\langle \widetilde{H}_1 \rangle$ value, which permits to find from the tables of normal distribution the probability that $\langle \widetilde{H}_2 \rangle$ value is different from $\langle \widetilde{H}_1 \rangle$ value.

Values of G criterion for different positions of area "2" is given in Table I.

TABLE I
VALUES OF *G* CRITERION FOR DIFFERENT POSITIONS OF AREA "2"

Beginning of area "2"	– 70	– 50	– 30	– 10	0	+ 20	+ 40	+ 60
End of area "2"	– 20	0	+ 20	+ 40	+ 50	+ 70	+ 90	+ 110
G criterion	2.02	3.08	3.43	3.73	3.20	3.16	2.71	2.69

It is seen from Table 1 that in the neighborhood of a flare the effect of significant disturbance of uniformity is observed. One can suppose that this effect indicates registration by the neutron monitor of particles from the Sun on the background of galactic radiation. However, the effect of disturbance of uniform distribution discovered on the level of three standard deviations in the area (– 50 ÷ 0) demand special investigation. It is possible, that some methodic phenomenon disturbing uniform distribution reveals itself in this way.

To see in what areas and to what degree the uniform distribution is disturbed, we broke down the four-hour period of each event into 60-minute area "A" and 180-minute area "B" additional to area "A". Figure 2 shows these areas. The beginning of area "A" was placed in different places of the four-hour period both till the moment of the start of the X-ray flare are after it. Area "A" was broken into 12 and area "B" into 36 five-minute intervals.

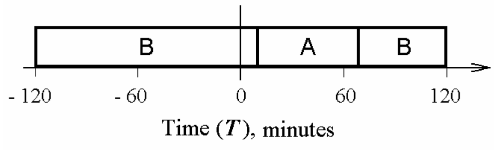

Figure 2. Areas where average by intervals numbers of particles were compared.

We built a "summary" event where 232 events were superimposed in such a manner that the moment of the start of X-ray flares would coincide, and for each interval of such "summary" event the sum of the number of particles falling in such interval in all 232 events was calculated. In such "summary" event, the average number of particles $\langle N \rangle_A$, found from 12 intervals of area "A", compared with the average number of particles $\langle N \rangle_B$, found from 36 intervals of area "B" for each position of area "A".

For each position of area "A", the value of K criterion was calculated by formula

$$K = \frac{\langle N \rangle_A - \langle N \rangle_B}{\sqrt{S_A^2 + S_B^2}} \,. \tag{5}$$

Here $\langle N \rangle_A$ is average number of particles falling in one interval of area "A", S_A^2 is estimation of dispersion of average number of particles falling in one interval of area "A"; N_B and S_B^2 are the same for area "B".

Averages $\langle N \rangle_A$ and $\langle N \rangle_B$ and estimation of dispersions S_A^2 and S_B^2 were found for 232 events, so the behavior of K criterion is described well by normal distribution. It follows that the value of K criterion can be considered as the number of standard deviations of $\langle N \rangle_A$ value from $\langle N \rangle_B$ value, which permits to find the probability of difference of $\langle N \rangle_A$ value from $\langle N \rangle_B$ value from the tables of normal distribution.

Table II gives K values for different positions of area "A".

TABLE II
K CRITERION VALUES WITH DIFFERENT POSITIONS OF AREA "A"

Beginning of area "A"	– 60	– 30	0	+ 10	+ 20	+ 30	+ 40	+ 60
End of area "A"	0	+ 30	+ 60	+ 70	+ 80	+ 90	+ 100	+ 120
K criterion	–0.39	+1.34	+ 3.27	+ 4.28	+ 4.69	+ 3.99	+ 2.95	+ 2.55

It is seen from Table II that statistically valid exceeding of $\langle N\rangle_A$ above $\langle N\rangle_B$ is observed when the beginning of area "A" is located after the moment of the start of a flare. Before the start of a flare, statistically provided excess in area "A" is not observed, also there is not statistically valid excess in area "A" when the beginning of area "A" is more than 40 minutes from the moment of the start of a flare.

If one interprets the observed excess of particles as neutrons generated on the Sun at the moment of the start of an X-ray flare, then distribution of such excess of particles by the times of their coming to the high-altitude neutron monitor "Alma-Ata B" permits to evaluate the energy of such neutrons.

Time delay of neutrons with kinetic energy E_k relatively of X-ray photons can be found by formula

$$\Delta t = \frac{L_C}{c}\left(\frac{E_k + mc^2}{\sqrt{E_k^2 + 2E_k mc^2}} - 1\right). \qquad (6)$$

Here L_C is distance from the Sun to the Earth, m is mass of neutron, c is velocity of light.

Figure 3 shows the dependence of the neutrons delay times Δt with respect to the front of X-ray radiation depending on the kinetic energy of the neutrons E_k. Photons pass the distance from the Sun to the Earth for the time of 8.3 minutes, and neutrons with the energy of less than 100MeV, as it is seen from Figure 3, will come 10 minutes and more after photons.

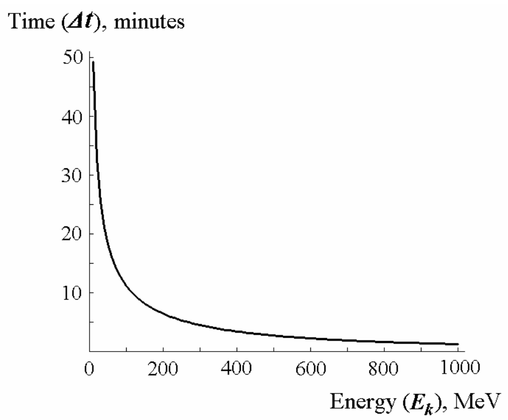

Figure 3. Delay time of neutrons from photons Δt depending on the neutrons' kinetic energy E_k.

It is seen from Table II that the main excess of particles was registered at the high-altitude neutron monitor "Alma-Ata B" for 10-30 minutes after the start of an X-ray flare. It means that with interpretation of this excess by coming of direct solar neutrons, most of such neutrons must have energy from 10 MeV to 100 MeV.

Conclusion

This work allows righting the following conclusions.

1. With selection of events when X-ray flares occurred on the Sun from April tilll August for the periods of time ±2 hours relative to the noontime of Almaty, the number of the analyzed events decreased more than two times in comparison with works [4], [5], however, probability of the receives results increased.
2. Statistically significant effect of distribution uniformity disturbance of coming particles was discovered in the neighborhood of the start of X-ray flares in the data of the high-altitude neutron monitor "Alma-Ata B".
3. The main excess of particles was registered by means of neutron monitor "Alma-Ata B" for 10-30 minutes after the start of the X-ray flare.
4. With interpretation of such excess as direct solar neutrons coming, most of such neutrons must have energy from 10 MeV to 100 MeV.

References

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