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Modeling the solar cosmic ray event of 13 December 2006 using ground level neutron monitor data

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Abstract

In order to understand the physics under extreme solar conditions such as those producing ground level enhancements of solar cosmic rays, it is important to use accurate and reliable models. The NM-BANGLE Model is a new cosmic ray model which couples primary solar cosmic rays at the top of the Earth's atmosphere with the secondary ones detected at ground level by neutron monitors during GLEs. This model calculates the evolution of several GLE parameters such as the solar cosmic ray spectrum, anisotropy and particle flux distribution, revealing crucial information on the energetic particle propagation and distribution. The total output of the NM-BANGLE Model is a multi-dimensional GLE picture that gives an important contribution to revealing the characteristics of solar energetic particle events recorded at ground level. In this work, the results of the NM-BANGLE Model application to the recent GLE of 13 December 2006 are presented and discussed. Moreover, a comparison with the extreme event of 20 January 2005 (GLE69) has been realized.

Keywords: Solar cosmic rays; Ground level enhancement; Neutron monitor; Solar energetic particles; Modeling

1. Introduction

Ground Level Enhancements (GLEs) characterize only the relativistic part of the entire solar cosmic ray spectrum corresponding to energies bigger than 500 MeV/nucleon. The historical beginning of solar cosmic rays (SCR) observations was set by the occurrence of the GLE on 28 February 1942 whereas the greatest ground level enhancement of solar cosmic rays ever recorded until January 2005 was observed on 23 February 1956 (Belov et al., 2005a and references therein). Since then hundreds of proton events and tens of GLEs were registered, but all of them rank below that one by one order of magnitude or more. On 20 January 2005, one of the largest ground level enhancements ever recorded, also known as GLE69, was registered at the neutron monitors of the worldwide network (Belov et al., 2005b; Plainaki et al., 2007). On 13 December 2006, another big GLE was recorded at the ground cosmic ray detectors (Plainaki et al., in press; Vashenyuk et al., 2007).

Several techniques for modeling the dynamical behavior of GLEs throughout their evolving are presently available (Humble et al., 1991; Shea and Smart, 1982; Duldig et al., 1993; Cramp et al., 1997; Belov et al., 2005a,b; Bieber et al., 2005; Plainaki et al., 2007). Realistic geomagnetic field models that take into account possible geomagnetic disturbances (Tsyganenko, 1987, 1989) enabling the accurate determination of viewing directions for ground level instruments, are usually incorporated. On the basis of the Coupling Coefficient Method (Dorman, 2004), a new improved and extended GLE-Model which couples primary solar cosmic rays at the top of the Earth's atmosphere with the secondary ones detected at ground level by neutron monitors (NMs) during GLEs, was recently proposed (Plainaki et al., 2007). The results of the applica-

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tion of the so called NM-BANGLE Model to GLE69 were analytically presented in Plainaki et al. (2007) whereas some preliminary analysis of GLE70, based on the same model, has been also presented (Plainaki et al., in press).

In this work an extensive and analytical study of the GLE of 13 December 2006 has been realized. Moreover the evolution of several important GLE parameters, during the period that GLE70 took place, calculated on the basis of the NM-BANGLE Model, is presented and discussed.

2. Observational analysis on GLE70

In December 2006, on the minimum of the 23rd cycle of solar activity, several events occurred on the Sun and the interplanetary space between the Sun and the Earth. On 7 December, a Forbush Decrease (FD) was registered at the neutron monitors of the worldwide network (Plainaki et al., in press). The big X3.4/4 B solar flare, originating from sunspot 930 at S06W26, was accompanied by a powerful proton event that produced a sharp growth of cosmic ray flux in the near-Earth space and at ground level. This flare was also associated with Type II (shock velocity 1534 km/s) and Type IV radio bursts as well as a fast full-halo CME (velocity ~1500 km/s) (http://sgd.ngdc.noaa.gov/sgd/jsp/solarindex.jsp).

