Modeling of the GLE70 event

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Abstract—**Solar cosmic ray models contribute to the understanding of physics taking place under extreme solar conditions. 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 Ground Level Enhancements (GLEs). The evolution of several GLE parameters such as the solar cosmic ray spectrum and anisotropy as well as the particle flux distribution, are calculated. As a results, crucial information on the energetic particle propagation and distribution is revealed. The total output of the NM-BANGLE model is a multi-dimensional GLE picture of the characteristics of solar energetic particle events being 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) is realized.**

Key Words— Solar cosmic rays, ground level enhancement, neutron monitor, solar energetic particles, modeling

I. 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 ([1] and references therein). 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. On 20 January 2005, one of the largest ground level enhancements ever recorded, also known as GLE69, was registered in the neutron monitors of the worldwide network ([2], [3]). Recently, on 13 December 2006, another big GLE was recorded by the ground cosmic ray detectors ([4], [5]).

Several techniques for modeling the dynamical behavior of GLEs throughout their evolving are presently available ([1], [2], [3], [6], [7], [8], [9], [10]). Realistic geomagnetic field models which take into account possible geomagnetic disturbances ([11], [12]) enabling the accurate determination of viewing directions for ground level instruments, are usually incorporated. On the basis of the Coupling Coefficient Method ([13]), 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 ([3]). The results of the application of the so called NM-BANGLE Model to GLE69 were analytically presented in Plainaki et al. (2007a) whereas some preliminary analysis of GLE70, based on the same model, has been also presented ([4]).

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.

II. OBSERVATIONAL ANALYSIS ON GLE70

In December 2006, on the minimum of the 23rd cycle of solar activity, several events occurred on the Sun as well as in 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 ([4]). 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/sec) and Type IV radio bursts as well as a fast full-halo CME with velocity ~ 1500 km/sec (http://sgd.ngdc.noaa.gov/sgd/jsp/solarindex.jsp).

Energetic solar cosmic rays on 13 December were guided toward 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 cutoff rigidity effects in the intensities recorded by various NM stations can be clearly seen. 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.

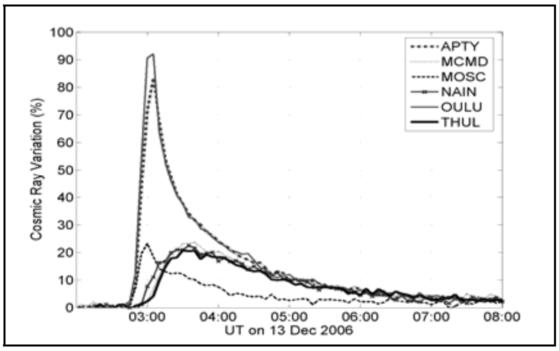

Fig. 1. GLE70 recorded by neutron monitors

III. APPLICATION OF THE NM-BANGLE MODEL – RESULTS

The NM-BANGLE Model, based on the Coupling Coefficient Method ([13]) calculates the evolution of several GLE parameters such as the SCR spectrum and anisotropy as well as the particle flux distribution, revealing crucial information on the SCR particle propagation and distribution ([3], [4]). As an input the NM-BANGLE model uses cosmic ray GLE data from NM stations widely distributed around the world. A detailed presentation of the model can be found in Plainaki et al. 2007a; b.

Five-minute GLE data from 37 NM stations, widely distributed around the Earth, were incorporated to apply the NM-BANGLE Model on the event of 13 December 2006. For the evaluation of the asymptotic directions and the cut-off rigidities for each NM location the Tsyganenko89 model has been used ([12]). 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:

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 (γ = -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. 2. 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 recorded on 29 September 1989 (~600 pfu) and on 14 July 2000.

