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Modeling ground level enhancements: Event of 20 January 2005

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[1] The solar cosmic ray event associated with an X7.1 class solar flare on 20 January 2005 was one of the greatest enhancements ever recorded by the ground level worldwide network of neutron monitors. The event occurred during a Forbush decrease, almost at the end of the 23rd cycle of solar activity. In this work a ground level enhancement model for getting the broadest possible picture, as well as for understanding the physics of solar cosmic ray particles under extreme solar conditions, is proposed. Neutron monitors responses from 41 stations widely distributed around the Earth have been modeled to an anisotropic solar proton flux, using an optimization method based on the Levenberg-Marquardt algorithm. The parameters of the primary solar particles outside the magnetosphere and their dynamics, as well as the characteristics of solar cosmic rays during this event are obtained and discussed.

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1. Introduction

[2] Relativistic solar cosmic rays (SCR) can effectively be used for studying the processes of particle acceleration within the flare region and the corona, as well as their escape from the solar atmosphere and their propagation in the interplanetary space. The Sun occasionally emits cosmic rays (CR) of sufficiently high energy to cause increases of the intensity recorded by ground level detectors such as neutron monitors (NM) and muon telescopes, known as ground level enhancements (GLEs) [*Shea and Smart*, 1993; 2002; *Storini and Laurenza*, 2003]. These enhancements characterize only one relativistic part of the entire solar cosmic ray spectrum. Muon detectors respond to primary high-energy protons of kinetic energy bigger than 4 GeV interacting at the top of the atmosphere [*Miroshnichenko*, 2001]. The detection threshold for neutron monitors of standard type (NM-64 or IGY) is significantly lower arising to primary proton kinetic energy 435 MeV/nucleon (or magnetic rigidity 1 GV/nucleon). If the energy of primary protons is less than 400 MeV ($R < 0.44$ GV), neutron monitors do not practically respond them due to atmospheric absorption of neutrons. The maximum neutron monitor response is placed within 1–5 GV meaning that all high-latitude NMs start to record secondary neutrons efficiently from the same rigidity of the primary protons (about 1 GV), irrespectively of the neutron monitor nominal "geomagnetic cutoff rigidity" R_c. Consequently, the rigidity of 1 GV turns out to be the characteristic cutoff at the polar neutron monitor stations [*Smart and Shea*, 1996].

[3] A historical beginning of SCR observations was set by the occurrence of the GLEs on 28 February 1942, in July 1946, and November 1949. The greatest ground level enhancement of solar cosmic rays ever recorded by neutron monitors (until January 2005) available to detailed analysis was observed on 23 February 1956. The characteristics and the peculiarities of this event have been studied by many researchers [*Meyer et al.*, 1956; *Pfotzer*, 1958; *Miroshnichenko*, 1970; *Adams and Gelman*, 1984; *Smart and Shea*, 1990; *Belov et al.*, 2005a, 2005b]. Since that time, hundreds of proton events and tens of GLEs were registered, but all of them rank below this one by one order of magnitude or more. However, on 20 January 2005, one of the largest ground level enhancements ever recorded was registered in the neutron monitors of the worldwide network [*Belov et al.*, 2005c; *Plainaki et al.*, 2005b; *Storini and Signoretti*, 2005].

[4] Several techniques for modeling the dynamical behavior of GLEs throughout their evolving are presently available. The responses of ground level neutron monitors world wide are modeled to determine a best fit spectrum and spatial distribution of the particles arriving from the Sun. Usually, a least squares procedure is being applied in order to define the values of the parameters that fit the GLE model used. The functions that are being used have been chosen as to represent the physical processes involved in the particle rigidity distribution and propagation as well as the responses of the atmosphere to energetic solar particle fluxes. A special method for calculating the NM response during a solar proton event has been developed over many years [*Shea and Smart*, 1992; *Humble et al.*, 1991; *Duldig et al.*, 1993] and it is described by *Cramp et al.* [1997]. During the 1990s, significant improvements of the modeling have included more accurate calculations of the effect of the Earth's magnetic field on the particle arrival [*Flückiger and Kobel*, 1990] using better and more complex representations of the field [*Tsyganenko*, 1989]. Current modeling

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techniques incorporate realistic geomagnetic field models which take into account possible geomagnetic disturbances [*Tsyganenko*, 1987, 1989]. These models enable the accurate determination of viewing directions for ground level instruments [*Vashenyuk et al.*, 1993]. A method of using separately isotropic, anisotropic and compound models at different parts of GLE was applied to detailed study of the proton events on 23 February 1956 [*Belov et al.*, 2005a, 2005b]. Moreover, the method of using a compound model for the SCR flux was applied for the event on 20 January 2005 [*Belov et al.*, 2005c]. All the above described methods intend to achieve the determination of several descriptive GLE parameters. The use of an accurate GLE model gives important insights into the particle acceleration mechanisms at the Sun.

[5] In order to work effectively all GLE techniques need to incorporate data from as many neutron monitors as possible at a wide range of locations around the Earth. In this work, cosmic ray data from a large number of neutron monitors (41) covering a wide range of cutoff rigidities and asymptotic viewing directions have been analyzed and processed in order to model more precisely the behavior of solar cosmic rays during the extreme event of 20 January 2005. A general GLE modeling technique based on the method of coupling coefficients [*Dorman*, 1957, 2004] as well as the determination of the asymptotic directions for each one of the neutron monitors participating in the analysis is proposed. An efficient optimization method based on the Levenberg-Marquardt algorithm has been applied in order to calculate the various GLE parameters in the most reliable and precise way [*Levenberg*, 1944; *Marquardt*, 1963; *Moré*, 1977]. Applying this technique to as many historical data sets as possible would allow comparison of the features of different events and could lead to better understanding of the acceleration and propagation mechanisms.

2. Observational Analysis

[6] A series of hard X-ray flares accompanied by a significant number of CMEs took place in January 2005 (http://www.sec.noaa.gov) starting from 14 January despite the fact that the solar cycle 23 was already very close to its minimum. This activity was clearly revealed in CR variations even at such low-latitude stations as Athens (Figure 1). After a sudden storm commencement on 17 January at 0748 UT the worldwide network of neutron monitors recorded a significant Forbush decrease with magnitude about 19% in 10 GV galactic CR density, associated with a severe geomagnetic storm [*Flückiger et al.*, 2005]. During the recovery phase of the Forbush decrease the X7.1 solar flare from the active region NOAA AR10720 near the west limb produced a strong and long-lasting X ray burst which started at 0636 UT and had a peak emission at 0701 UT. The hardest and most energetic proton event of solar cycle 23 resulted in a new ground level enhancement observed by several NMs of the worldwide network [*Belov et al.*, 2005c; *Cordaro et al.*, 2005; *Olivares et al.*, 2005] some minutes after the flare onset (at 0648 UT), on the background of relatively quiet geomagnetic activity [*Belov et al.*, 2005c; *Plainaki et al.*, 2005b]. By the time the GLE began, the magnetic storm was already over and the intensity of the interplanetary magnetic field (IMF) had returned to the normal level. However, there are some reasons that do not allow the situation during the GLE to be considered as quiescent. First, the solar wind velocity remained to be essentially elevated; at the beginning of 20 January it decreased down to ~650 km/s by, but directly before the event it started to rise up again reaching at least 850 km/s. This may be evidence of the new interplanetary disturbance arrival. Second, during the GLE the direction of the IMF was anomalous and varied essentially. During the first hours of GLE it was directed across the ecliptic plain, and later, Bz component of IMF has changed sign. Third, the geomagnetic activity rose up again on the second half of 20 January reaching a level corresponding to a small magnetic storm.

[7] In this work the extraordinary event on 20 January 2005 has been analyzed, using cosmic ray intensity data from 41 neutron monitors widely distributed around the Earth covering a wide range of longitudes, latitudes, and rigidities. The distribution of these NM stations is illustrated in Figure 2. An overview of this GLE event, as observed by high-latitude neutron monitors of both hemispheres, is presented in Figure 3. All used data are 5-min count rates corrected for pressure, expressed as a percent variation over the galactic cosmic ray background, which was calculated as averaged neutron monitor intensity for the time interval 0500–0600 UT, on 20 January 2005. The complexity of the event of 20 January 2005 is illustrated clearly in Figure 3 and well revealed in the time profiles of the CR variations. The southern NMs of South Pole, Terre Adelie, and McMurdo recorded extremely sharp increases of more than 2000%, as derived by the 5-min average data, whereas all the other stations recorded significantly smaller fluxes. The difference in the count rates at the first stage may be attributed to different asymptotic viewing directions more than to difference in geomagnetic cut off rigidities.

[8] The onset of the GLE was derived from 1-min neutron monitor data and it was placed at about 0648 UT. The maximum amplitude was recorded by the neutron monitor at South Pole. From 1-min data it was found that the biggest enhancement during 20 January 2005 corresponded to ~5000%. This is the largest increase ever recorded by the neutron monitors and is partly owned to the unique South Pole location at high latitude (and therefore small cut-off rigidity) and high altitude. Therefore due to its enormous magnitude, this event may be comparable to the greatest GLE over the history of observations, that on 23 February 1956, appearing almost to exceed it! It should be also noted that the increase recorded at McMurdo was the largest at sea level since the famous 1956 event.

