A new version of the Neutron Monitor Based Anisotropic GLE Model : Application to GLE60

C. Plainaki[(1),(2)], H. Mavromichalaki[(2)], A. Belov[(3)], E. Eroshenko[(3)], M. Andriopoulou[(2)], V. Yanke[(3)]

(1) INAF-IFSI, Via del Fosso del Cavaliere 100, 00133, Roma, Italy Christina.Plainaki@ifsi-roma.inaf.it

(2) Nuclear and Particle Physics Section, Physics Department, Athens University Pan/polis-Zografos 15771 Athens, Greece

(3) Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation (IZMIRAN), 42092, Troitsk, Moscow Region, Russia (abelov@izmiran.rssi.ru)

Abstract

In this work we present a cosmic ray model that 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 Neutron Monitor Based Anisotropic GLE Pure Power Law (NMBANGLE PPOLA) Model constitutes a new version of the already existing NMBANGLE Model, differing in the solar cosmic ray spectrum assumed. The total output of the model is a multi-dimensional GLE picture that reveals part of the characteristics of the big solar proton events recorded at ground level. We apply both versions of the model to the GLE of 15 April 2001 (GLE60) and compare the results.

Keywords: Earth, Plasmas, Methods: data analysis.

1. Introduction

The Sun occasionally emits particles of sufficiently high energies to cause increase of the intensity of the secondary cosmic rays recorded at ground level by Neutron Monitors (NMs). These events, known as Ground Level Enhancements (GLEs) of Solar Cosmic Rays (SCRs), characterize only the relativistic part of the entire SCR spectrum, corresponding to energies bigger than ∼500 MeV/nucleon. The GLEs constitute the relativistic extension of the solar energetic particle (SEP) events. The historical beginning of SCR observations was set by the occurrence of the GLE on 28 February 1942 whereas the greatest GLE ever recorded, 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 15 April 2001, one of the largest GLEs of the 23rd cycle of solar activity took place, whereas on 20 January 2005, the second largest GLE ever recorded, also known as GLE69, was registered at the NMs of the worldwide network (Belov et al., 2005b; Plainaki et al., 2007a).

The GLE can be defined as a cosmic ray phenomenon in association with either the X-class solar flares or the fast (> 1000 km/s) Coronal Mass Ejections (CMEs) (Bombardieri et al., 2007). However, observations and solar physics models, up to now, have not provided a clear and uniformly accepted key signature of relativistic proton acceleration at the Sun. Relativistic protons can be accelerated either by processes involving magnetic reconnection (Cane et al., 2006) giving rise to GLEs, or at coronal or CME-driven shocks (Reames, 1999). Moreover, recent studies based on the observational data from a suite of spacecraft and ground-based instruments, show that there is a strong possibility that flares and CMEs are manifestations of the same eruptive process (Lin et al., 2005). This suggests that proton acceleration can occur from multiple sources during a major solar eruption, for example at coronal or CME-driven shocks and coronal sites associated with magnetic reconnection (e.g., solar flares and current sheets), as well as on the neutral current sheets, directly by DC electric fields (Bombardieri et al., 2007). The directions of the SEPs arriving at the vicinity of the Earth are affected by their scattering by the turbulent magnetic field in the interplanetary space and by the reflection at large-scale magnetic structures (Meyer, et al., 1956; Dröge, 2000; Bieber et al., 2002; Sáiz et al., 2008). Thus, comparing signatures of accelerated solar particles at the Sun with the measurements of the relativistic particles at the Earth is a not trivial task; it often requires the use of accurate and reliable models of the arrival of relativistic particles at 1 AU. 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., 1994, Cramp et al. 1997; Belov et al., 2005a;b; Bieber et al., 2005; Bombardieri et al., 2007, 2008; Plainaki et al., 2007, 2009a; Masson et al., 2009). 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), the NMBANGLE Model, which couples primary solar cosmic rays at the top of the Earth's atmosphere with the secondary ones detected at ground level by NMs during GLEs, was recently proposed (Plainaki et al., 2007). The results of its application to the GLE69 and GLE70 were analytically presented in Plainaki et al. (2007) and Plainaki et al. (2009a) respectively. Moreover, a first attempt to create a real-time application of this model, using as an input the NM data of the European Neutron Monitor Database Network (NMDB), was recently realized. In this work we present a new version of the above mentioned model: the NMBANGLE Pure Power Law (PPOLA) Model which, using a slightly different solar cosmic ray spectrum, calculates the evolution of several GLE parameters such as the SCR spectrum, the anisotropy and the SCR particle flux distribution Although this model constitutes only a version of the already existing NMBANGLE Model,for reasons of simplicity, from now on inside this text, we shall refer to it as 'NMBANGLE PPOLA Model'. Application of both model versions to the GLE of 15 April 2001 (GLE60) reveals the characteristics of the SEP event, testing also the reliability and goodness of each GLE-model version. Furthermore, we compare the model outputs and discuss the criteria that define the conditions under which each model version leads to reliable results.

2. The NMBANGLE PPOLA Model

The NMBANGLE PPOLA version of the NMBANGLE Model couples primary solar cosmic rays at the top of the Earth's atmosphere with the secondary ones detected at ground level NMs during GLEs. This model calculates dynamically the SCR spectrum, the SCR anisotropy and the SEP flux distribution, outside the Atmosphere, during a GLE. As an input the model uses cosmic ray GLE-data from NM stations widely distributed around the world, whereas its total output is a multi-dimensional GLE picture that attempts to describe solar particles' behaviour under extreme solar conditions.

