Modeling of the solar energetic particles recorded at Neutron Monitors

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Abstract. Last year the worldwide network of neutron monitors recorded a new ground level enhancement (GLE) of cosmic ray intensity (CR) on 20th of January 2005, during the recovery phase of a series of Forbush effects taking place at a time-period very close to the minimum of the current cycle of solar activity. This enhancement seems to be the greatest GLE of the current solar cycle, reaching almost 5000% in some polar stations. A joint analysis of data from ground level stations (neutron monitors) and satellite measurements has been performed in order to calculate the amplitude and the anisotropy of the event as well as the energy of the more fast particles arriving at the Earth. A new GLE – model has been created in order to couple the primary solar cosmic ray flux on the top of the magnetosphere with the flux recorded by neutron monitors and define this way the primary solar cosmic ray spectrum during the event. Moreover, the absorption length of solar energetic particles propagating through the Earth's atmosphere has been calculated applying the Wilson et al. method (1967). These results have been compared with the respective results calculated for other ground level enhancements. Finally, a comparison between this enhancement and the big GLE of 1956 has been performed.

Keywords: GLE, solar energetic particles, neutron monitor, solar cosmic rays
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INTRODUCTION

Solar cosmic rays can effectively be used for studying the processes of particle acceleration in the solar atmosphere and their propagation in interplanetary space, as well as for understanding the electromagnetic conditions at the Sun. When a high flux of solar nucleons with energy greater than a few hundred MeV strikes Earth's atmosphere, the nuclear products cascade to Earth's surface resulting in a "ground level enhancement" known as GLE [1].

A new ground level enhancement (GLE) was recorded on January 20, 2005 by the worldwide network of neutron monitors. It took place during the recovery phase of a Forbush decrease, on the background of a relatively quiet geomagnetic activity

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(Kp changed from 2 to 4). This GLE was associated with an X7.1 flare starting at 6:36 UT of the same day, in AR720 (N12 W58). It is remarkable that this solar particle event, as well as the three ground level enhancements of October-November 2003 period [2], occurred in the descending phase of the 23rd cycle, at a time-period very close to the minimum of solar activity. Nevertheless it exceeds all previous events of this solar cycle and may be comparable by order of magnitude to the greatest GLEs over the history of observations. The peak of the cosmic ray variations on 20 January 2005 reached several thousands of percentages at southern polar stations. Time profiles of three of the most significant ever recorded GLEs using data from those neutron monitors that recorded maximum effect, are given in Figure 1.

In this work we analyzed the ground level observations on 20 January 2005 in order to define a model for the behavior of solar cosmic rays. Data from 37 neutron monitors were incorporated so that the main characteristics of this extraordinary event are revealed. Moreover, the absorption length of solar energetic particles propagating through the Earth's atmosphere has been calculated on the basis of Wilson et al. method [3], using data of two conventional neutron monitor stations (Erevan and Erevan3). A more complete analysis will be presented elsewhere.

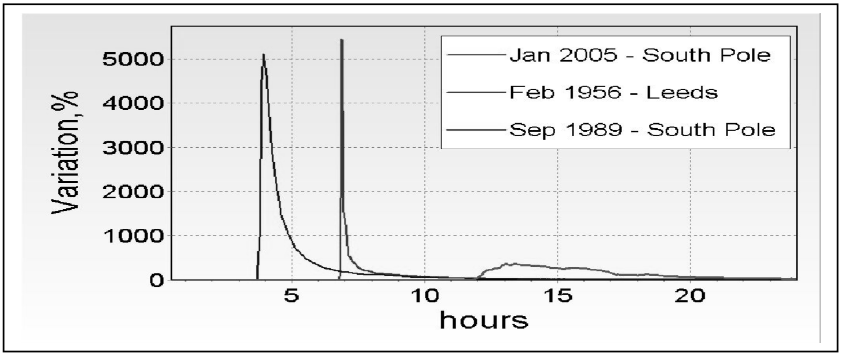


FIGURE 1. Time profiles of the greatest GLEs derived from 5-minute neutron monitor data.

MODEL FOR COSMIC-RAY VARIATIONS

Cosmic ray variations recorded by a ground level detector during a GLE of cosmic rays may be written as follows [4], [5], [6].

$$\frac{\Delta N}{N_0}(t,t_0) = \frac{\int_{E_c}^{E_u} W(E,t_0,h)\frac{\Delta I}{I_0}(t,E)dE}{\int_{E_c}^{E_u} W(E,t_0,h)dE} \qquad (1)$$

where N_0 is the basic background counting rate resulted by galactic cosmic ray flux I_0 and measured at the moment t_0 , h is the atmospheric depth at the point of observation in b, Ec is the threshold kinetic energy of the primary protons that cause the secondary flux recorded by a specific detector and Eu is the upper energy limit for the solar particle registered during the event. Coupling coefficients $W(E, t_0, h)$ were calculated analytically for each station separately according to Clem and Dorman [7], taking into consideration, however, the different neutron monitor response in the lower energy range [6],8]. A power law spectra of the form E^γ was considered for the primary CR intensity variations $I(t, E)$ which were supposed to consist of an isotropic part and an anisotropic one, characterized by an angular distribution function taken as:

$$\Psi = \exp[-n_a{}^2 \sin^2(x - x_0)] \tag{2}$$

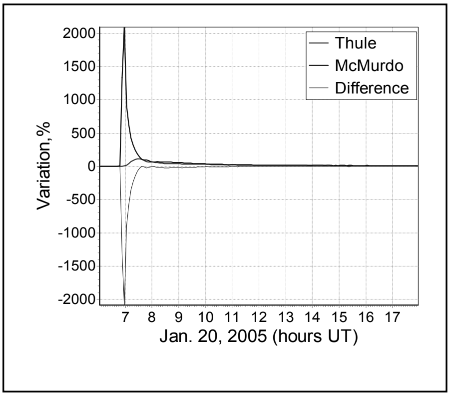
where x_0 corresponds to the direction in which Ψ equals to maximal value 1.

