Study of the ground level enhancement of 20 January 2005

C. Plainaki, A. Belov, E. Eroshenko, H. Mavromichalaki and V. Yanke

Abstract—**The determination of several descriptive GLE parameters using a simulation gives important insights into the particle acceleration mechanisms at the Sun. The event of 20 January 2005, associated with an X7.1 class solar flare, has been one of the biggest enhancements observed by the ground level neutron monitors. In this work the CR variations during this enormous event have been modeled to a completely anisotropic solar proton flux, using an optimization method, based on the Levenberg-Marquardt algorithm. It seems that the first solar particles entered the atmosphere of the Earth forming a narrow beam originating from southern hemisphere. The integral primary proton spectrum during the first time intervals of the event is rather complicated suggesting different kind of possible acceleration and propagation scenarios. Several parameters of these primary solar particles, such as the position of the anisotropy source and its time evolution, are obtained and discussed. Finally a comparison of the results obtained from the application of the current anisotropic model with those obtained from a more compound model is presented.**

I. Introduction

A ground level enhancement (GLE) is defined as a sharp increase of small duration in the counting rate of ground-based cosmic ray detectors caused by the accelerated charged particles from the Sun, the so called solar cosmic rays (SCR), to energies sufficiently high to penetrate along the geomagnetic field and the Earth's atmosphere. 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. The greatest GLE of solar cosmic rays ever recorded by neutron monitors (until January 2005) was observed on 23 February 1956. Detailed analysis of the characteristics and the peculiarities of this event, based on the analysis of the limited number of data available from that epoch, have been accomplished by many researchers [1], [2], [3], [4], [5], [6], [7]. Since that time hundreds of proton events and tens of GLEs were registered, but all of them rank below this one by more than one order of magnitude or more. However, on 20 January 2005, a new GLE comparable in magnitude with that of 1956 was registered in the neutron monitors of the worldwide network.

The determination of several descriptive GLE parameters can be achieved by a number of different methods presently available [8], [9], [10], [11]. In this work a GLE modeling technique based on the method of the coupling coefficients [12], [13] applied for the GLE of 2005 is proposed. Cosmic ray data from a large number of neutron monitors (forty-one) covering a wide range of cut-off rigidities and asymptotic viewing directions have been analyzed and processed in order to model the behavior of solar cosmic rays during the extreme event of 20 January 2005 (Fig. 1).

II. Description of the Event

The GLE of 20 January 2005 falls into the descending phase of solar cycle 23 which by that time was already very close to its minimum. A series of hard X-ray flares accompanied by series of coronal mass ejections took place in January 2005 starting from 14th of January. A significant Forbush decrease with magnitude about 19 % in 10 GV galactic cosmic ray density, occurred on 17th of January at 07:48 UT. 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 06:36 UT and had a peak emission at 07:01 UT. The hardest and most energetic proton event of

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solar cycle 23 resulted in a new ground level enhancement observed by several NMs of the worldwide network some minutes after the flare onset (at 06:48 UT), on the background of relatively quiet geomagnetic activity [11], [14]. 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, the geomagnetic activity rose up again on the second half of 20 January reaching a level corresponding to a small magnetic storm.