The NMBANGLE PPOLA Model assumes a slightly different expression of the SCR rigidity spectrum in respect to tha assumed in the NMBABGLE Model; whereas the NMBANGLE Model uses a quasi-power law dependence on rigidity, the NMBANGLE PPOLA Model uses a pure power law. Below, this main difference of the two models is described in detail.

According to the NMBANGLE Model, possible time variations of the total neutron counting rate, observed at cut-off rigidity R_c , at level h in the atmosphere at some moment t, are determined by the following expression (Dorman, 2004; Belov et al., 2005a; b; Plainaki et al., 2007):

$$\Delta N(R_c, h, t, t_0)/N_0(R_c, h, t_0) = \int_{R_c}^{R_u} W(R, h, t_0)\, A(R, \Omega, t)\, b(t)\, R^{\gamma(t)}\, dR \qquad (1)$$

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, $\gamma(t)$ is the exponent of the quasi-power law SCR spectrum, $A(R,\Omega,t)$ is the anisotropy function with Ω being the solid angle of asymptotic directions as defined in Plainaki et al. (2007), R_u is the upper limit for the rigidity of the primary SCR particles, considered as 8 GV in this study. Parameter $b(t)$, inside Eq. (1), is considered rigidity-independent and defined as follows :

$$b(t) = b_1(R, t)/I_0(R, t_0) \qquad (2)$$

with $b_1(R,t)$ being the rigidity-dependent amplitude of the primary SCR rigidity spectrum and $I_0(R,t_0)$ the Galactic Cosmic Ray (GCR) primary flux. Therefore, in the NMBANGLE Model, the SCR rigidity spectrum has a quasi-power law form since the primary SCR flux amplitude depends also on rigidity.

On the other hand, in the NMBANGLE PPOLA version of the model, we assumed a pure power law SCR spectrum of the form $b_1(t)\cdot R^{\gamma}$, where $b_1(t)$ is rigidity-independent. Therefore, the basic equation of the NMBANGLE PPOLA Model becomes:

$$\Delta N(R_c, h, t, t_0)/N_0(R_c, h, t_0) = \int_{R_c}^{R_u} \frac{W(R, h, t_0) A(R, \Omega, t) b_1(t) R^{\gamma(t)}}{I_0(R, t_0)} dR \qquad (3)$$

where $b_1(t)$ is the amplitude of the SCR rigidity spectrum.

As an input the NMBANGLE PPOLA Model uses cosmic ray GLE data from NM stations widely distributed around the world, whereas its total output is a multi-dimensional GLE picture. For the evaluation of the asymptotic directions and the cut-off rigidities for each NM location, the Tsyganenko89 model (Tsyganenko, 1989) is considered. The model's scope is to reproduce the observed SCR increases and to define the time-evolution of several GLE parameters (i.e. spectral index, SCR flux outside the atmosphere, etc.). A least-squares fitting technique based on the Levenberg Marquardt algorithm allows the efficient derivation of the optimal solution for each of the time intervals considered and consequently the definition of the respective GLE parameters values.

3. Model application to GLE60 - Results

On 15 April 2001 a strong flare (X14.4/2B) was observed at the west limb of the solar surface at the position S20W85. This flare, associated with a fast CME (>1200 km/s) has been the largest of a series of solar eruptions that occurred inside a period of extreme solar activity, beginning at 28 March, and ending at 21 April, 2001. According to the observation of the GOES satellite, the flare started at 13:19 UT and reached maximum at 13:50 UT. The gamma-ray spectrometer (GRS) on-board Yohkoh satellite started detecting gamma-rays (in the 4-7 MeV range) at 13:45 UT (Muraki et al., 2008). The soft and the hard X-ray telescopes on-board Yohkoh satellite could also observe the flare from the initial stage at 13:22 UT through the maximum until 13:56 UT. The X-rays increased abruptly from M4 to X10 within 3 min between 13:45 and 13:48 UT (Muraki et al., 2008). CME onset was estimated to be at about 13:32 UT, on the basis of height-time measurements extrapolated back to the solar surface (Gopalswamy et al., 2003). Following the detection of gamma and X-rays, the High Energy Proton and Alpha Detector on board GOES 10 satellite recorded sudden increases in relativistic protons (510-700 MeV) between 13:50 UT and 13:55 UT

(Bombardieri et al., 2007).

High energy protons and possibly neutrons, associated with the above mentioned solar events, were detected by the ground-level NMs of the worldwide network, starting at about 13:50 UT in 5-min NM data. The SCR intensity-time profiles registered at NMs of different cut-off rigidities are presented in Fig. 1, where the pre-increase baseline period used for deriving the % GLE60 data, was set as 15 April, 12:00 UT-12:55 UT. The event was seen by polar and mid-latitude NMs, whereas some low-latitude NMs (i.e. high *Rc*) registered it also; the Potchefstroom NM (*Rc*∼7.30 GV) recorded a peak at 13:50 UT whereas the Athens NM (*Rc*~8.53 GV) did not register any significant increase. This implies that solar protons with rigidity at least 7.3 GV must have been present at 1 AU, during the event of 15 April 2001, if the GLE was due to solar protons. The largest ground level response (about 225.4%) was observed at the South Pole NM, partially because of its unique location at high-latitude and high-altitude.

In general a GLE can be due to solar protons and/or solar neutrons. For the event of 15 April 2001, different scenarios have been proposed leading to diverse studies. Vashenyuk et al. (2003), have assumed that the GLE60 was due to solar protons and on the basis of this consideration they modeled the SCR energy spectra as well as pitch-angle distributions at different times of the event. Bombarideri et al. (2007) have also assumed that the GLE60 was due to high energy solar protons and modeled the ground-level response with a technique that deduces their spectrum, arrival direction and anisotropy. On the other hand Muraki et al. (2008) based on the 'non traditional' form of the CR intensity time-profile registered at the NM of Chacaltaya, assumed that the GLE60 was due to solar neutrons. In this study we assume that the GLE60 is mainly due to solar protons.