Energetic solar cosmic rays on 13 December were guided towards the Earth by the interplanetary magnetic field and caused increase in the count rates of the ground based cosmic ray detectors. As a result, on 13 December, 2006 the worldwide network of NMs recorded the third biggest GLE of the 23rd cycle of solar activity, leaving behind only the enhancements of 15 April 2001 and 20 January 2005, classified as GLE70, starting at ~2:50 UT (Fig. 1). Anisotropy and cut-off rigidity effects in the intensities recorded by various NM stations can be seen in Fig. 1. The maximum cosmic ray variation on 5-min data (~92%) was recorded in Oulu NM at ~3:05 UT. The fact that the maximum enhancement was not registered at sub-polar stations as usual, but at lower latitudes (mid cut-off rigidity stations) leads to the conclusion that the source of anisotropy must have been located near the ecliptic plane. Mid and high latitude stations registered the GLE70 with different amplitudes, giving evidence of strong anisotropy, especially during the initial phase of the event. Nevertheless the north-south anisotropy was small.

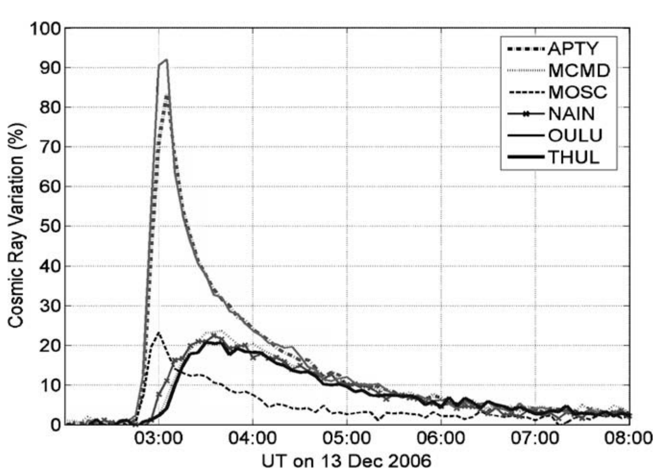

Fig. 1. GLE70 recorded by neutron monitors.

3. The NM-BANGLE Model

The NM-BANGLE Model (Plainaki et al., in press) couples primary solar cosmic rays at the top of the Earth's atmosphere with the secondary ones detected at ground level neutron monitors during GLEs. This model calculates the evolution of several GLE parameters such as the SCR spectrum, the anisotropy and the particle flux distribution. As an input the NM-BANGLE Model uses cosmic ray GLE data from NM stations widely distributed around the world, whereas the total output of the NM-BANGLE Model is a multi-dimensional GLE picture that gives an important contribution to understanding the physics of solar cosmic ray particles under extreme solar conditions.

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 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. According to the NM-BANGLE Model, possible time variation of the intensity of any the total neutron counting rate, observed at cut-off rigidity R_c, at level h in the atmosphere at some moment can be determined by (Dorman, 2004; Belov et al., 2005a,b; Plainaki et al., in press):

$$\frac{\Delta N(R_c,h,t,t_0)}{N_0(R_c,h,t_0)} = \frac{\int_{R_c}^{R_u} W(R,h,t_0)\,\frac{\Delta I(\Omega,R,t)}{D_0(R)}(t,R)\,\mathrm{d}R}{\int_{R_C}^{R_u} W(R,h,t_0)\,\mathrm{d}R} \tag{1}$$

where $W(R,h,t_0)$ is the rigidity dependent coupling function between secondary and primary cosmic rays arriving at the top of the atmosphere (Dorman, 2004), $\Delta I(\Omega,R,t)$ is the differential rigidity spectrum of solar cosmic rays at the top of the atmosphere and $D_0(R)$ 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. The anisotropic differential rigidity spectrum $\Delta I(\Omega,R,t)$ is 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:

$$\Delta I(\Omega,R,t) = \Delta D(R,t)\cdot\Psi(\Omega,R,t) \tag{2}$$

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:

$$\Psi(\Omega, R, t) = \exp\left(-n_a^2 \sin^2 \frac{\Omega}{2}\right) \tag{3}$$

where index n_a characterizes the width of the solar particle beam: big values of n_a correspond to narrow solar particle fluxes. Anisotropy function $\Psi(\Omega, R, t)$ represents the distribution of the arriving anisotropic 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.