[9] One interesting feature of this GLE, also mentioned by other researchers [*Miyasaka et al.*, 2005; *Vashenyuk et al.*, 2005; *Saiz et al.*, 2005], was the two-peak structure of the solar cosmic ray increase observed by several stations (Figure 4). This feature was clearly observed mainly by the midlatitude sunward viewing neutron monitors (e.g., Kiel, Magadan, Moscow). Moreover, Sanae NM recorded three-peak profile of the solar cosmic rays [*Moraal et al.*, 2005]. Indications of a two-peak structure have been also reported for the GLE on 29 September 1989 [*Mathews and Venkatesan*, 1990; *Ahluwalia and Xue*, 1991; *Smart et al.*, 1991]. For the majority of stations the first peak occurred between 0700 UT and 0720 UT, depending on the orienta-

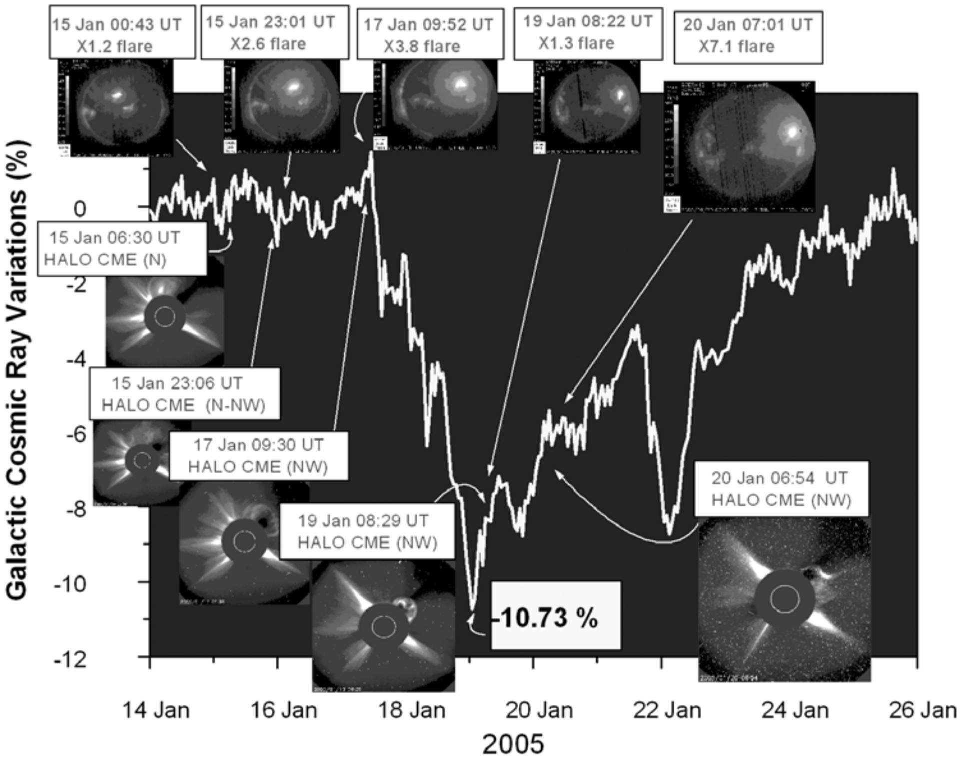

Figure 1. Solar activity in relation with galactic CR variations as recorded by Athens NM. Solar images are taken from SOHO/LASCO.

tion of the station's asymptotic cone in relation with the anisotropy source. The second peak in neutron monitor fluxes during the GLE event of 20 January occurred at about 0755–0800 UT and it was observed clearly by those stations that had cut-off rigidity in the 2–4 GV range. This second maximum in the GLE data is probably related to SCR density maximum and it is more prolonged than the first one. It is actually the main maximum of the event, observed by almost all neutron monitor stations. The first (additional) peak is observed only by several best-located stations and it is related with the anisotropic beam of solar particles. If the anisotropy were not so big during the first time intervals of the event of 20 January 2005, only the second maximum would be observed by the majority of the stations. Such was the case of the event on 15 June 1991 [*Akimov et al.*, 1996]. Time of the flux maximum differs between different NMs.

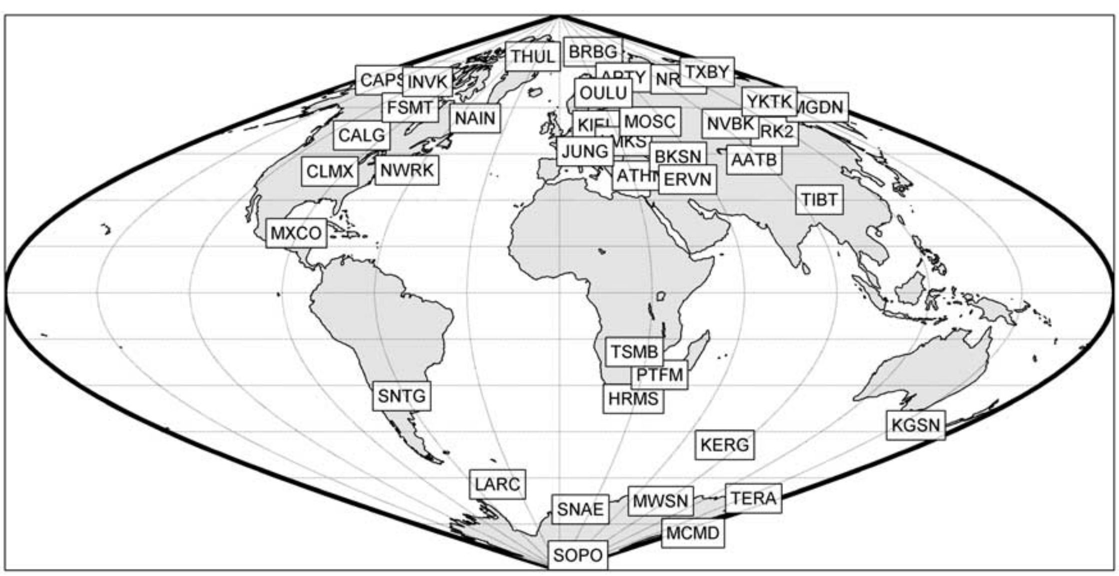

Figure 2. Neutron monitor stations over the globe used in this analysis.

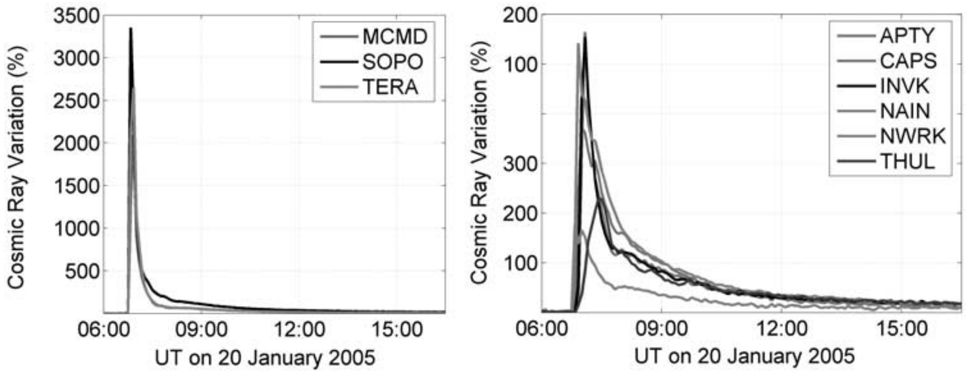

Figure 3. The GLE of 20 January 2005 as observed by polar neutron monitors located at (left) the southern hemisphere and (right) the northern hemisphere.

The NM at Thule recorded only one maximum significantly later than all the other high-latitude stations (at about 0730 UT).

[10] The GLE of 20 January 2005 displayed an almost usual decay. Intensities recorded at South Pole and McMurdo declined to the one tenth of their peak value on 20 January, at 0725 UT, namely 30–35 min after having reached their maximum. In comparison, NM intensities during the typical GLE of Easter 2001 reached the same percentage of their maximum 4 hours after the onset, whereas the fluxes during the GLE on 28 October 2003 remained elevated for a total of about 19 hours after the onset of the event [*Bieber et al.*, 2005; *Plainaki et al.*, 2005a]. This fast decay of cosmic ray intensity during the considered event seems to have been caused also due to large anisotropy.

[11] Indeed, the ground level enhancement on 20 January 2005 is an extremely anisotropic one. This fact can be seen clearly when compared the time-intensity profiles recorded by two neutron monitors of the same cut-off rigidity located at more or less the same altitude above sea level but differing strongly in latitude and having therefore different asymptotic cones of acceptance. Owing to the fact that these monitors have essentially identical energy responses to primary solar nucleons, they record particles corresponding to the same part of the solar cosmic ray spectrum incoming however from different parts of the sky. Therefore any difference in their counting rates during a GLE can be attributed to the different viewing asymptotic directions. Thus such pairs of neutron monitors can be used for studying the anisotropic cosmic ray flux. As it can be seen in Figure 5, the event of January 2005 was recorded much bigger in McMurdo (0 GV, 48 m, southern) than in Thule (0 GV, 260 m, northern) meaning that the arrival of solar energetic particles was strongly anisotropic. Moreover, the fact that only three neutron monitors (at McMurdo, Terre Adelie, and South Pole) have a higher by order count rate than all the other NMs of the worldwide network during the first time intervals implies that the SCR direction of propagation must have been very narrow at that period.

[12] On 20 January 2005, at 0700 UT, the NM at Tibet due to its local time was found in favorable position for recording possible solar neutrons. Neutrons are a signature of very high-energy protons and are generated mostly by protons and alpha particles interacting with ambient H and He inside the solar atmosphere. They usually accompany pion decay radiation in the largest flares. The very high-energy neutrons (~1 GeV) can be also detected by ground-based neutron monitors indicating the presence of protons of roughly the same energy [*Debrunner et al.*, 1983; *Kudela*, 1990; *Usoskin et al.*, 1997]. On 20 January 2005, the solar neutron telescope at Yangbajing, (Tibet: 30.11°N, 90.53°E) detected a significant excess between 0700 UT and 0720 UT [*Zhu et al.*, 2005]. However, according to the results of the solar neutron telescope data analysis made by *Zhu et al.* [2005], the detected signal was not due to the solar neutron event but protons and nuclei of solar origin.