Five-minute GLE data from 28 NM stations (see Table-1), widely distributed around the Earth, were incorporated to fit the Equations *(1)* and *(3)*, applying the Levenberg-Marquardt non-linear optimization algorithm. These data were modeled every 5 minutes between 13:45 UT and 14:55 UT. Each indicated time represents the start of a 5 minute integrated time interval. For the evaluation of the NM asymptotic directions of viewing, in both model versions we used the Tsyganenko89 model (Tsyganenko, 1989) applying the method described in Plainaki et al. (2009b). The k_p index of geomagnetic activity, for the time period examined in this study (13:45 UT – 14:55 UT) was equal to 4. The NM vertical asymptotic directions of viewing, on 15 April 2001 at 14:00 UT, are presented in Fig. 2. We note that the asymptotic directions of viewing of the Fortsmith (FSMT) NM Station (*Rc*~0.30 GV, effectively ~ 1 GV because of the atmospheric cut-off, *altitude* ~ sea level) are near the nominal Parker spiral (GSE longitude at -45^0). As a result the FSMT NM registers a bigger enhancement than that recorded by the Apatity (APTY) polar NM (*Rc*~0.65 GV, effectively ~ 1 GV because of the atmospheric cut-off, *altitude* ~ 177 m). This difference in the SCR intensity-time profiles between these NMs is demonstrated in Fig. 3.

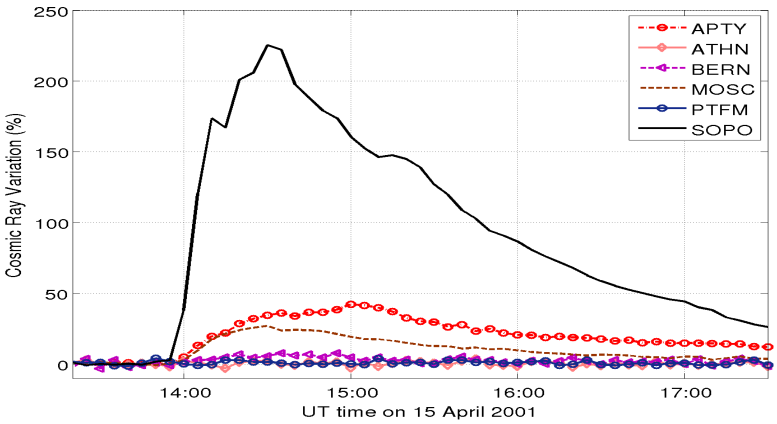

Fig. 1: SCR intensity-time profiles at 15 April 2001, as recorded at Apatity (APTY, *Rc*~0.57GV), Athens (ATHN, *Rc*~8.53GV), Bern (BERN, *Rc*~4.49GV), Moscow (MOSC, *Rc*~2.43GV), Potchefstroom (PTFM, *Rc*~7.30GV), South Pole (SOPO, *Rc*~0.11GV) NMs.

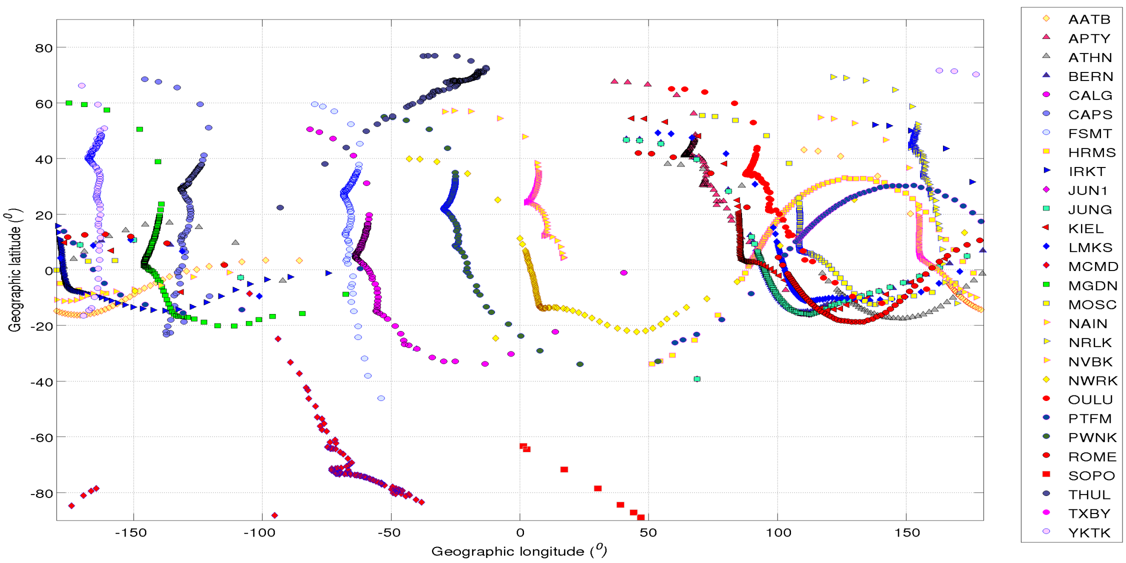

Fig.2: NM vertical asymptotic directions of viewing, on 15 April 2001, at 14:00 UT. Geomagnetic conditions were slightly disturbed (k_p=4). The calculation step in rigidity scale was taken as 0.1 GV. Stations abbreviations are: AATB (Alma Ata B), APTY (Apatity), Athens, (ATHN), Bern (BERN), Calgary (CALG),

Cape Schmidt (CAPS), Fort Smith (FSMT), Hermanus (HRMS), Irkutsk (IRKT), Jungfraujoch (JUNG), Jungfraujoch-1 (JUN-1), Kiel (KIEL), Lomnický Štit (LMKS), Magadan (MGDN), McMurdo (MCMD), Moscow (MOSC), Nain (NAIN), Newark (NWRK), Norilsk (NRLK), Novosibirsk (NVBK), Oulu (OULU), Potchefstroom (PTFM), Peawanuck (PWNK), Rome (ROME), South Pole (SOPO),Thule (THUL), Tixie Bay (TXBY) and Yakutsk (YKTK).