4. Application of the NM-BANGLE Model – Results

Five-minute GLE data from 37 NM stations (Fig. 2), widely distributed around the Earth, were incorporated to fit the main Eq. (1), applying the Levenberg–Marquardt non-linear optimization algorithm. For the evaluation of the asymptotic directions and the cut-off rigidities for each NM location the NM-BANGLE Model uses the Tsyganenko89 model (Tsyganenko, 1989).

The beginning of the event was 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 NMs. The application of the NM-BANGLE Model on GLE70 provided us with special quantitative information on the GLE particle spectrum evolution, solar cosmic ray fluxes and anisotropy. The interpretation of our results regards the following areas:

4.1. Rigidity spectrum – solar cosmic ray fluxes

In the beginning phase of the event (~2:45–2:55 UT) the solar cosmic ray rigidity spectrum outside the atmosphere appears hard enough, with a spectral index varying between 0 and −1.9, whereas in the next 5-min time interval it softens significantly ($\gamma = -4.3$). This fact implies that on 13 December 2006 the contribution of high energy particles took place in the early phase of the event. However it should be stated that the spectral index has in general a limited range of applicability. Almost all GLE spectra have a variable slope with rigidity and this variation changes with time. Especially at the initial onset, exists a severe limit on the range of applicability of a specific spectral slope. This is evident in Fig. 3 where the uncertainty in the spectral index is quite large until 03:15 UT when it stabilizes. Therefore the range of applicability of the derived spectral slope is rather placed at the time period after 03:15.

The behavior of the mean integral fluxes of the lower energy solar cosmic ray particles on 13 December 2006, on the basis of the NM-BANGLE Model is presented in Fig. 3. The results displayed for energies greater than 100 MeV and 300 MeV are of course obtained by extrapolation, assuming that the spectral index is independent on energy. It is clearly seen that during the first time intervals, while the anisotropy is big, the mean integral flux is also very big. One should note however that during the first half hour of the event the values of parameters are changing rather rapidly and the corresponding errors are big. The mean integral flux F_{mean} (>100 MeV) is in good agreement with the satellite observations (http://www.sel.noaa.gov/today.html). The estimated flux for particles with energy >100 MeV takes similar values to those obtained in the case of GLE69, exceeding only by a factor of ~2 the fluxes