3. Ground Level Enhancement Model

[13] The SCR intensity distribution observed at the Earth depends on the source site, acceleration mechanism, coronal transport, and the ejection profile as well as on the transport of accelerated particles through the interplanetary magnetic field (IMF). The problem of determining the variations in the SCR distribution outside the magnetosphere using the NM observations presents considerable difficulties. To solve this problem, one requires adequate assumptions

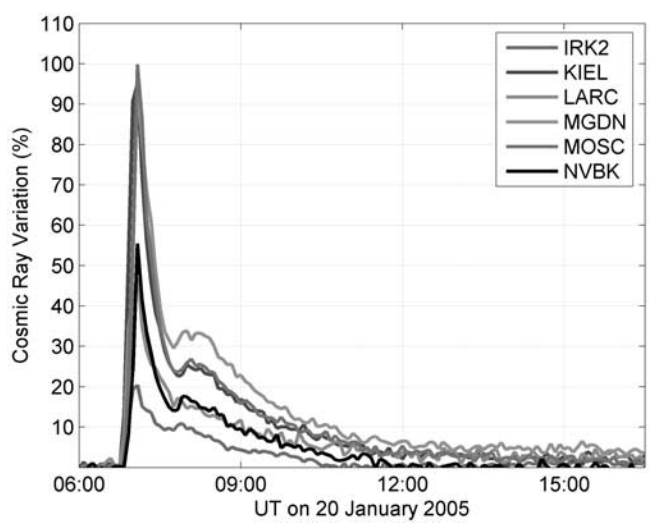

Figure 4. Two-peak structure of the GLE of 20 January 2005.

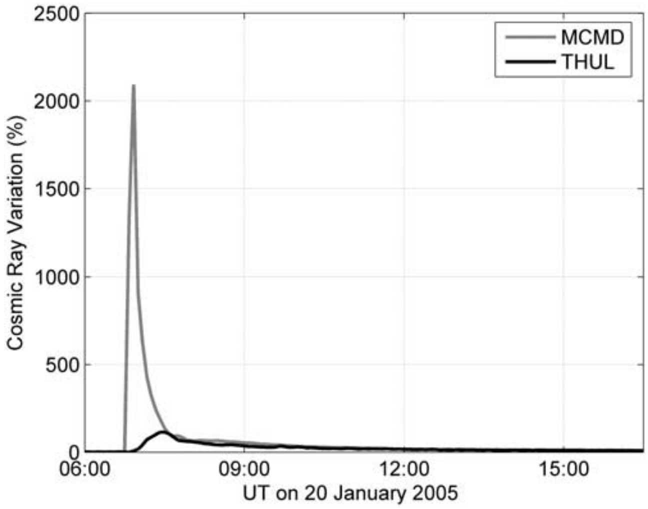

Figure 5. Evidence of anisotropy from the comparison of time-intensity profiles of McMurdo and Thule neutron monitors.

about the form of the SCR intensity distribution as well as knowledge of particle trajectories in the magnetosphere and the atmospheric interactions that create the secondary particles observed by ground-based stations.

[14] Possible time variation of the intensity of any cosmic ray component of type *i* (e.g., total neutron counting rate, muon component on the ground and underground at different depths, electron-photon component), observed at cut-off rigidity $R_c(t)$, at level $h_o(t)$ in the atmosphere at some moment *t* can be determined from [*Dorman*, 2004]:

$$\delta N_i(R_c(t), h_o(t), t)/N_{io} = \int_{R_{co}}^{\infty} \frac{\delta m_i(R, h_o(t), g(t), T(h,t), E(h,t))}{m_{io}} W_i(R_{co}, R)dR - \delta R_c(t) W_i(R_{co}, R_{co}) + \int_{R_{co}}^{\infty} \frac{\delta D(R,t)}{D_0(R)} W_i(R_{co}, R)dR \quad (1)$$

where

$$W_i(R_{co}, R) = \frac{D_o(R) m_{io}(R, h_{oo}, g_o(t), T_o(h), E_o(h))}{N_{io}}$$

is the coupling function between secondary CR of type *i* and primary CR arriving at the top of the atmosphere. In equation (1), $D(R, t)$ is the primary CR spectrum outside the atmosphere and m_i (R, $h_o(t)$, $g(t)$, $T(h, t)$, $E(h, t)$) is the integral multiplicity (i.e., number of total secondary CR particles of type *i* generated from one primary particle with rigidity *R*) which depends on the atmospheric depth at which secondary particles are being registered, $g(t)$ is the gravitational acceleration, $T(h, t)$ is the temperature, and $E(h, t)$ is the atmospheric electric field.

[15] Coupling functions were firstly introduced by *Dorman* [1957]. In this work, the rigidity dependent coupling functions $W(R, z, t_0)$ were calculated after parameterization of the results of *Dorman and Yanke* [1981] using an altitude dependent Dorman function [*Clem and Dorman*, 2000]. The form of the coupling functions in the low kinetic energy range 0.5 GeV < *E* < 2 GeV (or 1 GV < *E* < 2.78 GV) was considered as a power law with respect to kinetic energy of the primary particles, close to $E^{3.17}$ [*Belov and Struminsky*, 1997]. These functions have been used many times in the study of galactic cosmic ray variations and GLEs [*Belov et al.*, 1994; *Belov and Eroshenko*, 1996; *Belov et al.*, 2005a, 2005b], mainly for the NM64 neutron monitors. However, as it was shown by *Clem and Dorman* [2000], the difference between coupling coefficients of IGY and NM64 neutron monitors is not significant. Furthermore, taking into consideration that the ground level enhancement of 20 January 2005 occurred during a Forbush decrease, the final formula for the coupling functions becomes:

$$W(R,h,t_0)dR = \begin{cases} W_T(R,h,t_0)[1+\delta_{t0}(R)]dR & , \quad R \geq 2.78\,GV \\ W(R=2.78\,GV, h, t_0)\left(\frac{E}{2\,GeV}\right)^{3.17} dR, & R < 2.78\,GV \end{cases} \quad (2)$$

where

$$W_T(R,h,t_0) = a \cdot (k-1) \cdot \exp\left(-a \cdot R^{-k+1}\right) R^{-k} \quad (3)$$

is the total response function with parameters *a* and *k* described by *Clem and Dorman* [2000], accurate for the rigidity region 1 GV $\leq R_C \leq$ 2.78 GV. Parameters *a* and *k* depend on the atmospheric depth at which the NM is located and they characterize the phase of the solar cycle, thus they were taken as to reflect the minimum of solar activity [*Clem and Dorman*, 2000]. Factor $\delta_{t0}(R)$ in equation (2) is the galactic cosmic ray variation derived for this period by the Global Survey Method (GSM) by *Belov et al.* [2005c].

[16] The results of determining coupling functions for neutron component at sea level (~1013 mb) and on mountains (~700 mb) for the time period during the GLE on January 2005, are shown in Figure 6.

[17] Equation (1) can be applied in many cases of different cosmic ray phenomena (e.g., ground level enhancements, geomagnetic effects, etc.). Count rate variations recorded by a ground level detector during a GLE may be written as follows [*Dorman*, 1963; *Belov et al.*, 1994; *Belov et al.*, 2005a]:

$$\frac{\Delta N(R_c,h,t,t_0)}{N_0(R_c,h,t_0)} = \frac{\int_{R_c}^{R_u} W(R,h,t_0)\frac{\Delta I(\Omega,R,t)}{D_0(R)}(t,R)dR}{\int_{R_C}^{R_u} W(R,h,t_0)dR} \quad (4)$$

where $\Delta I(R, t)$ is the differential rigidity spectrum of solar cosmic rays at the top of the atmosphere and $N_0(R_c, h, t_0)$ is the background of the galactic cosmic ray variation, recorded at ground level.

[18] Taking into consideration the obvious observational remark that the event of 20 January 2005 turned out to be

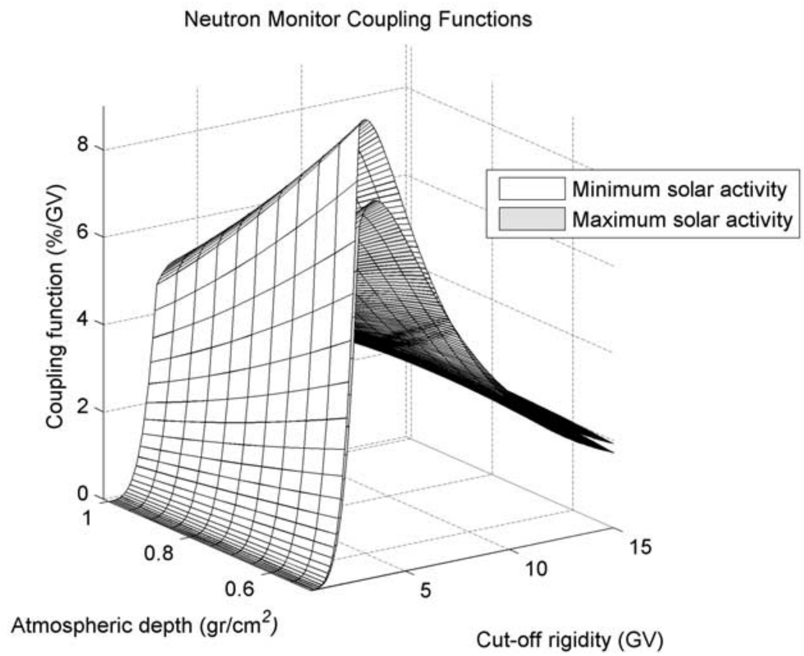

Figure 6. Coupling functions for the neutron component at different atmospheric depths.

extremely anisotropic, we assumed a completely anisotropic solar cosmic ray flux characterized by the differential rigidity spectrum ΔD in a solid angle of asymptotic directions, Ω, as a subdivision of the entire 4π celestial sphere. For each different point of observation characterized by asymptotic coordinates (λ, ϕ), we determined Ω as the angular length of the side of the spherical triangle defined by O, A(λ, ϕ) and B(λ_o, ϕ_o), where B points out the location of the anisotropy source on the top of the atmosphere (Figure 7). On the basis of the above method, solar cosmic ray differential flux can be written as a product:

$$\Delta I(\Omega, R, t) = \Delta D(R, t) \cdot \Psi(\Omega, R, t) \tag{5}$$

where $\Psi(\Omega, R, t)$ is the anisotropy function reflecting the angular dependence of the flux for particles with rigidity R coming from asymptotic direction Ω, and $\Delta D(R, t)$ is the differential SCR rigidity spectrum.