TABLE I

Characteristics of the NMs ised in this analysis

(Data derived from the NMDB Database , http://cosmicrays.oulu.fi/nmdbinfo/)

Station	**Latitude (deg)**	**Longitude (deg)**	***Rc* (GV)**	**Altitude (m)**
Alma Ata	43.25	76.92	6.69	3340
Apatity	67.55	33.33	0.65	177
Athens	37.97	23.72	8.53	40
Bern	46.95	7.98	4.49	570
Calgary	51.08	-114.13	1.08	1128
Cape Schmidt	68.92	-179.47	0.45	0
Fort Smith	60.02	-112	0.3	0
Hermanus	-34.42	19.22	4.9	26
Irkutsk	52.47	104.02	3.66	433
Jungfraujoch	46.55	7.98	4.48	3550
Jungfraujoch-1	46.55	7.98	4.48	3550
Kiel	54.33	10.11	2.29	54
Lomnický Štit	49.2	20.22	4	2634
McMurdo	-77.85	166.72	0.01	48
Magadan	60.12	151.02	2.1	0
Moscow	55.47	37.32	2.46	200
Nain	56.55	-61.68	0.4	0
Norilsk	69.26	88.05	0.63	0
Novosibirsk	54.8	83	2.91	163
Newark	39.68	-75.75	1.97	50
Oulu	65.02	25.5	0.81	15
Peawanuck	54.98	-85.44	0.5	0
Potchefstroom	-26.68	27.1	7.3	1351

Rome	41.86	12.47	6.32	60
South Pole	-90	0	0.1	2820
Thule	76.5	-68.7	0.1	260
Tixie Bay	71.6	128.9	0.53	0
Yakutsk	62.02	129.73	1.7	105

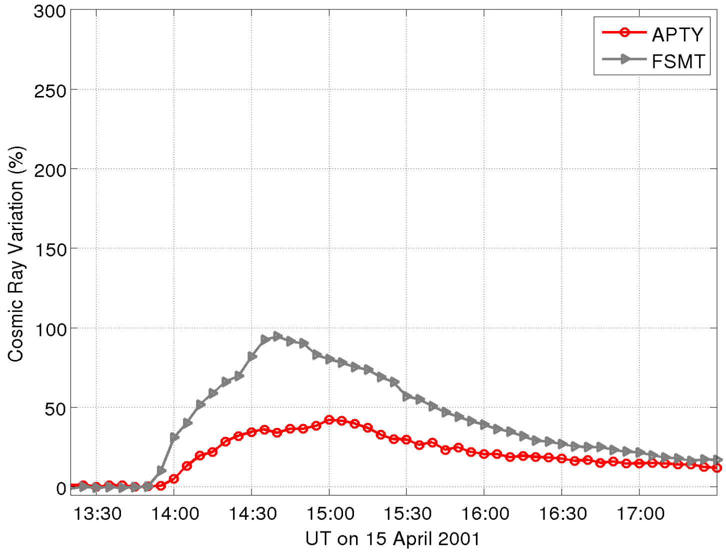

Fig.3: SCR intensity-time profiles at 15 April 2001, as recorded at Apatity (APTY, *Rc*~0.57GV, *alt~177m*) and Fortsmith (FSMT, *Rc*~0.30 GV, *altitude* ~ sea level).

NMBANGLE Model Results

The correlation coefficient *C* characterizing the goodness of the NMBANGLE Model fit determines the time-period that the application of the actual model is most reliable. Therefore, for the case of GLE60, the NMBANGLE Model results are most reliable from 14:00 UT (of 15 April 2001) and afterwards, since *C* takes values between 80 % and 85% at that period, whereas during the inital moments *C* becomes smaller than 35%. On the basis of this fact, below we shall present and discuss the model outputs corresponding to the time-period after 14:00 UT..

At 14:00 UT the spectral index takes is -6.8±0.3, whereas later reamins more or less constant exhibiting, however, a small peak at 14:50 UT equal to -6.7±0.2. These result demonstrate a soft SCR spectrum for the time period after 14:00 UT. The behavior of the mean integral fluxes of the SCR particles reaching the upper atmosphere, on 15 April 2001 is presented in Fig. 4. The results displayed for E> 100 MeV, E> 200 MeV and E> 300 MeV, are of course obtained by extrapolation, assuming that the spectral index is independent on energy. The flux of particles of energy >100 MeV has a maximum of about 2700 pfu, at 14:00 UT. The location of the apparent source of solar particles direction, a quantity that in general it is difficult to determine, is a dynamical output of the NMBANGLE Model. In this model it is assumed that the relativistic particles arrive in the vicinity of the Earth forming a beam, the width of which differs among different events (Plainaki et al., 2007a). 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; 2009). The time dependent variation of the position of the maximum anisotropy source near Earth, in GSE coordinates, is demonstrated in Fig. 5. At the time period 14:00 UT-14:55 UT, when the model becomes more reliable, the apparent SCR source direction was mostly located close to the ecliptic plane; its GSE latitude varied between $21.4^0 \pm 51.3^0$ and $34.3^0 \pm 38.3^0$. In the same time-period the GSE longitude of the source does not vary significantly; after 14:10 stabilizes at $107.9^0 - 116.8^0$.