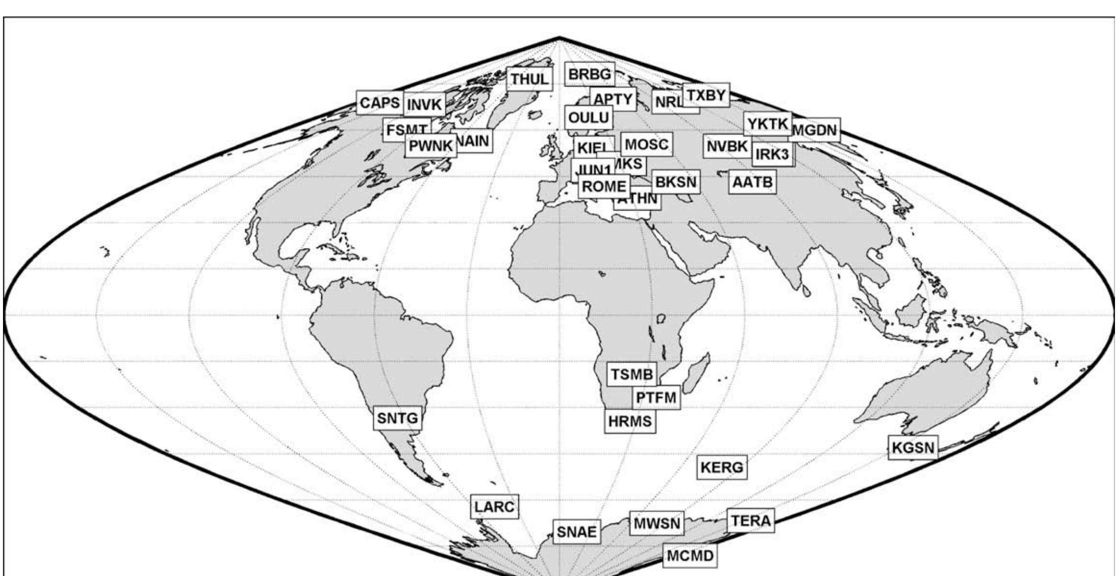

Fig. 2. NM stations of the worldwide network.

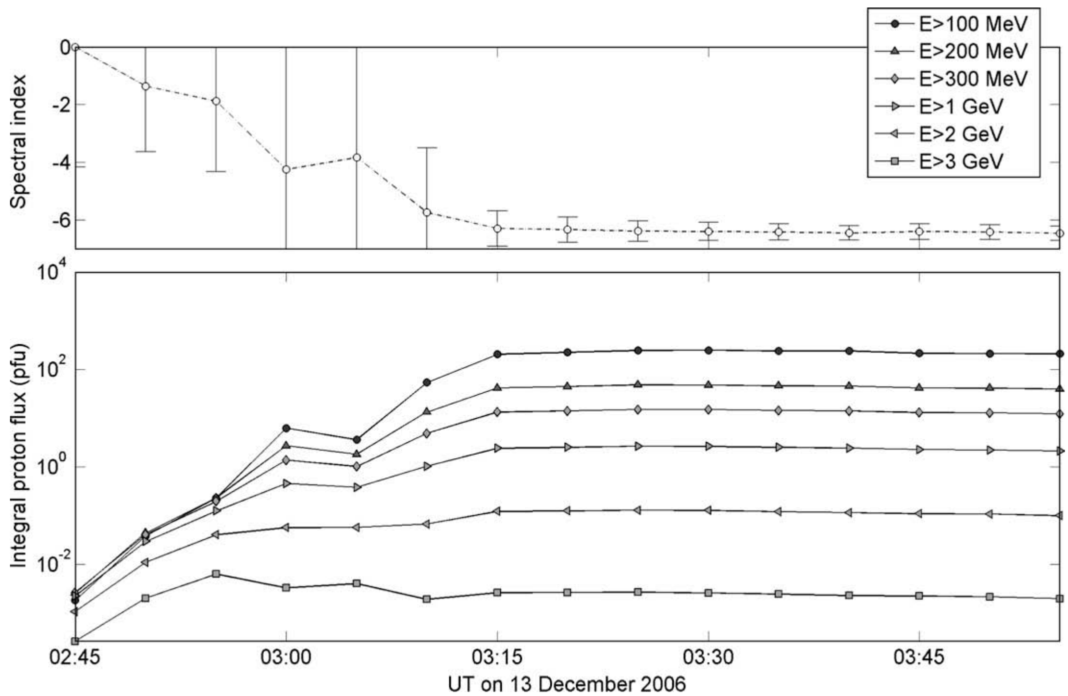

Fig. 3. SCR integral proton fluxes together with spectral index evolution, on 13 December 2006.

recorded on 29 September 1989 (~600 pfu) and on 14 July 2000.

