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Solar extreme events on the data of Alma-Ata neutron monitor: Identification of ground level enhancements

R.U. Beisembaev [a], V.I. Drobzhev [b], E.A. Dryn [b], O.N. Kryakunova [b,*], N.F. Nikolaevskiy [b]

[a] Lebedev Physical Institute, Russian Academy of Sciences, 117924, 53 Leninsky Prospect, Moscow, Russia
[b] Institute of Ionosphere, Ministry of Education and Science of Republic of Kazakhstan, Kamenskoe Plato, 050020 Almaty, Kazakhstan

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Abstract

Ground level enhancements of cosmic ray intensity registered by means of neutron monitors at middle latitudes were studied by using Student's criterion. Three of these events on 6 November 1997, 24 August 1998, and 13 December 2006 were analyzed in detail. It is shown that the use of Student's criterion allows revealing effectively the ground level enhancements at middle latitudes.

Keywords: Ground-level enhancements; Neutron monitors; Student's criterion; Relativistic solar protons; GLE

1. Introduction

Relativistic protons with energy >1 GeV can be generated during powerful solar flares. They are registered at ground based detectors - neutron monitors and muon telescopes. These events have been named ground level enhancements (GLEs) of solar cosmic rays (Smart and Shea, 1989; Shea and Smart, 1990).

The GLE is rare event: during 65 years (from the first event on 28 February 1942 up to now) only 70 events have been registered (Belov et al., 2005). There is a problem of detection of solar cosmic rays flux on a background of galactic particles. For unification of the approach to GLE detection the uniform base hour is entered for each event.

The effects are observed in high-latitudes. Only powerful GLE can be found out by sight in midlatitudes. For all period of the investigation of such events by means of high mountain Alma-Ata B neutron monitor (3340 m above sea level, geomagnetic rigidity $R_c = 6.7$ GV) the maximal amplitude of effect was observed during event on 29 September 1989 (151%) (Kryakunova et al., 2001; Duldig et al., 1993; Smart et al., 1991). Amplitudes of the majority of events are about 1–5% for middle latitude Alma-Ata B neutron monitor (Aushev et al., 1993; Kryakunova et al., 2001). The main goal of this work is to use one of the statistical criterions to reveal small GLE by mid-latitude neutron monitors.

2. Description of statistical criterion

With the purpose of detection GLE by means of the high mountain neutron monitor Alma-Ata B, we had been carried out the statistical analysis of cosmic ray intensity. For every GLE, found out at any station of the worldwide network of neutron monitors, we investigated ten-hour time interval, registered by means of Alma-Ata B neutron monitor. The beginning of the base hour of the examined GLE data was accepted as the beginning of a time interval.

For everyone GLE average value of intensity of the particles registered by means of the monitor within base hour was defined

$$\widetilde{J}(t_{base}) = \frac{1}{n} \cdot \sum_{k-1}^{n} J_k(t_{base}). \tag{1a}$$

* Corresponding author.
E-mail address: krolganik@yandex.ru (O.N. Kryakunova).

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Also average values of intensity of particles for each hourly interval of time outside of base hour were defined

$$\widetilde{J}(t) = \frac{1}{n} \cdot \sum_{k-1}^{n} J_k(t). \tag{1b}$$

In (1a) and (1b) n is the number of steps of registration during an hourly interval of GLE and it is defined by an interval of registration of this GLE ($n = 12$ if the interval of registration is equal to 5 min, $n = 60$ if the interval of registration is equal to 1-min);

- $J_k(t_{base})$ is the quantity of particles registered by means of neutron monitor on that step of registration inside of base hour.
- $J_k(t)$ is the quantity of particles registered by means of neutron monitor on that k-th step of registration inside of an interval of time $(t; t + \Delta t)$, where Δt=1 hour.