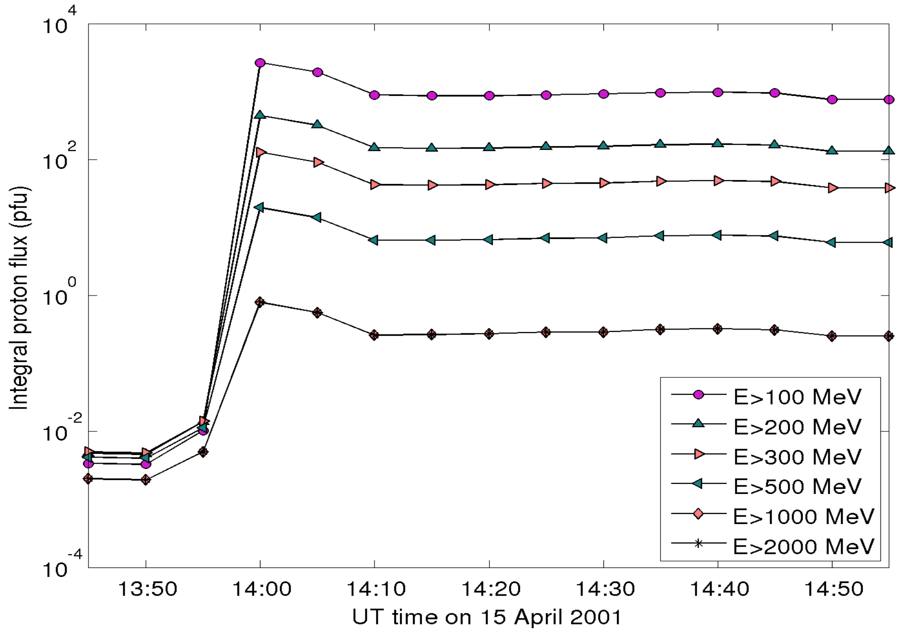

Fig. 4: SCR integral proton fluxes on 15 April 2001, as extracted by the NMBANGLE Model .

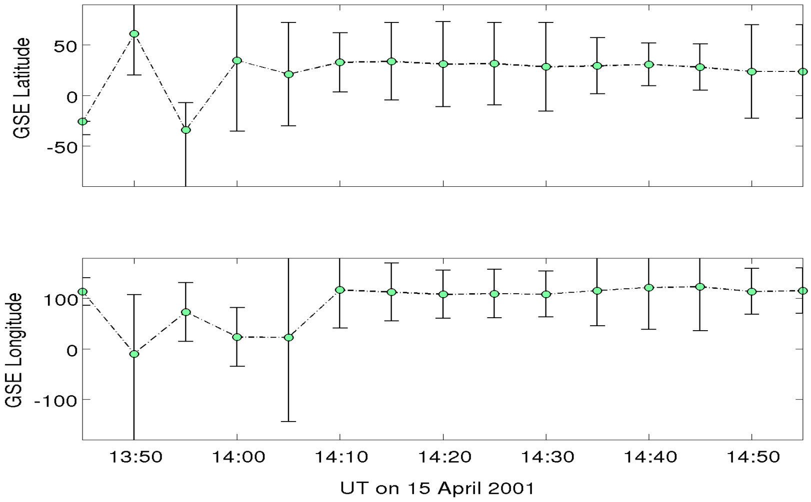

Fig. 5: Location of the anisotropy source in GSE coordinates, on 15 April 2001, as extracted by the NMBANGLE Model .

NMBANGLE PPOLA Model Results

During the initial phase of the GLE60 the correlation coefficient *C* is bigger than that corresponding to the NMBANGLE Model, however the statistical errors on the definition of the various GLE parameters continue to be big enough. At later phases (> 14:00UT) *C* ranges between 57% and 70%. The time evolution of the spectral index is presented in Fig. 6. During the initial phase of the event the SCR spectrum seems to be hard,but the big error bars at moments 13:50 UT and 13:55 UT render the respective results less reliable. However, it is worth noticing that for this GLE event, a very hard spectrum in the beginning of the event, using a power-law SCR spectrum, has been also derived by other researchers (for example see in Vashenyuk et al., 2003). At the time period after 14:00 UT the model becomes more reliable and the value of the spectral index ranges around the value -5.5±0.3.

The behavior of the mean integral fluxes of the SCR particles reaching the upper atmosphere, on 15 April 2001 has a maximum of about 130 pfu, at 14:00 UT. The time dependent variation of the position of the maximum anisotropy source near Earth, in GSE coordinates, is demonstrated in Fig. 7. During the initial phase of the event (13:34 UT – 14:00 UT), when the model is less reliable, the apparent SCR source was mostly located close to the ecliptic plane with its GSE latitude varying between $-34.5^0 \pm 80.5^0$ and $21.5^0 \pm 117.3^0$ After 14:00 UT the GSE latitude stabilizes at about 48^0 and the GSE longitude at about 25^0.

According to this mode-version, the GLE60 seems to be very anisotropic. Parameter n_a, characterizing the width of the anisotropic beam of SCR particles (see Plainaki et al., 2007 for analytical definition of n_a) at 13:55 UT takes the value of ~2.8 meaning a narrow SCR spatial distribution, demonstrated also in Fig.8. At later phases n_a descends to ~ 1.