Moreover, we found that all three fluxes of particles of lower energy, remain at a high level during the first hour of the event. This result derived from the application of our model to the GLE on 13 December 2006 is also verified by the satellite observations of particles in the lower energy range (>50 MeV and >100 MeV). The main part of SCR fluxes of different energies reached maximum at about 3:15 UT. After that moment the SCR flux slowly decreased keeping a soft spectrum with an index varying between −6.4 and −6.0. According to the results of the application of the NM-BANGLE Model the behavior of the most energetic particles (>3 GeV) differs from that corresponding to particles of less energy, reaching the point of maximum flux significantly earlier (at ~3:00 UT). Probably, it is not worth to give more emphasis to peculiarities of the profiles for the time period 3:00–3:10 UT, due to the fact that they are more or less related to statistical errors since the form of the rigidity spectrum was defined with the less accuracy at that period.

4.2. Anisotropy

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. 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 longitudes (Belov et al., 2005a; Plainaki et al., 2007, in press). The time dependent variation of the position of the anisotropy source near Earth, in GSE coordinates, is demonstrated in Fig. 4. It is clearly seen that the source of solar particles was mostly located close to the ecliptic plane. This result is indeed obtained in Vashenyuk et al. (2007). In Fig. 4 the mean latitude values are about −50 degrees. According to Fig. 4, during the first half hour the errors of the parameter definition are large and therefore the model does not fit well at that time. This may be due to two main reasons: (a) at the very first moments the increases at cosmic ray intensities were not big yet or (b) the physical model is not sufficiently adequate for the beginning phase of the event. In other words, it is possible that the form and the angular dependence of the anisotropy and the shape of the energy spectrum differ sufficiently from the real ones. Starting approximately at 3:15 UT the model works much better and the parameter variations become sufficiently small. The source of anisotropy is initially located westwards (longitude = −50°), close to the ecliptic plane, whereas it moved eastwards with time (longitude = ~0° after 3:00 UT). It is worth noticing that, according to the ACE spacecraft data taken from OMNIWEB, the IMF vector during these hours has a location in the right sector (longitudes −26° and −14° during the 3rd and 4th hours) and it is located close to the ecliptic plane (latitudes −10° and −4°).

According to Fig. 4, the anisotropy source moved southwards with time. The longitude parameter as extracted from our model does not vary significantly after the time of maximum of the event, leading to the possible conclusion that after 3:00–3:10 UT the anisotropy decreased significantly. Moreover, the shape of the anisotropy function (Eq. (3)) in

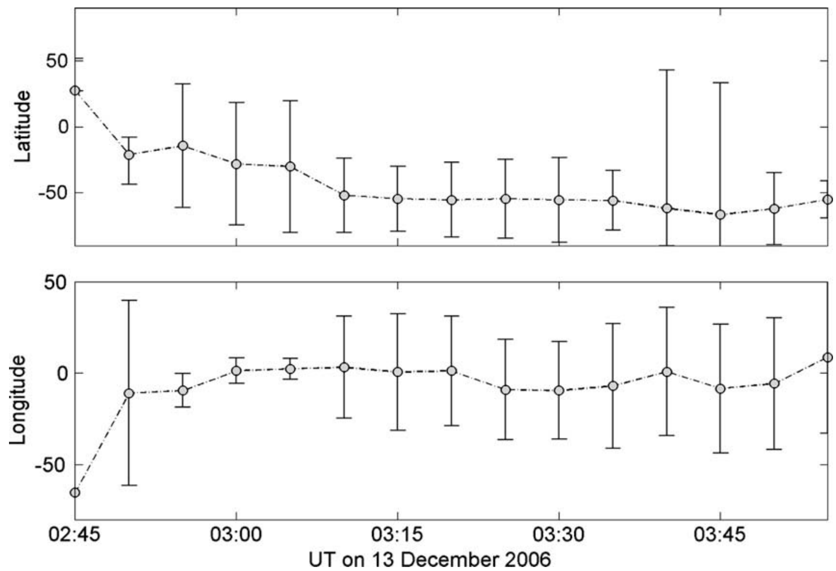

Fig. 4. Location of the anisotropy source in GSE coordinates.