At each value t the average value of intensity $\widetilde{J}(t)$ was compared to average value of intensity $\widetilde{J}(t_{base})$ by means of Student's criterion

$$K_S(t) = \frac{\widetilde{J}(t) - \widetilde{J}(t_{base})}{\sqrt{\widetilde{D}(t) + \widetilde{D}(t_{base})}}. \tag{2}$$

Estimations of dispersions for averages intensities $\widetilde{J}(t)$ and $\widetilde{J}(t_{base})$ were defined, accordingly, under formulas

$$\widetilde{D}(t) = \frac{1}{(n-1) \cdot n} \cdot \sum_{k=1}^{n} (J_k(t) - \widetilde{J}(t))^2, \tag{3a}$$

$$\widetilde{D}(t_{base}) = \frac{1}{(n-1) \cdot n} \cdot \sum_{k=1}^{n} (J_k(t_{base}) - \widetilde{J}(t_{base}))^2 \tag{3b}$$

Student's criterion is a random variable which submits to Student's law with $N = 2n - 2$ degrees of freedom and is described by density of distribution

$$f(K_s) = B_N \cdot \left(1 + \frac{K_S^2}{N}\right)^{-\frac{N+1}{2}}, \tag{4}$$

where B_N – normalizing multiplier which depends only on number of degrees of freedom N.

Cosmic ray intensity was registered during 1978–1990 by means of neutron monitor Alma-Ata B with five-minute time interval, and during 1991–2005 – with one-minute interval (http://213.211.74.116/CosRay/prod05.htm). On a hourly interval of time $(t; t + \Delta t)$ it is necessary $n = 12$ five-minute and $n = 60$ one-minute interval of registration. Therefore, at use of data with 5-min interval of registration it is necessary to take Student's distribution with $N = 22$ degrees of freedom, and for data with one-minute step of registration to take Student distribution with $N = 118$ degrees of freedom.

Let's assume: (1) within base hour only galactic cosmic rays are registered; (2) in any interval of time considered after base hour $(t; t + \Delta t)$ intensity of galactic particles which are registered by means of the monitor, remains the same, as well as at base time interval. Then size $K_S(t)$ serves as confidential border, which allows to calculate probability $P(t)$ that in an interval of time $(t; t + \Delta t)$ the intensity of particles of solar cosmic rays, in the form of surplus above a background of galactic particles is found out under the formula

$$P(t) = \int_{-\infty}^{K_S(t)} f(x)dx. \tag{5}$$

3. Processing of experimental data of neutron monitors by means of statistical criterion

3.1. Event of 6 November 1997 (GLE55)

In Fig. 1 cosmic ray intensity registered on 6th November 1997 by means of neutron monitors Alma-Ata B (latitude 43.1°), Moscow (latitude 55.5°) and Apatity (latitude 67.5°) are shown. In the same figure the behavior of Student's criterion $K_S(t)$, showing excess of average intensity of particles on hourly intervals after base hour above average intensity within base hour is shown.

In Fig. 1 we can see that on the time interval reaching after base hour registered on the neutron monitor Alma-Ata B, "visually" GLE it is not found out. Student criterion $K_S(t)$ finds out on seven intervals surplus of an intensity of particles above an intensity at base hour. Statistical validity of this surplus exceeds a level 0.9995. It means that the probability of random occurrence of surplus on each of these intervals is less than 0.05%. Probability of random occurrence of surplus on seven intervals simultaneously it will be essential less.

Cosmic ray intensity on 6 November 1997 during GLE55 is well visible by means of neutron monitor Moscow. Student's criterion $K_S(t)$ reaches great values equal to 10 and above. It is visible, that dependence $K_S(t)$ from time approximately reflects the form of a curve of a trend time of some and shows, that duration GLE was not less than 6 h.

Cosmic ray intensity during GLE55 by means of Apatity neutron monitor has proved essentially more strongly, than by means of Moscow neutron monitor. Student's criterion $K_S(t)$ reaches values exceeding 20, i.e. Moscow reveals GLE on a time series of this monitor with security of much greater, than on the monitor. Dependence $K_S(t)$, from time reflects the form of a trend time of some and shows, that duration GLE was not less than 8 h.

3.2. Event of 24 August 1998 (GLE58)

In Fig. 2 the cosmic ray intensity registered by means of Alma-Ata B, Moscow and Apatity monitors during time since the base hour chosen for GLE58 on 24 August 1998 are shown. This intensity are interesting to that GLE58 has visually proved by means of Alma-Ata neutron monitor stronger, than by mans of Moscow