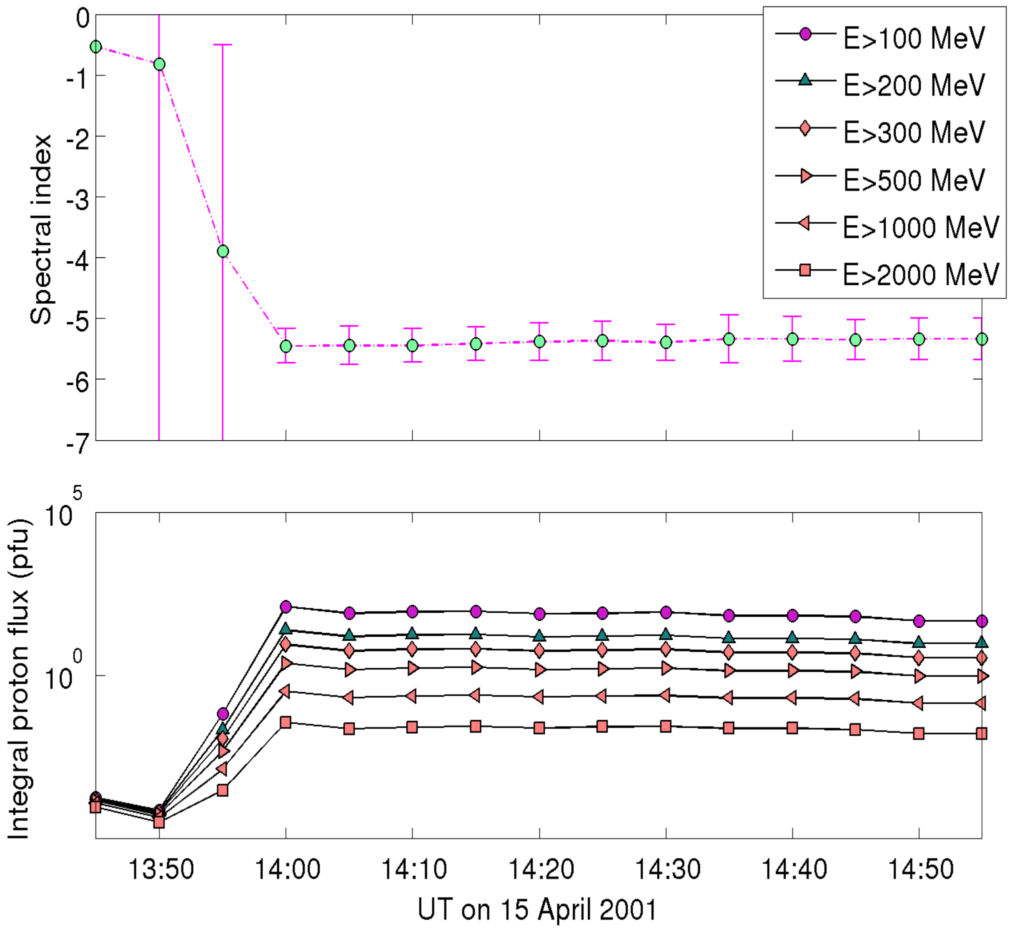

Fig. 6: Time evolution of the spectral index together with SCR integral proton fluxes, on 15 April 2001, as extracted by the NMBANGLE PPOLA Model.

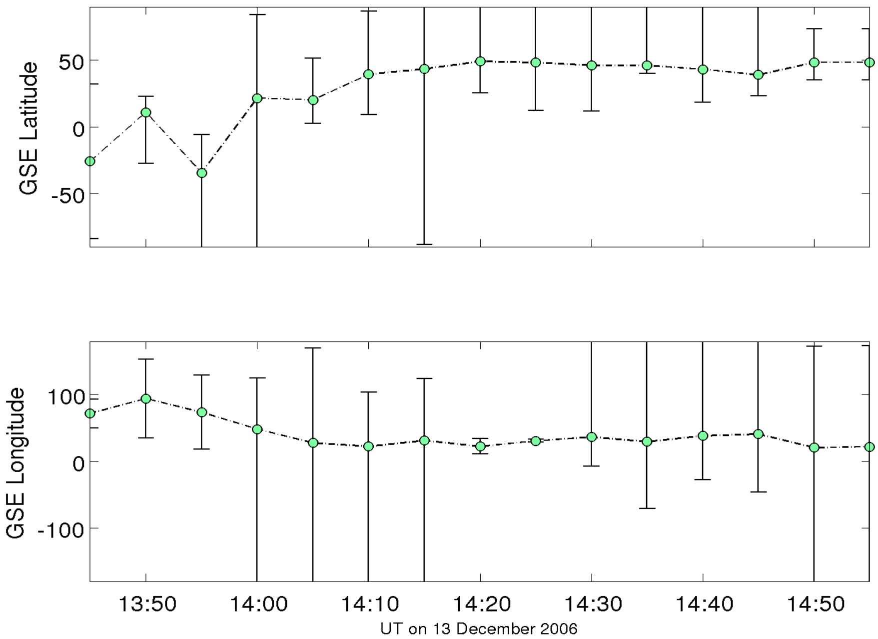

Fig. 7: Location of the anisotropy source in GSE coordinates, on 15 April 2001, as extracted by the NMBANGLE PPOLA Model .