[19] Anisotropy function represents the distribution of solar cosmic ray particles at the top of the atmosphere during a GLE, revealing information on the way these particles propagated in the interplanetary magnetic field and finally arrived at the vicinity of the Earth. The form of $\Psi(\Omega, R, t)$ is a crucial point in this analysis, since it characterizes in the most significant way the anisotropic GLE model that is being applied. In this work $\Psi(\Omega, R, t)$ was chosen as to describe a narrow-beam like relativistic particle arrival. Such an approach is quite reasonable if one takes into consideration the following facts:

[20] 1. There were large differences in the recorded cosmic ray variations between neutron monitors of the same cut-off rigidity and altitude, located at different latitudes (Figure 5).

[21] 2. There were certain neutron monitor stations of low cut-off rigidity (e.g., South Pole, McMurdo, Terre Adelie) that were already recording large enhancements in a very early phase of the event, while other low-rigidity NM stations of different viewing directions (e.g., Thule) had not started to register the event.

[22] Consequently, one can be driven to the assumption that the very first particles arrived at the vicinity of the Earth forming narrow beams, which were only "seen" by those ground level neutron monitors that at that certain time had

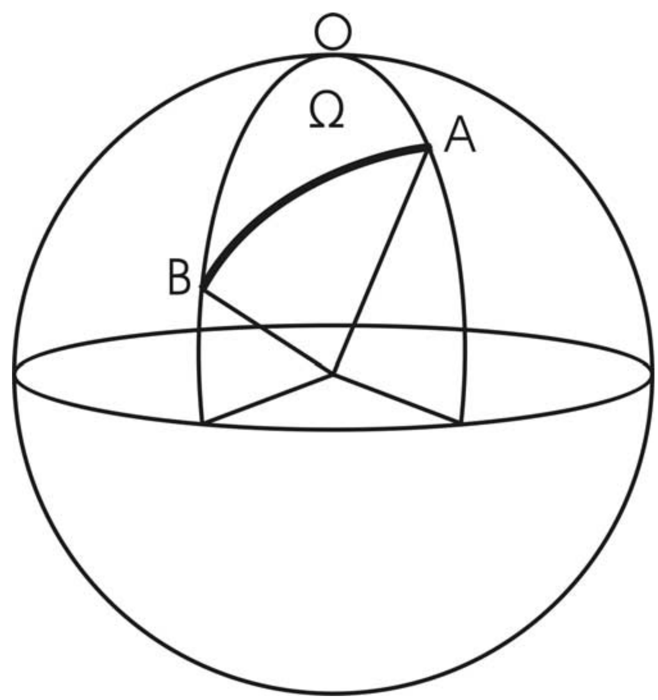

Figure 7. Definition of the angular parameter.

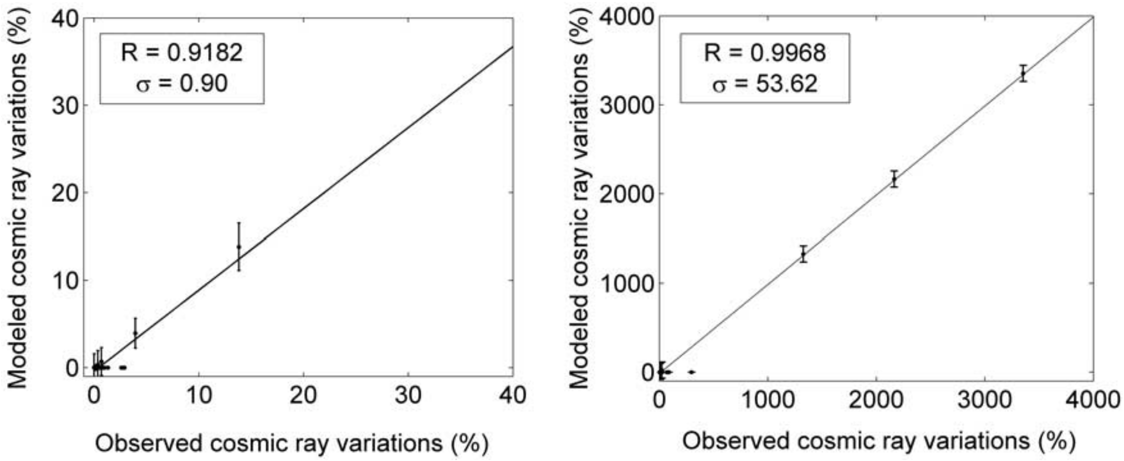

Figure 8. Goodness of the model at the first time-intervals of the event: (a) 0645–0650 UT and (b) 0650–0655 UT of 20 January 2005.

asymptotic cones intersecting the particle beams. On the basis of the above, the anisotropy function was chosen as:

$$\Psi(\Omega, R, t) = \exp\left(-n_a^2 \sin^2 \frac{\Omega}{2}\right) \quad (6a)$$

where index n_a characterizes the width of the solar particle beam: big values of n_a correspond to narrow solar particle fluxes. In order to understand better the sense of this parameter, equation (6a) may be rewritten as following:

$$\Psi(\Omega, R, t) = \exp\left(-\sin^2 (\Omega/\Omega_0)\right), \quad (6b)$$

where Ω_0 = 2 arcsin(n_a), in assumption that $n_a > 1$. At Ω_0, angular distance from the direction of the flux maximum the flux decreases exponentially. The value Ω_0 may be considered as a characteristic width of the flux. The width $\Omega_0 \approx 12°$ corresponds to parameter n_a = 10, and for n_a = 5 it increases up to $\approx$23°.

[23] The dependence of primary solar cosmic ray flux, $\Delta D(R, t)$, was assumed to be power law in rigidity:

$$\Delta D(R) = b \cdot R^{\gamma} \quad (7)$$

4. Data Analysis

[24] Five-minute data from 41 NM stations, widely distributed around the Earth, were incorporated to fit the main equation (4), applying the Levenberg-Marquardt nonlinear optimization algorithm [*Levenberg*, 1944; *Marquardt*, 1963; *Moré*, 1977]. For the evaluation of the asymptotic directions and the cut-off rigidities for each NM location the Tsyganenko89 model has been used [*Tsyganenko*, 1989]. The beginning of the event is very difficult to model due to the extremely anisotropic direction of propagation of the solar particles and due to the big differences (1–2 orders of magnitude) in the counting rates recorded between different neutron monitors. However, the results of the above described model based on the Levenberg-Marquardt algorithm proved to be relatively reliable. The goodness of our fit for the first time intervals of the event is presented in Figure 8. For later moments the dispersion between observed and calculated CR variations was reduced, whereas the correlation coefficient remained big enough.

5. Results and Discussion

[25] The application of the GLE model described above on the event of 20 January 2005 provided us with special quantitative information on the GLE particle spectrum evolution, solar cosmic ray fluxes, and cosmic ray anisotropy. The interpretation of our results regards the following areas.

5.1. Rigidity Spectrum

[26] According to the results of our modeling the primary SCR rigidity spectrum outside the magnetosphere appears hard enough ($\gamma = -4.4$) during the initial phase of the event (0645–0650 UT); in fact, the spectrum is hard only for the last 1.5–2 min of this interval. This fact implies that on 20 January 2005 there had been quite significant fluxes of higher-energy solar particles. In the second 5-min interval (0650–0655 UT) the spectrum became significantly softer ($\gamma \sim -8.4 \pm 2.8$) while during the third one (0655–0700 UT) it hardened ($\gamma \sim -7.6 \pm 0.7$). This behavior is quite unexpected taking into consideration the fact that before the maximum event the proton spectrum is usually harder than on the maximum itself [*Akimov et al.*, 1996]. In the next 45 min the spectrum shape changes slightly, while spectral index ranges between −6.6 and −7.6. As can be seen in Figure 9, in the beginning of the event the contribution of higher-energy particles is bigger compared to that after 0650 UT.