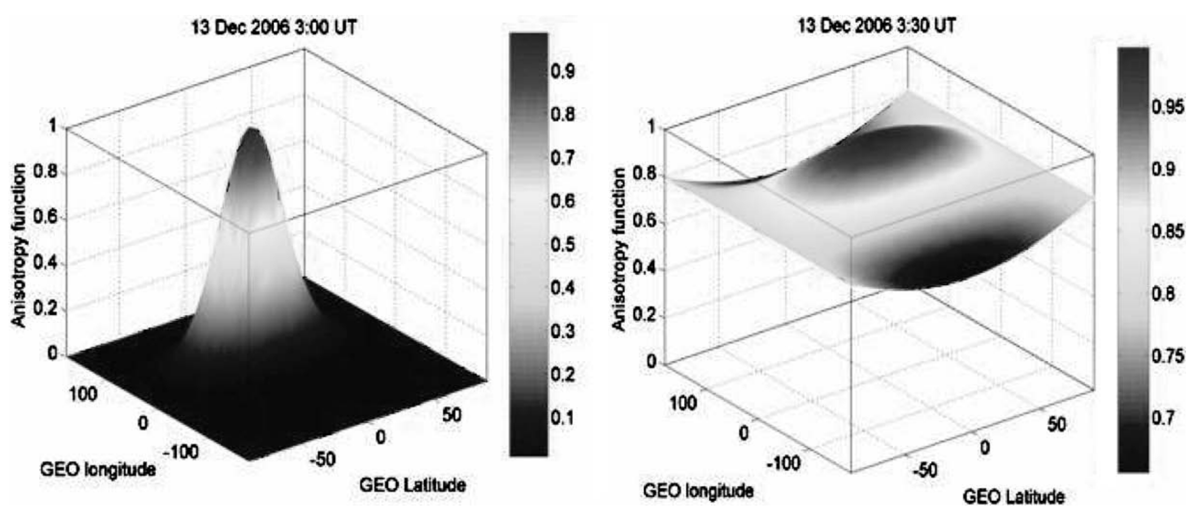

Fig. 5. Anisotropy function versus geographical latitude and geographical longitude of the anisotropy source, according to the NM-BANGLE Model. Left panel corresponds to 13 December 2006 at 3:00 UT, whereas the right panel at 3:30 UT.

Fig. 5 suggests a narrow angular distribution during the initial period of the event. Unfortunately, the errors at the beginning are large and therefore the respective peculiarities extracted by the NM-BANGLE Model are not much reliable. As a result the concept of the narrow beam particle distribution continues to comprise a subject of continuous analysis. However, if these peculiarities really exist one can be drawn to the conclusion that there is evidence of either a long lasting particle acceleration on the Sun, with variable efficiency, or changing in particle propagation conditions in the Sun–Earth interplanetary space. Later the beam widened suggesting a wider particle distribution.

5. GLE69 and GLE70 comparison – discussion

Comparing the above results with those calculated after applying the same NM-BANGLE Model to GLE69 the following conclusions emerge:

(a) In both cases solar particles seem to have started propagating forming a narrow beam, sensed initially by those NMs owning the most favorable positions. A more wide angular distribution occurred with time, in both cases.
(b) The narrow beam effect, however, was more intense in case of GLE69 than in case of GLE70 (the angular parameter took bigger values in the former case).
(c) In both cases the SCR spectrum appears hard in the beginning but it softens during later phases. However the unusual behavior of the spectral index revealed for GLE69 (Plainaki et al., 2007) was not noticed in GLE70.
(d) Integral proton fluxes for low energy particles calculated on the basis of the NM-BANGLE Model lead to reliable results, testified by the satellite data, in both cases.

As a conclusion, one can say that the application of the NM-BANGLE Model to GLE70 gave satisfactory results concerning the evolution of several important GLE parameters such as the integral solar proton fluxes as well as the position of the anisotropy source, especially in the time period after 3:10 UT. Future improvements of the model regarding the form of the anisotropy and/or the spectrum, as well as model application to more GLEs, may give results that will enrich our current knowledge on solar extreme events.

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