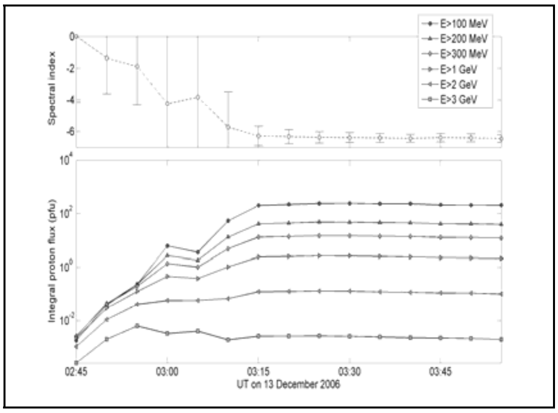

Fig. 2. SCR integral proton fluxes times together with spectral index evolution, on 13 December 2006.

Moreover, we found that all three fluxes of lower energy particles, 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 >100MeV). 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.

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 ([1], [3], [4]). The time dependent variation of the position of the anisotropy source near Earth, in GSE coordinates, is demonstrated in Fig. 3. It is clearly seen that the source of solar particles was mostly located close to the ecliptic plane. This result is indeed obtained in [5]. In Fig. 3 the mean latitude values are about -50 degrees. According to Fig. 3, 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 from 3:15 UT the model works much better and the parameter variations become sufficiently small. The source of anisotropy is initially located westwards (longitude=-50^0), close to the ecliptic plane, whereas it moved eastwards with time (longitude=~0^0 after 3:00 UT). It's 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 3-rd and 4-th hours) and it is located close to the ecliptic plane (latitudes -10°and -4°).

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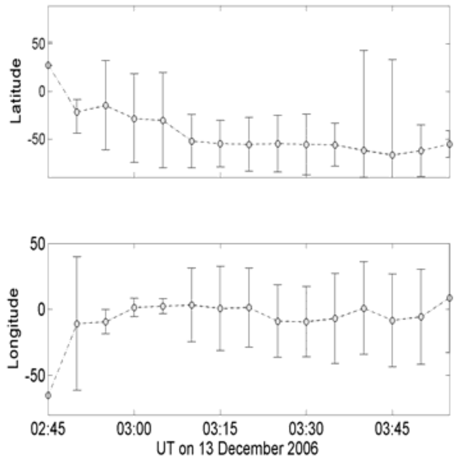

Fig. 3. Location of the anisotropy source in GSE coordinates.

According to the NM-BANGLE Model, 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 angular distribution is narrow during the initial period of the event (Fig. 4). 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.

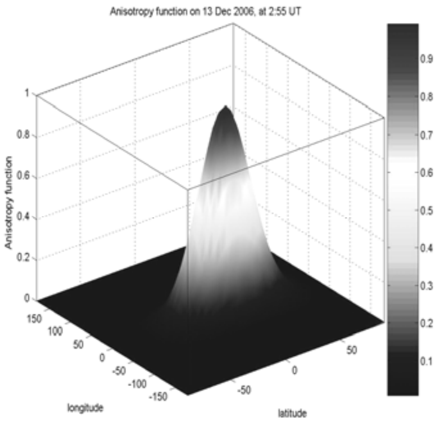

Fig. 4. Anisotropy function versus geographical latitude and geographical longitude of the anisotropy source, according to the NM-BANGLE model, on 13 December 2006 - 2:55 UT.

IV. 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 ([3]) 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.

ACKNOWLEDGMENT

Thanks are due to all our colleagues from the neutron monitor stations, who kindly provided us with the data used in this analysis: Alma Ata, Apatity, Athens, Baksan, Barentsburg, Cape Schmidt, Fort Smith, Hermanus, Inuvik, Irkutsk-1, 2,3, Jungfraujoch, Jungfraujoch-1, Kerguelen, Kingston, Kiel, Larc, Lomnicky Stit, Magadan, Mawson, McMurdo, Moscow, Nain, Norilsk, Novosibirsk, Oulu, Potchefstroom, Peawanuck, Rome, Sanae, San Tiago, Terre Adelie , Thule, Tsumeb, Tixie Bay and Yakutsk.

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