[27] After having defined the model parameters for each 5-min interval and time profiles of the proton fluxes for different rigidities the peak spectrum within the rigidity range between 0.1 GV and 15 GV can be obtained (Figure 9). It should be noted that in the low-rigidity range the results have been obtained by extrapolation. As one can see in Figure 9, the peak spectrum is quite close to power law. The respective spectral index calculated within the rigidity range 1–15 GV, where neutron monitors are effec-

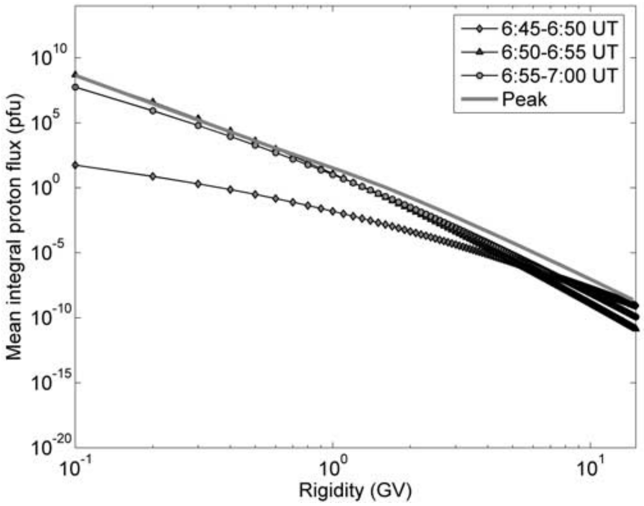

Figure 9. Integral rigidity spectrum of solar cosmic rays near the Earth calculated for the three first 5-min intervals and the peak spectrum for the 20 January 2005 event.

tive, was $\gamma_{Peak} = -8.3 \pm 0.2$. The peak spectrum of SCR in the vicinity of the Earth gives the rigidity dependence of the maximum proton fluxes as well as information on the injection spectrum shape [*Akimov et al.*, 1996; *Belov and Eroshenko*, 1996]. For example, calculations made by *Fedorov et al.* [2002] and *Fedorov and Shakhov* [2003] for the event of 15 June 1991 occurring under conditions of fairly turbulent interplanetary magnetic field, have shown that the difference between injected CR spectrum and peak spectrum near the Earth was sufficiently small. According to *Belov et al.* [1994], the event of 15 June 1991 was characterized by a very low level of anisotropy, rather short injection of energetic particles, and sufficiently high level of SCR scattering in the interplanetary medium. However, contrary to 15 June 1991, the event on 20 January 2005 is more anisotropic. In this case the form of peak and emission spectra cannot be supposed as coincided.

[28] Taking into consideration the sharp CR increases appearing in the time profiles of the NM counting rates during the GLE event on 20 January 2005 (Figure 3 and 4) one can assume that the propagation of the first solar particles in the interplanetary magnetic field must have been rather scatter-free than diffusive. However, this event seems to be neither scatter-free nor diffusive totally. However, even in case of a full scatter-free propagation, we cannot affirm that peak spectrum is very representative of the injection spectrum shape because of the possible influence of the magnetic field. Consequently, the question on the type of particle propagation requires an additional study.

[29] The changes of dynamic spectrum obtained on the basis of this model for the various moments of the event were compared to that reported by *Flückiger et al.* [2005]. It was found that both spectra are broadly consistent, with a tendency to be slightly softer in our case. This may be attributed to different neutron monitor response functions and/or number of stations used in the analysis.

5.2. Solar Cosmic Ray Fluxes

[30] The mean solar cosmic ray differential flux on the top of the atmosphere was calculated for different rigidities on the basis of the results derived from our model, averaging angular dependence for all directions:

$$\Delta I_{mean} = \iint_{4\pi} \Delta D(R) \cdot \Psi(\Omega, R)\, d\Omega = \iint_{4\pi} b \cdot R^{\gamma} \cdot \exp\left(-n_a^2 \sin^2 \Omega/2\right) d\Omega = \frac{b \cdot R^{\gamma}}{n_a^2} \cdot \left(1 - \exp\left(-n_a^2\right)\right) \quad (8)$$

The time evolution of the SCR differential flux is presented in Figure 10. The peak time $t_{\max}$ turned out to be the same for all higher rigidity particles (1 GV, 2 GV, and 3 GV). Consequently, if to judge by the NM data, the proton enhancement in the vicinity of Earth for solar particles with rigidity at least >5 GV must have been of very short duration. A difference in the profiles for 1 and 2 GV might be an argument for two episodes of the acceleration.

[31] The integral SCR flux can be calculated from:

$$F_{mean} = \int_{R_c}^{R_u} \frac{b \cdot R^{\gamma}}{n_a^2} \cdot \left(1 - \exp\left(-n_a^2\right)\right) dR = \left[\frac{b \cdot R^{\gamma+1}}{(\gamma+1) \cdot n_a^2} \cdot \left(1 - \exp\left(-n_a^2\right)\right)\right]_{R_c}^{R_u} \quad (9)$$

[32] The behavior of the mean integral fluxes of the lower-energy solar cosmic ray particles on 20 January 2005 is presented in Figure 11. The results displayed for energies greater than 100 MeV and 300 MeV are of course obtained by extrapolation, due to the fact that none of the NMs can record CR particles with energy $\lesssim$500 MeV (or R $\lesssim$ 1 GV). At this point we should clarify that the results in this energy range are derived upon the assumption that spectral index is independent of energy. In Figure 11 it is clearly seen that during the first time intervals, while the anisotropy is big, the mean integral flux is also very big. Moreover, the time of maximum flux seems to depend on the energy of the solar particles. The mean integral flux F_{mean} (>100 MeV) obtained by extrapolation on the basis of our model is in good agreement with the satellite observations (http://www.lmsal.com/solarsoft/protons/eit_protons_20050120_ 0623.html), taking values of the same order of magnitude. The estimated flux for particles with energy >100 MeV exceeds only by a factor of $\sim$2 the flux recorded on 29 September 1989 ($\sim$600 pfu) and on 14 July 2000. Moreover, we found that all three fluxes of lower-energy particles presented in Figure 11 remain at a surprisingly high level during the first hour of the event. This result derived from the application of our model to the GLE on 20 January 2005 is also testified by the satellite observations of particles in the lower-energy range (>50 MeV and >100 MeV). Therefore our results based on the application of a definite model with a big contribution of the anisotropy (as described by equations (5) and (6)) seem reliable, at least for the time period during the first 1.5 hours.

[33] The station-specific effective rigidity of the primary SCRs, R^i_{eff}, defined as the rigidity at which the variation of

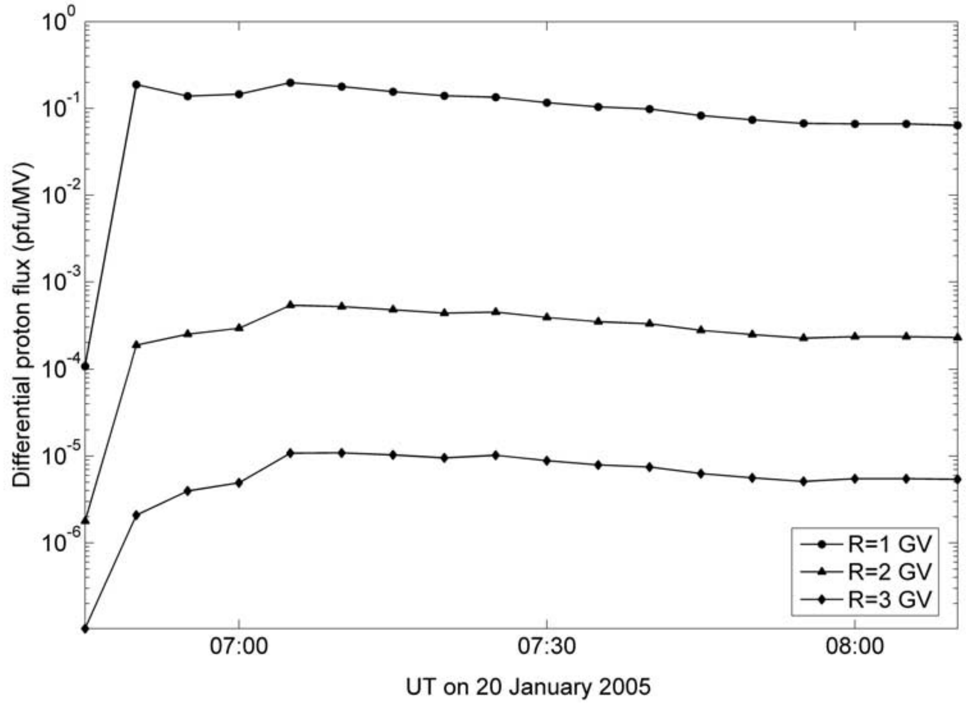

Figure 10. Mean differential flux on the top of the atmosphere for the higher rigidity particles.

the primary solar cosmic rays is equal to the counting rate variation at the station, in case of a power-law rigidity spectrum, was calculated as:

$$\frac{\Delta I}{I_o} = \frac{\Delta N}{N_o} \Rightarrow \frac{b \cdot \left(R^i_{eff}\right)^{\gamma} \cdot \Psi(R, \Omega, t)}{I_o} = \frac{\Delta N}{N_o} \Rightarrow \ln R^i_{eff} = \frac{1}{\gamma}\left(\ln \frac{\Delta N}{N_o} - \ln \frac{\Delta I(R = 1\,GV)}{I_o}\right) \quad (10)$$

For the whole NM network the effective rigidity at a specific time has been calculated as the average of the station-specific R^i_{eff}:

$$R_{eff} = \sum_{i=1}^{N} w_i R^i_{eff} / \sum_{i=1}^{N} w_i \quad , \quad (11)$$

where N is the number of NM stations and w_i is the weight function, for which the magnitude of the effect in this

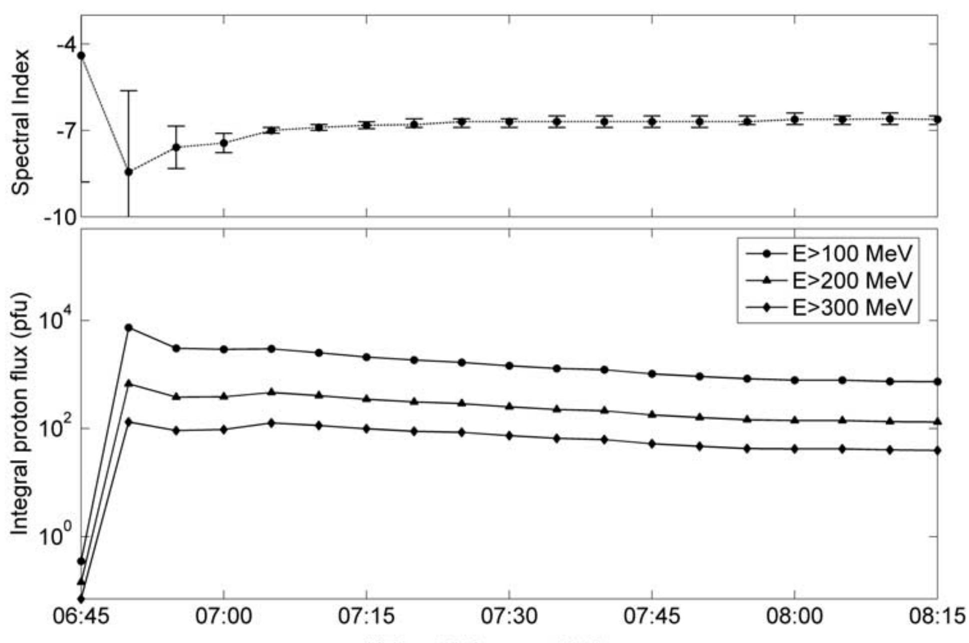

Figure 11. Mean integral fluxes extrapolated for energies >100, >300, and >500 MeV.