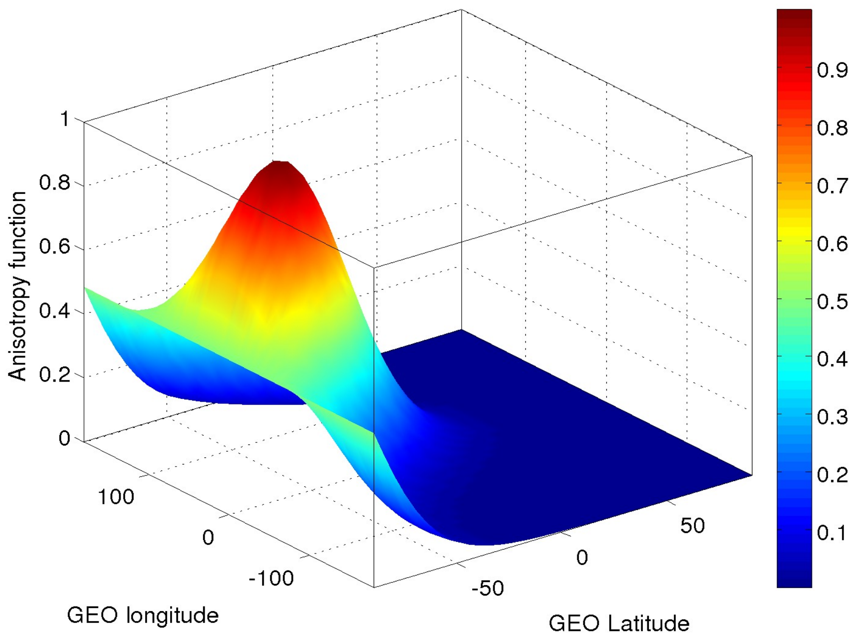

Fig. 8: Anisotropy function, according to the NMBANGLE PPOLA Model, on 15 April, at 13:55 UT.

4. Comparison of the two model versions – Discussion

The initial phase of the GLE60 was very difficult to model due to the extremely anisotropic direction of propagation of the solar particles and due to the big differences in the counting rates recorded between different NMs. The application of both versions of the NMBANGLE and NMBANGLE Models at that phase leads to less reliable results, with the NMBANGLE PPOLA Model being a little better in respect to the other one (exhibiting a better correlation coefficient). After 14:00 UT both models become reliable; the NMBANGLE Model seems to be a little better since the correlation coefficients characterizing the goodnes of the modelling are higher.

SCR Spectrum

The SCR spectrum derived by the NMBANGLE PPOLA Model is harder in respect to that derived by the NMBANGLE Model. At 14:00 UT, when most NMs have already started registering the GLE, the spectral index calculated by the NMBANGLE PPOLA Model is γ = -5.4 $\pm$ 0.3; at the same moment the respective output value of the NMBANGLE Model is γ= -6.8 $\pm$ 0.3. At later times, the calculated spectral indexes vary little from the above values, in both models. In the initial phase of the event the NM BANGLE Model is more reliable than the NMBANGLE PPOLA; therefore, inside certain uncertainty limits (see Fig. 5), the model reveals a quite hard SCR spectrum with γ = -3.9 $\pm$ 3.4, at 13:55 UT. We note that inside the (difficult to model) initial GLE phase, the moment 13:55 UT is the one corresponding to the best goodness of the fit. The above results are in general in good agreement with those obtained in other studies. For example, Bombardieri et al. (2007) have modeled the SCR spectrum during the GLE60 using a modified power law in rigidity form and found also that in the beginning of the event the spectrum was hard. At later times these authors found that the spectrum softened and at 14:30 UT (peak phase) the spectral index was -4.75, with a $\delta\gamma \sim$ 0.60 (for analytical description of this model see in Bombardieri et al. 2006; 2007 and 2008).

SCR fluxes

The calculated, by the two model-versions, lower-energy (> 100 MeV) SCR integral fluxes differ at about 1 order of magnitude, with those extracted by the NMBANGLE Model, being the higher ones. As one moves to the higher energy range the difference in the SCR flux values calculated by these model-versions steepens. For example at fluxes of SCR particles of energy > 500 MeV the difference is less than 1 order of magnitude. Moreover, the SCR fluxes (at all energies) calculated by the NMBANGLE Model remain at a high level for at least 10 minutes more than those calculated by the NM BANGLE PPOLA Model (see Fig. 3 in comparison with lower panel of Fig. 5). In Fig. 9 the modeled SCR integral flux (>100MeV) is presented together with that 5-min GOES observations. It is clearly seen that in general the NMBANGLE PPOLA Model simulates better the real SCR flux than the NMBANGLE Model. In the time-period 14:00 UT – 14:10 UT, both models give bigger SCR flux values (up to 2 orders of magnitude) than those registered at the satellite. After 14:10 UT the NMBANGLE PPOLA Model simulates well the real proton fluxes outside the atmosphere, whereas the NMBANGLE Model gives flux values that differ constantly from the real ones at about 1 order of magnitude. Probably, it is not worth to give more emphasis to peculiarities of the profiles at the initial GLE phase, since statistical errors render less accurate the derived SCR fluxes.

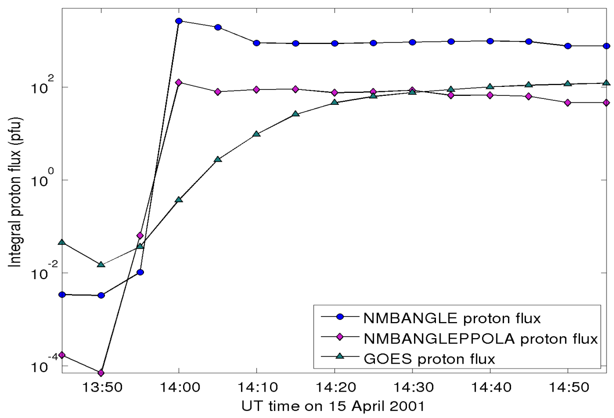

Fig. 9: Modeled SCR integral fluxes (>100MeV) together with those registered at GOES satellites (GOES data were derived from http://spidr.ngdc.noaa.gov/spidr/).