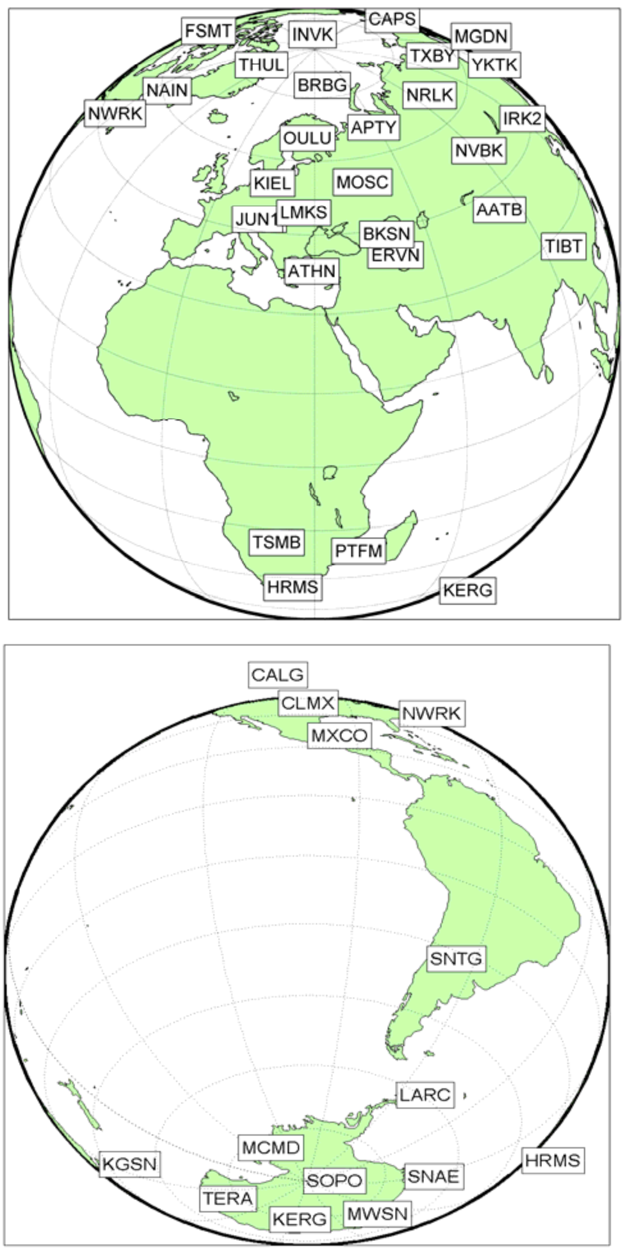

Fig. 1: Neutron Monitor stations used in this analysis

An overview of this GLE event, as observed by the polar neutron monitors of both hemispheres, is presented in Fig. 2. The event of 20 January 2005 appears to be complex enough if to judge from the time profiles of the CR variations of various stations. 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 polar stations recorded significantly smaller fluxes. Differences in the count rates at the first stage of the event may be attributed to different asymptotic viewing directions more than to difference in geomagnetic cut off rigidities. It is remarkable however, that the equatorial neutron monitor station at Tibet (cut-off rigidity ~ 14.1 GV) recorded the GLE, registering an increase of about ~ 2% whereas other low latitude neutron monitors did not observe the ground level enhancement (e.g. Athens neutron monitor station, Fig. 3)!

The GLE of 20 January 2005 is clearly anisotropic. The north-south anisotropy is manifested by the different time profiles of Thule and McMurdo stations respectively. It can be attributed to the different viewing asymptotic directions, since the cut off rigidities for these stations are identical. 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.

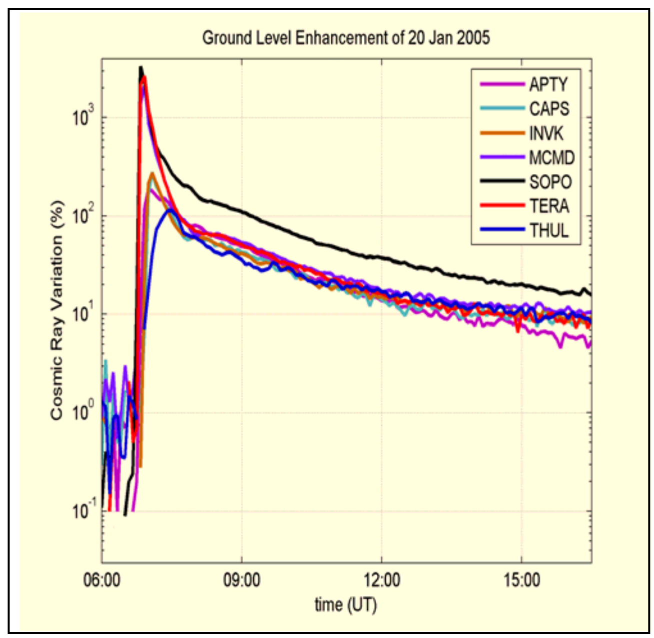

Fig. 2: The ground level enhancement of 20 January 2005 as observed by polar neutron monitors

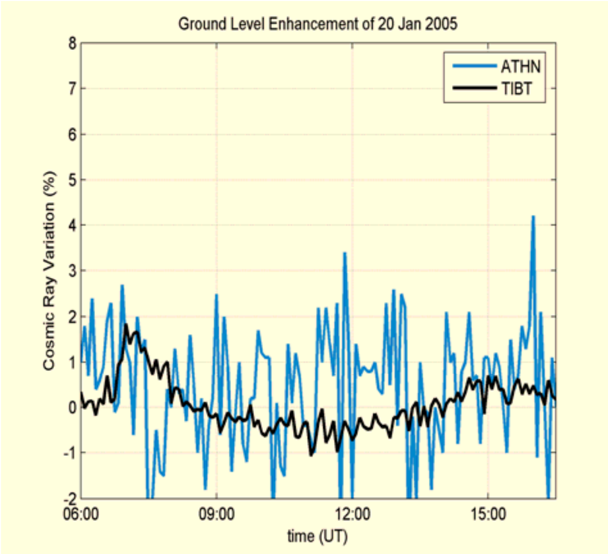

Fig. 3: Cosmic Ray Variation recorded by Athens and Tibet Neutron Monitor Stations.