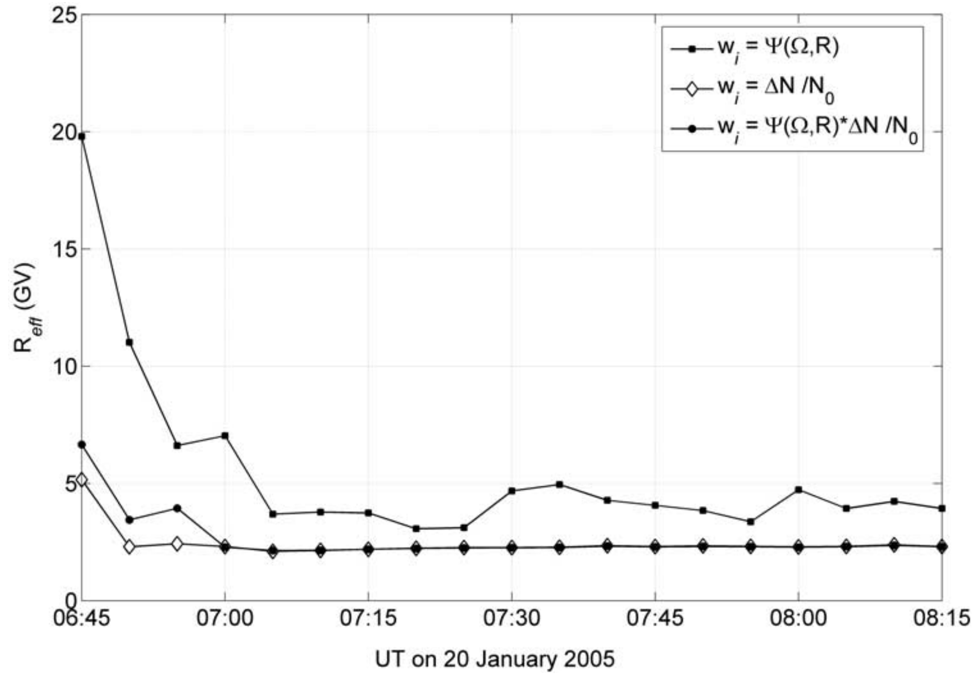

Figure 12. Effective rigidity for the whole neutron monitor network on 20 January 2005.

station at any fixed time is most naturally used. However, we have tried three different weight functions w_i, which were assumed equal to: (1) the anisotropy function, (2) the enhancement of the event, and (3) the product of the anisotropy function with the enhancement. The respective results gave similar values for the effective rigidity of the event (Figure 12). It was found that during the GLE of January 2005 the effective rigidity was high only in the beginning of the event. In a very short time period of about 15 min it dropped to values smaller than ~5 GV, suggesting that the record of most energetic particles must have been of a very short duration.

5.3. CR Anisotropy

[34] The exact location of the apparent source of solar particles direction is generally difficult to determine. In our analysis we assumed that the relativistic particles arrived in the vicinity of the Earth forming a narrow beam, expressed by relation (6). Such an approach for the anisotropic arrival of particles is quite reasonable, if one takes into account the large differences in the cosmic ray variations between neutron monitors of the same cut-off rigidity and altitude, located at different latitudes (Figure 5).

[35] The time-dependent variation of the position of the anisotropy source near Earth, in geographical coordinates, is demonstrated in Figure 13. In the beginning the source of solar particles was located almost perpendicular to the equatorial plane, whereas later it moved to northern locations, remaining however to the southern hemisphere. The longitude parameter as extracted from our model seems to vary significantly for almost the first 1 1/2 hours of the event, covering a wide range of values. This strange behavior of the longitude parameter could be attributed to the specific GLE model used. However, we think that it is evidence of real anomaly that mirrors the anisotropic propagation of solar particles in the variable conditions of interplanetary space.

[36] The position of the source of SCR during the extreme event of 20 January 2005 was studied by other researchers as well [*Vashenyuk et al.*, 2005; *Belov et al.*, 2005b; *Flückiger et al.*, 2005]. In all of these papers it was also found that the solar particles arrived from south directions. However, the calculated longitudes for the anisotropy source differ from model to model [*Bazilevskaya*, 2005].

[37] The anisotropy contribution in averaged SCR fluxes was calculated by:

$$A_{mean} = 1 - \Psi_{mean}(R) \tag{12}$$

where $\Psi_{mean}(R)$ is the average anisotropy function over all possible directions of particle arrival:

$$\Psi_{mean}(R) = \iint_{4\pi} \Psi(\Omega, R)\, d\Omega = \iint_{4\pi} \exp\left(-n_a^2 \sin^2 \Omega\right)\, d\Omega = \frac{\left(1 - \exp\left(-n_a^2\right)\right)}{n_a^2} \tag{13}$$

[38] The values of the anisotropy contribution in maximum and mean SCR fluxes, as defined above, are presented together with the parameter n_a controlling the width of the angular distribution in Figure 14. It is clearly seen that the anisotropy contribution in mean fluxes coincides with that in maximum fluxes during the first moments of the event (0645–0700 UT) implying that strong anisotropy existed during the initial phase of the event. The angular distribution is narrow during the time interval 0645–0700 UT, with an index n_a taking values between 3 and 15. Later n_a becomes smaller (~1), suggesting a wider angular distribu-

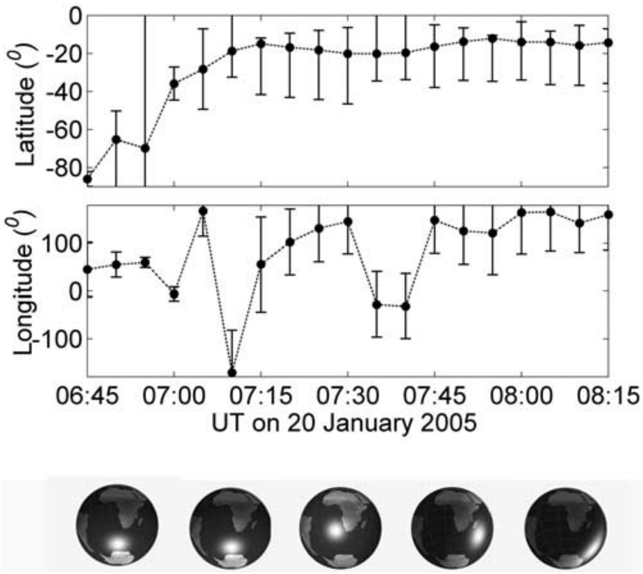

Figure 13. Position of the anisotropy source on 20 January 2005 in geographical coordinates is shown in the upper panel. The evolution of the position of the anisotropy source corresponding to time intervals: 0645–0650 UT, 0650–0655 UT, 0700–0705 UT, 0720–0725 UT, 0810–0815 UT is presented in the lower panel.

tion of SCR particles spread along various latitudes and longitudes. The anisotropy function Ψ remained to be of big values during the time period between 0705 UT and 0755 UT. This fact is confirmed by the data from the majority of neutron monitors (especially the polar ones): they recorded relatively high fluxes of solar particles for quite a long time after the onset with a big difference at different stations as an evidence of sufficiently high anisotropy. The contribution of anisotropy into the mean flux (averaged over all directions), was mostly significant during the time interval 0650–0705 UT. During the first time intervals, the giant impulse like increase was recorded at the three southern polar stations. To fit the axis symmetric anisotropy function, given in relation (6), we need very narrow beam like form (i.e., large values of parameter n_a) in combination with a hard rigidity spectrum.

[39] The shape of the angle distribution of the flux, described by equation (12), is plotted in Figure 15, as a function of latitude and longitude for the first half hour of the event. As it is clearly seen, during the first time intervals of the event, the anisotropy in the direction of the particle arrival has a narrow beam-like form, centered around specific locations. As time evolves the distribution of the anisotropy function spreads and Ψ obtains simultaneously bigger values. The way the anisotropy function evolves gives an explanation to the big differences in the counting rates recorded by NM stations located at different longitudes around the globe. In the beginning of the event only the stations with asymptotic cones falling into this narrow beam of energetic particles recorded significant enhancements (e.g., South Pole, McMurdo, Terre Adelie). Later, the particle beam widens and the energetic particles can be sensed by more neutron monitors since the anisotropy function distribution covers an extended range of longitudes and latitudes (Figure 15). As a result, there were continuously more and more NM stations that were observing significant enhancements. This result is confirmed by the observations as well.

[40] The narrow particle beam, at the beginning of the event can be seen in Figure 15. The particles fluxes seem to arrive in form of narrow beams and at 0650 UT the beam was centered above latitude −65° and longitude 55°. As time evolved, this beam widened and the number of neutron monitors falling inside its region became bigger. As it is clearly seen in Figure 15, the longitudinal distribution of the anisotropy function at some specific latitude depended strongly on time. This is quite reasonable since the position of the anisotropy source is moving as time evolves.