Five-minute data from 37 neutron monitors have been processed and analyzed in order to fit the main equation of the GLE model, in the basis of a least square method.

RESULTS – DISCUSSION

Our analysis showed that the event of 20 January 2005 was extremely anisotropic. This fact is testified by the time profiles of cosmic ray variations registered in two neutron monitors of the same cut-off rigidity, located at different longitudes and hemispheres (Figure 2). The earliest onset of the ground level enhancement event, as well as the biggest effect was recorded at South Pole and McMurdo. Analysis of the 1-min data showed that enhancement of almost 5000% was registered in the neutron monitor of South Pole. On the contrary, a relatively weak effect (for a small rigidity station) together with late particle arrival rigidity was observed at Thule. All other high latitude stations recorded effect in between of these two: the particle response at Nain and Forth Smith was more similar to that at McMurdo, whereas Cape Shmidt demonstrates a behavior that is more common the other polar stations.

The primary spectrum was very hard in the beginning of the event, with an index of -0.7±0.2. At the same time the anisotropy index n_a, in equation (2), was calculated as 4.7±0.2, meaning that the first particles have come from the Sun in the form of a narrow beam. Moreover, our model placed the anisotropy source at longitude = 69±7° and latitude -60±3°. The big enhancements observed by the polar stations of South Pole and McMurdo, already in a very early phase of the event, occurred as a consequence of the specific beam direction of the anisotropic primary proton flux. The relative positions of the asymptotic cones of these two stations and the direction of the solar particle beam favored the record of big secondary fluxes, since they were placed very close to the location of the anisotropy source. In the same time the effect was observed quite ordinary at the other high latitude stations (Figure 3). All parameters changed essentially during the evolution of the event. In particular, the spectral index γ became more negative, the position of the anisotropy source moved southwest, and the beam of solar particles arriving in an anisotropic way widened.



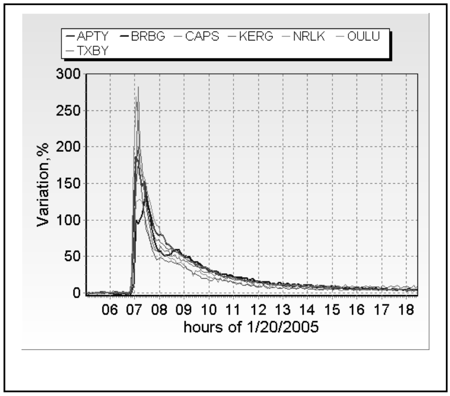


FIGURE 2. Anisotropic arrival of solar cosmic ray particles

FIGURE 3. The GLE of 20 January 2005 observed by high latitude neutron monitors

In order to determine the absorption length of solar energetic particles propagating through the atmosphere of the earth, we applied a method proposed by Wilson et al. [3]. According to this method, during a solar particle event, any difference in the recorded cosmic ray variation between two conventional neutrons monitor stations (i.e. stations of the same cut-off rigidity and coordinates, differing in altitude) can be attributed to the atmospheric particle absorption. Taking into account the different fluxes recorded by the conventional stations of Erevan and Erevan-3 neutron monitors we found that the absorption length was $\lambda = (105 \pm 11) gr/cm^2$. This value coincides with the value given in literature [9] and it is also very close to the values calculated for other GLE events. For example Wilson et al. [3] have found an absorption length $\lambda = (103 \pm 3) gr/cm^2$ for the GLE of 28 January, 1967.

There are a lot of characteristics in common between the GLE of 20 January 2005 and the GLE of 23 February 1956. Both enhancements were extremely big: increases of ~5000% recorded by polar stations in both cases. Moreover, the fluxes of the first relativistic protons reached the Earth by very narrow beams and had a very hard spectrum. It seems that the recent event of 2005 has got even higher amplitude than that of the famous GLE05 in 1956. However, during the event of 2005, it seems that the solar particles were of smaller energy compared with those in 1956 or in 1989. It should also be noted that the effect either was recorded faint by the majority of mid-latitude stations with cut off rigidity more than 6GV or it was completely absent. The most outstanding feature of these both proton enhancements seems to be an extremely high anisotropy narrow and intensive beam of ultra relativistic particles arriving at Earth during the first minutes after the onset.

CONCLUSIONS

Our conclusions derived from the January 2005 GLE analysis presented above, can be summarized as follows:

a) The recorded cosmic ray enhancement in the counting rate at some southern polar neutron monitors on January 20, 2005 places this event among the greatest GLEs in history. Nevertheless, high energy particles (>3 GeV) turned out to be less than in February 1956 and September 1989 events.

b) The first particles came from the Sun by a narrow beam and had very hard spectrum. Some minutes after the onset the spectrum became soft keeping its form for several hours (spectral index was ranging from -3.0 to -4.0).

c) The absorption length of solar particles propagating in the atmosphere during this GLE is calculated as~105 gr/cm^2. This is consistent with the results from other events.

d) Anisotropy dominates during the first minutes of the event. The asymptotic cones of South Pole and McMurdo fall into the narrow beam of the solar particles arrival.

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