III. THE NM-BANGLE MODEL – APPLICATION TO JANUARY 2005

Ground level enhancements are increases in the cosmic ray intensity recorded by ground based monitors due to solar accelerated particles. The primary solar cosmic ray rigidity spectrum in the vicinity of the Earth as well as the particle arrival distributions can be deduced by analysis of data from the worldwide network of detectors. Therefore the development of an accurate GLE model that will provide information about the solar particle propagation characteristics becomes a task of significant importance.

A new GLE model, the so called NM-BANGLE (Neutron Monitor BAsed Anisotropic GLE) model, is proposed [14]. According to the NM-BANGLE model the time variation of the intensity of any cosmic ray component of type i during a GLE (e.g. total neutron counting rate, muon component on the ground and underground at different depths), observed at cut-off rigidity $R_c(t)$, at level $h(t)$ in the atmosphere at some moment t can be determined from [15], [6]:

$$\frac{\Delta N(R_c,h,t,t_0)}{N_0(R_c,h,t_0)} = \frac{\int_{R_c}^{R_u} W(R,h,t_0)\frac{\Delta D(R,t)}{D_0(R)}(t,R)dR}{\int_{R_C}^{R_u} W(R,h,t_0)dR} \qquad (1)$$

where $W(R_{co},R)$ is the coupling function between secondary CR and primary CR arriving at the top of the atmosphere, firstly introduced by Dorman [12]. The form of a neutron monitor coupling function is briefly described in [13], in [16] and in [17]. In equation (1) $\Delta D(R,t)$ 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.

Ground level enhancement data from neutron monitor stations of the worldwide network, covering a wide range of rigidities and longitudes, can be used in order to reveal certain characteristics during a specific event. In order to determine the best-fit parameters in the GLE model described by equation (1) a least squares procedure is used.

Taking into consideration that the ground level enhancement of 20 January 2005 occurred during a Forbush decrease some further modifications based on the results of the Global Survey Method are needed [11], [18]. Since the event of 20 January 2005 seemed to be extremely anisotropic on the basis of our model 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. Therefore the differential SCR spectrum can be written as:

$$\Delta D(\Omega,R,t) = \Delta D(R,t)\cdot\Psi(\Omega,R,t) \qquad (2)$$

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

Five-minute data from 41 NM stations, widely distributed around the Earth, were incorporated to fit the equation (1), applying the Levenberg-Marquardt non-linear optimization algorithm [19], [20], [21]. For the evaluation of the asymptotic directions and the cut-off rigidities for each NM location the Tsyganenko89 model has been used [22].

IV. RESULTS-DISCUSSION

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 primary SCR rigidity spectrum outside the magnetosphere appears hard enough (γ = -4.4) during the initial phase of the event (6:45 UT - 6:50 UT) implying that on 20 January 2005 there had been quite significant fluxes of higher energy solar particles. Later the behavior of the spectral index is quite unexpected since it becomes significantly softer (γ ~ -8.4±2.8) only to harden again during the time interval 6:55 UT-7:00 UT (γ~ -7.6±0.7). In the next 45 minutes the spectrum shape changes slightly while spectral index ranges between -6.6 and -7.6. The peak spectrum calculated from time profiles of the proton fluxes for different rigidities derived from our model is quite close to power law. Contrary to the 15 June 1991 event, the form of peak and emission spectra in case of January 2005 cannot be supposed as coincided. This event seems to be neither scatter-free nor diffusive totally and nevertheless we cannot affirm that peak spectrum is very representative of the injection spectrum shape also due to possible influence of the magnetic field. Consequently, the question on the type of particle propagation requires an additional study.

The mean integral SCR flux can 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. As it can be seen from Fig. 5 the peak time $t_{\max}$ turned out to be the same for all higher rigidity particles (1GV, 2GV and 3GV). A difference in the profiles for 1 and 2GV might be an argument for two episodes of the acceleration. The results displayed for energies greater than 100 MeV and 300 MeV, obtained by extrapolation, are in good agreement with the satellite observations. Moreover, we found that all three fluxes of lower energy particles 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 >100MeV) rendering our model reliable enough at least for the time period during the first 1.5 hours.

The shape of the angle distribution of the SCR flux is plotted in Fig. 6, as a function of latitude and longitude for the second time interval of the event and for a later one. As it is clearly seen, in the beginning of the event, the anisotropy in the direction of the particle arrival has a narrow beam-like form, centered ever 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. 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.