[41] During later time intervals the anisotropy function seems to influence the flux in more or less the same way at all longitudes. For example at 0705 the anisotropy function is big enough for nearly all pairs of longitudes and latitudes. At later time intervals the anisotropic propagation of particles was continuing to exist, failing, however, to result in extremely big differences in the registration of the ground

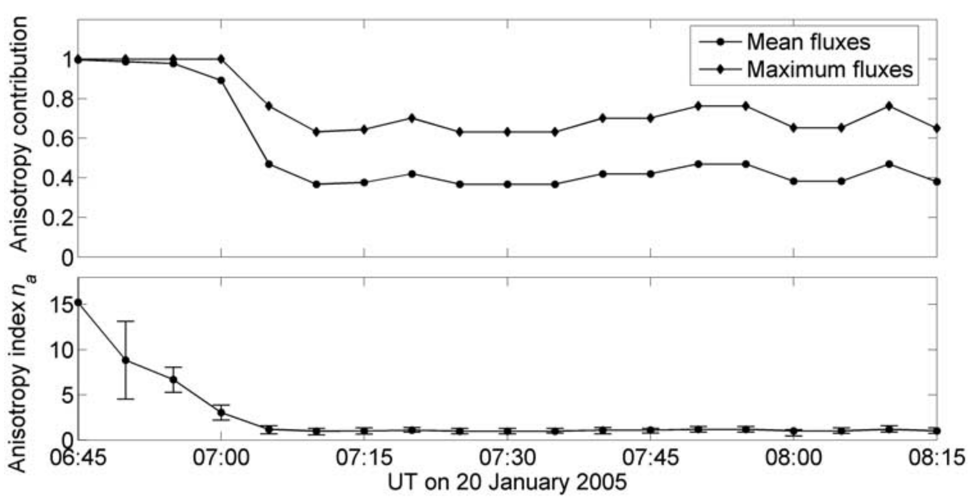

Figure 14. Anisotropy contribution in mean and maximum fluxes during the event of 20 January 2005.

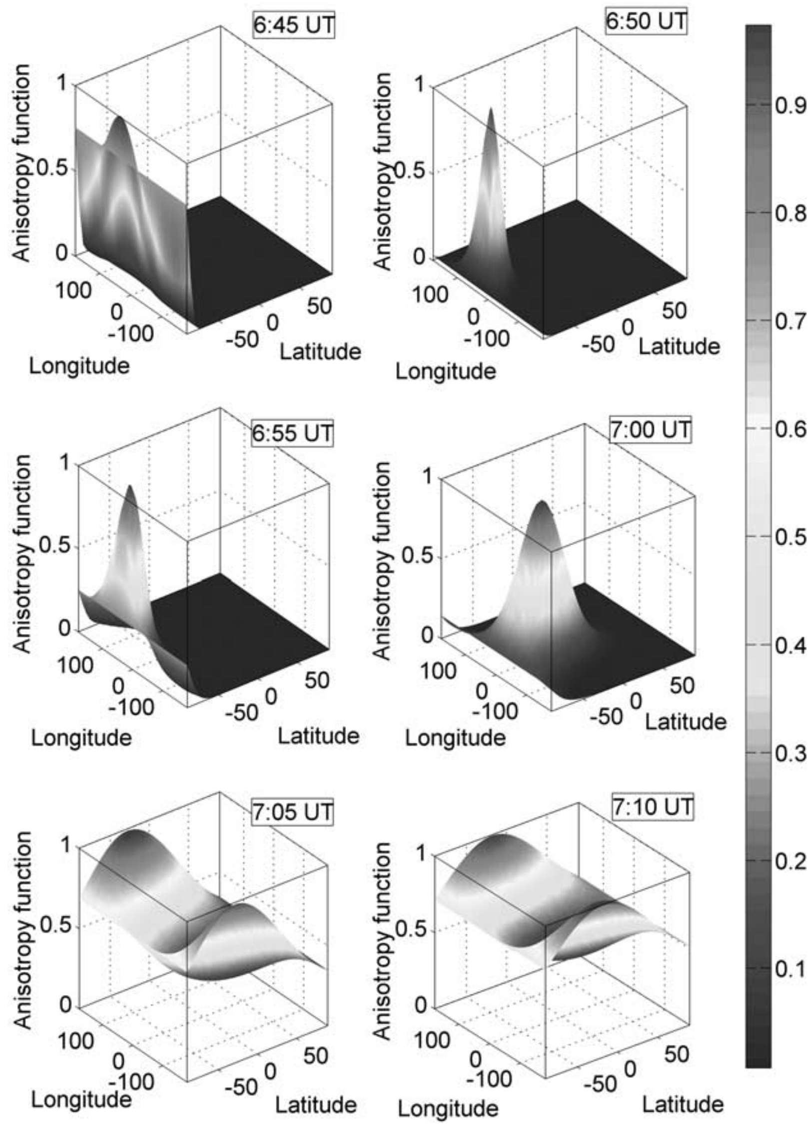

Figure 15. Time evolution of the anisotropy function $\Psi(\Omega, R)$.

level enhancement among different NMs, mainly due to the wider distribution of primary particles.

5.4. Interplanetary Magnetic Field

[42] We have compared the position of the anisotropy source derived from our model with the direction of the interplanetary magnetic field (IMF) calculated from the magnetic field data from OMNI (http://omniweb.gsfc.nasa.gov). Unfortunately, the only available data were those that corresponded to the first and the second hour of the event. In Figure 16 the "diamond" points represent the projection of the anisotropy vectors on the ecliptic plane, in GSE coordinates, for the various moments of the event. The "circle" points correspond to the projection of the IMF vector, in GSE coordinates. As one can see the position of the IMF in the time interval 0600–0700 UT is placed to 135° west from the Sun-Earth line, which coincides with the angle that corresponds to the classical Archimedean spiral path for a solar wind velocity of about 400 km/s. As can be clearly seen in Figure 16, the most of the anisotropy points are located in the same quadrant with the IMF at the time period 0645–0700 UT. The same result was obtained for the initial phase of many other events as well: for example for the event on February 1956 [*Belov et al.*, 2005a]. In the time interval between 0700 UT and 0800 UT, the IMF direction changes significantly. The time evolution of the angular difference between the directions of the anisotropy vector and the IMF, projected to the ecliptic plane, is presented in Figure 17. It can be seen that in the initial phase both directions are quite close, implying that perhaps these particles have arrived being directed almost along the magnetic field lines. Later the particle propagation must have been more complicated, since the anisotropy and the IMF directions differ significantly. The reasons of this are not explained yet, but we hope to obtain some more reliable results in the future after applying some interplanetary magnetic filed model for the period of the event.

[43] The asymptotic viewing directions of several NM stations that observed the GLE on 20 January 2005, together with the contour areas of the equal fluxes of

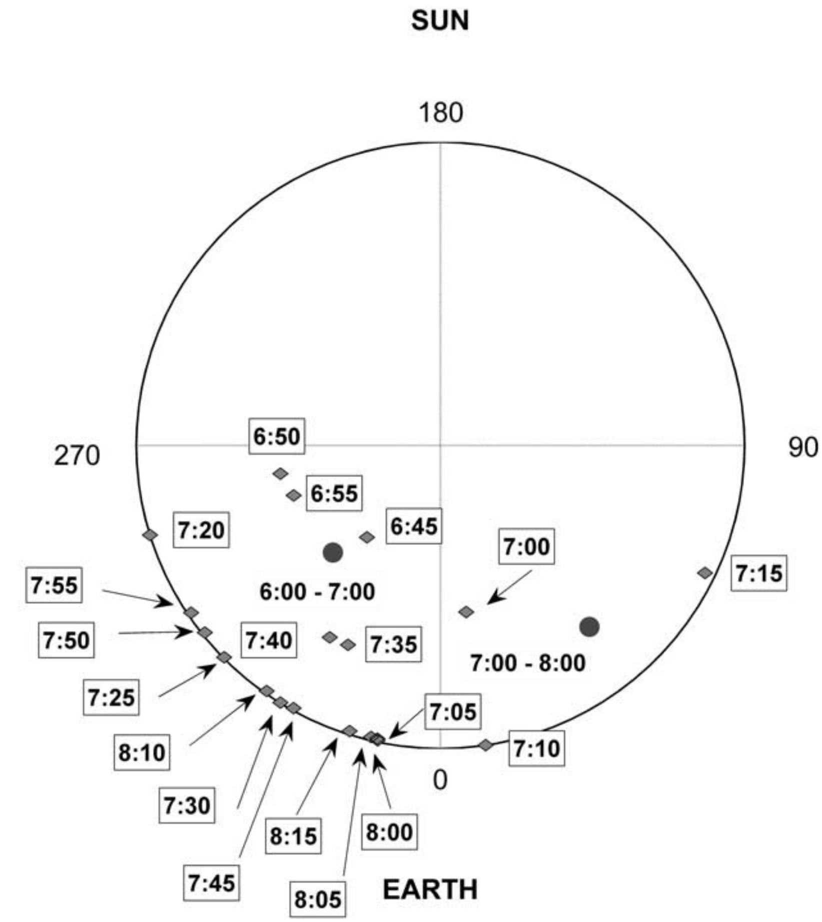

Figure 16. Projection of the IMF and the anisotropy vectors (in GSE coordinates) on the ecliptic plane (Diamonds correspond to anisotropy, circles to IMF).

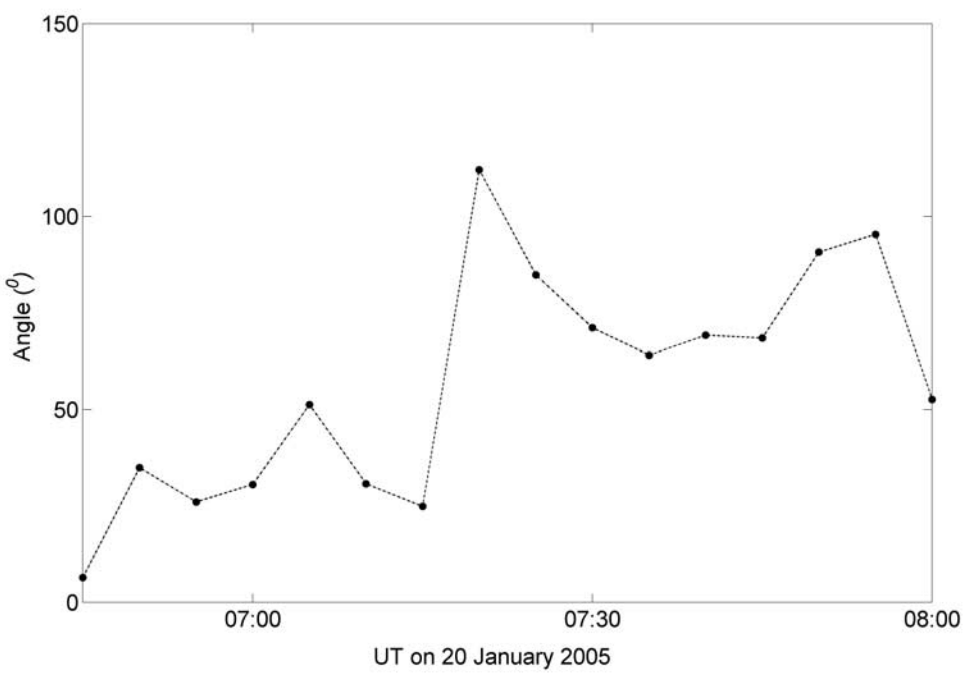

Figure 17. Angular difference between the IMF and the projections of the anisotropy on the ecliptic plane.

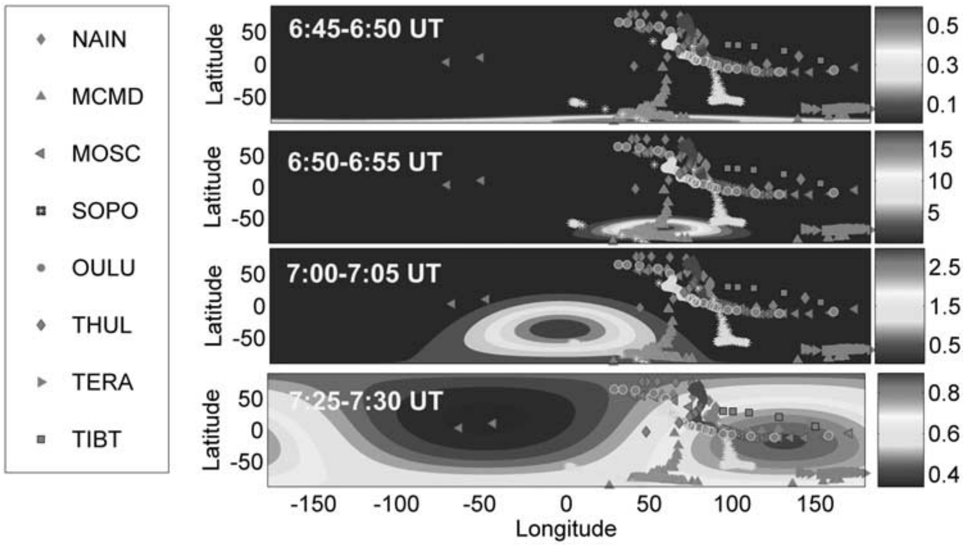

Figure 18. Contour areas of equal fluxes of particles with rigidity bigger than 1 GV together with asymptotic viewing directions of some NM stations for different moments during the event of 20 January 2005. The grey scale corresponds to SCR integral fluxes (in pfu) outside the atmosphere.

particles with rigidity bigger than 1 GV, during different phases of the event, are presented in Figure 18. It is clearly seen that during the initial phases of the event (upper panels of Figure 18), while the anisotropy is big, the highest particle fluxes are concentrated inside a narrow area. In the time interval 0650–0655 UT (second upper panel of Figure 18) the asymptotic cones of the neutron monitors at McMurdo and South Pole fall inside this narrow area. This fact seems to be the reason why these two stations recorded such big enhancement at that time. In particular, the fact that the McMurdo NM asymptotic cones of viewing turned out to be almost centered above the position of the anisotropy source explains the big variation recorded by this station at that time (~1328%), despite the fact that the detector is located at sea level. On the basis of the viewing directions criterion, South Pole station seems to be a little less favored than McMurdo in recording the GLE during its initial phase, since its asymptotic cones are not located that close to the anisotropy source. However, the South Pole station recorded the biggest enhancement of all other stations. The high altitude of the South Pole location turns out to be the crucial point that leads to registration of higher fluxes of SCR secondaries (~3200%, on the basis of 5-min data). It is noteworthy that the sea-level NM in Terre Adelie station recorded also maximum event having asymptotic cones located at a bigger distance from the anisotropy source than McMurdo. In particular in the time interval 0650–0655 UT the station in McMurdo was registering variation of 1328%, whereas that in Terre Adelie 2164%. This difference cannot be attributed to the relative position of the asymptotic cones of the Terre Adelie station. Maybe this anomaly is related either to the quality of the interpolated NM data registered at Terre Adelie or to the GLE model used, which does not account all possible directions of the particle arrival. In any case, these three stations are close to geographical sites that can provide the similar conditions for the SCR registration. Moreover, any possible nonnegligible temporal magnetic anomaly in the vicinity of the Earth would result in a geomagnetic field different from the one assumed using the Tsyganenko89 model. The subject is still unanswered but we hope to get more reliable conclusions in the near future, after employing atmospheric data as well as data from muon detectors.

[44] As far as the other NM stations in Figure 18 are considered, one can clearly notice that during the initial phases their asymptotic directions are located far from the area of maximum flux, during the first time-intervals. As a result, stations with the same cut-off rigidity as the South Pole and McMurdo record significantly smaller enhancements (1–2 orders of magnitude). Later, as the initially narrow beam of particles widens, the anisotropic SCR flux distribution spreads. At 0725–0730 UT (lowest panel of Figure 18) the solar particle beam has become wide enough to cover a wider range of longitudes and latitudes. The maximum of the CR variations at that time has already been reached at all stations recording the enhancement. This fact is in good agreement with Figure 18 (lowest panel). As it is clearly seen nearly all asymptotic directions of viewing "see" significant primary SCR fluxes.

[45] Consequently, the position of "viewing" directions of a NM in relation with the locations of the particle source is a factor that plays a significant role in the SCR variations recorded at ground level. However, the differences in time profiles among the NMs may be also due to other factors, for example: different penetration of particles initially reaching the magnetospheric boundary [*Kuznetsov et al.*, 2005].

6. Conclusions

[46] At the end of the 23rd solar cycle a giant ground level enhancement of relativistic solar protons took place on 20 January 2005. In order to analyze and interpret the peculiarities of this solar energetic particle event, a new GLE model, based on the consideration of the angular distribution of the SCR flux arrived at Earth, including its

narrow beam, has been constructed. After fitting the GLE data from a great number of neutron monitors and optimizing the ground level responses to a primary anisotropic cosmic ray flux, we may conclude the following:

[47] 1. The record enhancement in the counting rate at some southern polar NMs on 20 January 2005 ranks this event among the greatest GLEs in the history of observations.

[48] 2. The event of 20 January 2005 has a complex structure with two maxima. The first maximum appears due to the extremely anisotropic beam of solar particles arriving during the initial phases of the event, whereas the second one is probably related to SCR density maximum.

[49] 3. The time evolution of the rigidity spectrum has a rather complicated behavior. In the beginning of the event it appears hard. In the second time interval it softens abruptly and then it hardens again. During the later phases the spectral index varies between -6.6 and -7.6.

[50] 4. The extremely intensive narrow beams of solar relativistic particles arriving at the Earth during the time interval 0650–0655 UT had a width that did not exceed 10–40 degrees. The neutron monitors whose asymptotic directions at that time viewed the anisotropy source recorded enhancements of thousand of percents (e.g., McMurdo, South Pole). These initially narrow particle beams widened with time resulting in big enhancements recorded by all other high-latitude NMs.

[51] 5. Anisotropy remained in relatively high levels during the first hour of the event. The source of anisotropic flux was located in southern hemisphere. The position of the anisotropy source changed with time, moving to more northern locations.

[52] 6. The estimation of the integral flux for particles with energy >100 MeV on the basis of our model is in good agreement with the satellite observations. Moreover, it ranks this event among the largest proton enhancements ever recorded.

[53] 7. Many features of this GLE may be explained by the peculiarity of the particle interplanetary propagation.

[54] The results of this modeling of the January 2005 event are satisfactory enough, as it was noticed above. The calculated values for the integral proton flux of particles with energy >100 MeV are in very good agreement with the satellite observations. This implies that the proton fluxes obtained from our model using ground level NM data are very much consistent with the real fluxes recorded by space instruments. This result can be utilized in means of the space weather monitoring and/or prognosis. Application of this model to as many GLEs as possible is of great importance in order to reveal the characteristics of the solar proton flux distribution and magnitude in the vicinity of the Earth in as many cases as possible. For this reason historical GLE datasets, collected from the worldwide network of neutron monitors, should be modeled using upgraded techniques based on effective algorithms.

[55] Interpretation of possible common characteristics can also outcome from the utilization of data from different types of observing instruments (e.g., muon detectors, neutron telescopes, etc.). Information on X-ray flares is very important since it is often related to proton enhancements [*Belov et al.*, 2005d]. Incorporation of data from satellite particle detectors can also provide important information on particles of the lower rigidity range as well as on the X-ray flux. Therefore an extended integrated analysis combining all the above mentioned potentials may drive our current knowledge to a point that the forecasting of solar extreme phenomena will be attainable.

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