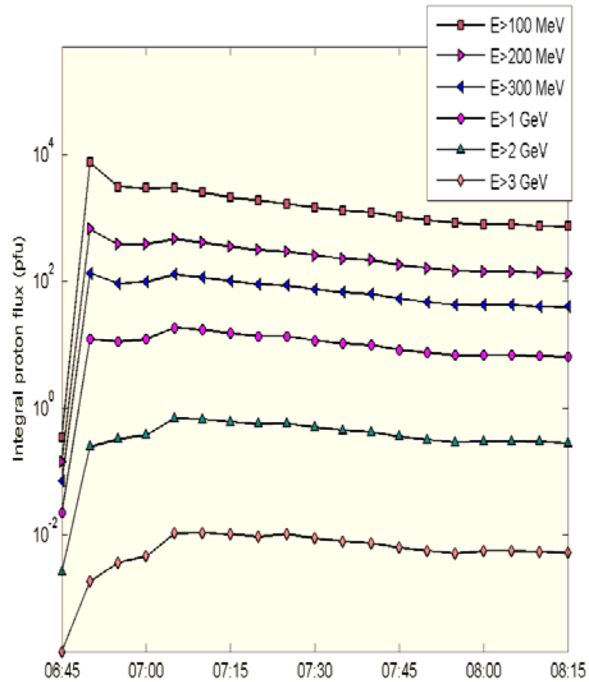

Fig. 5: Solar cosmic rays integral fluxes

Comparing our results from the application of a completely anisotropic GLE model described above with those obtained in case of a compound model (Belov et al., 2005c) we conclude the following:

1) Both models showed that during the initial phase of the event the anisotropy source was located in the south hemisphere resulting in extremely big enhancements registered in polar neutron monitor stations.

2) Both models showed that the initially narrow beam of solar particles arriving at the vicinity of the earth widened with time.

3) The SCR spectrum obtained here is generally softer than that in case of the compound model. We believe that this result is more realistic mainly because it is derived using data from 41 neutron monitors whereas in case of the compound model this number was much less.

V. CONCLUSION

Summarizing, one can say that the ground level enhancement of 20 January 2005 was the second biggest one (after that in 1956) in the history of ground level observations. Many neutron monitor stations widely distributed around the world covering a wide range of cut-off rigidities registered the GLE [11], [23], [24], [25]. The most characteristic feature of this ground level event seems to be a narrow beam of solar relativistic particles that reached the Earth during the first time-intervals of the GLE evolution. Only a few of the asymptotic cones of the neutron monitor stations did fall inside this narrow beam. The result was that these exact neutron monitor stations recorded big and sharp enhancements whereas the other recorded increases of one or two orders if magnitude less. As time evolved the beam widened and more and more monitors registered the event.

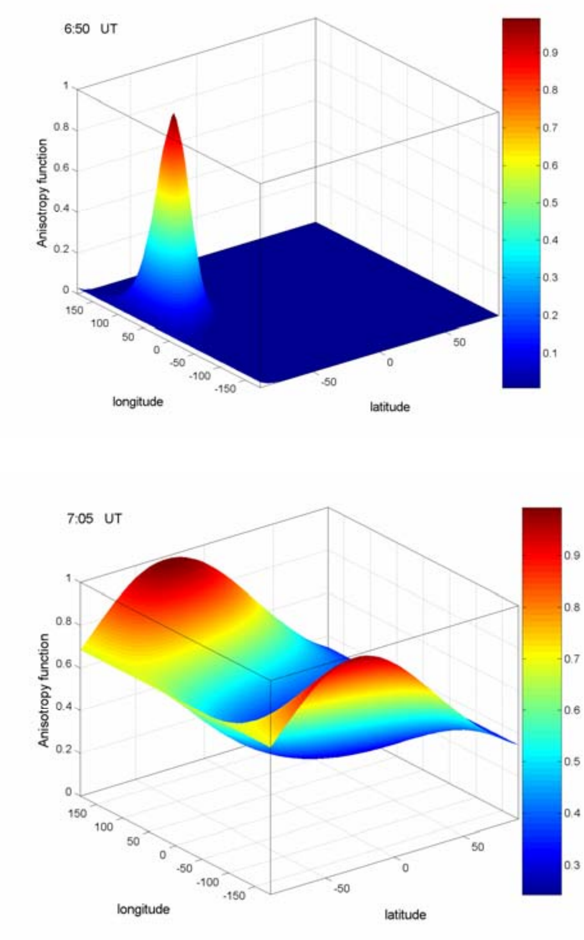

Fig. 5: Distribution of the anisotropy function $\Psi(\Omega, R)$ at two different moments of the GLE of 20 January 2005

The new NM-BANGLE model succeeds in producing satisfactory results on the anisotropy, flux and spectrum of solar cosmic rays. Especially, 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.

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