Location of the SCR source outside the atmosphere

During the initial phase of the event, the GSE latitude of the apparent SCR source, as extracted from both models, varies significantly around the ecliptic plane. However, at that period, both models do not work well since the correlation coefficients characterizing the goodness of each fit are small. This malfunctioning of the models can be due to 2 main reasons: a) existence of small increases in the CR intensity, that render difficult the modelling or/and b) inadequacy of the physical model to reproduce that 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 considered differ sufficiently from the real ones. After 14:00 UT the GSE latitudes extracted from both model-versions are very similar; both NMBANGLE and NMBANGLE PPOLA Models place the source direction at a GSE latitude between 21^0 - 49^0. The differences in the calculated (by the two models) values of the apparent SCR source's GSE latitude are presented in Fig. 10, where y-axis corresponds to the quantity $\phi_{NMBANGLE}$ - $\phi_{NMBANGLEPPOLA}$, where ϕ is the GSE latitude of the source. From this figure the difficulty in defining exactly the location of the anisotropic SCR flux source at the first moments of the GLE is revealed; in specific, at 13:50 UT the difference in the results extracted by the two models is maximum. At the time period after 14:00 UT, the similar results considering the location of the SCR anisotropic source, render both NMBANGLE and NMBANGLE PPOLA realistic and accurate.

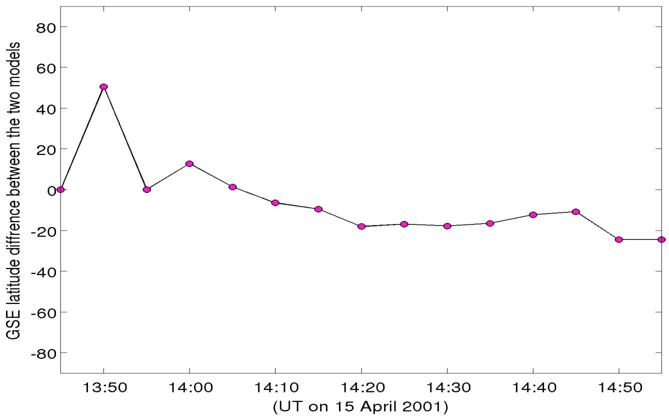

Fig. 10: Differences in the calculated values of the apparent SCR source's GSE latitude, extracted by the NM BANGLE and NM BANGLE PPOLA Models. The y-axis corresponds to the quantity $\phi_{NMBANGLE}$ - $\phi_{NMBANGLEPPOLA}$, where ϕ is the GSE latitude of the source.

5. Conclusions

The GLE of 15 April 2001 (GLE60) is modeled using two versions of the NMBANGLE Model, that use a slightly different SCR spectrum. Our results are summarized as follows:

1) The application of both NMBANGLE and NMBANGLE PPOLA Models at the initial phase of the

GLE (13:45 UT – 14:00 UT) leads to less reliable results, due to extremely anisotropic particle propagation. The NMBANGLE PPOLA Model, however, seems to be a little better, in that period, having a better correlation coefficient between the registered and the modelled NM counts.

2) After 14:00 UT both models become reliable; the NMBANGLE Model seems to be, in general, a little better since its correlation coefficients between real and model NM records is bigger.

3) The SCR spectrum derived by the NMBANGLE PPOLA Model is harder in respect to that derived by the NMBANGLE Model (at 14:00 UT, $\gamma_{NMBANGLE}$ = -5.4 ± 0.3 and $\gamma_{NMBANGLEPPOLA}$ = -6.8 ± 0.3). These results are in general in good agreement with those obtained in other studies. At later times, the calculated spectral indexes vary little from the above values, in both cases. In the initial phase of the event the NMBANGLE PPOLA Model is more reliable;

4) The calculated lower-energy (> 100 MeV) SCR integral fluxes between the two models (extrapolated in both cases) differ at about 1 order of magnitude, with those extracted by the NMBANGLE Model, being the higher ones. In general the NMBANGLE PPOLA Model simulates better the real SCR flux than the NMBANGLE Model. After 14:10 UT the NMBANGLE PPOLA Model simulates well the real proton fluxes outside the atmosphere, whereas the NMBANGLE Model gives flux values that differ constantly from the real ones at about 1 order of magnitude.

5) At the time period after 14:00 UT, the similar results considering the location of the SCR anisotropic source, render both NMBANGLE and NMBANGLE PPOLA Models realistic and accurate.

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References

Belov, A.,Eroshenko, E., Mavromichalaki, H. et al. 2005a, *Anal. Geophys. 23*, 2281

Belov, A., E. Eroshenko, H. Mavromichalaki, et al. 2005b, *Proc. 29th Int. Conf. Cosmic Rays ,1,* 189

Bieber, J.W., Dröge, W, Evenson, P.A. Et al. 2002,Astrophys. J., 567,1,622

Bieber, J.W., Clem, J., Evenson, P. et al. 2005, *Geophys. Res. Letters*, 32, 3, CiteID L03S02

Bombardieri, D.J., Michael, K.J.,Duldig, M.L. et al. 2007, ApJ, 665, 1,813

Bombardieri, D.J., Duldig,M.L., Humble, J.E. et al. 2008, ApJ, 682, 2, 1315

Cane, H.V., Mewaldt, R.A., Cohen, C.M.S. et al. 2006, J. Geophys. Res., 111, A6, CiteID A06S90

Cramp, J.L.; Duldig, M.L.; Flückiger,E.O. et al. 1997, J. Geophys. Res., 102, A11, 24237

Dorman, L.I. 2004, Cosmic Rays in the Earth's atmosphere and underground, Kluwer Academic Publishers (The Netherlands)

Dröge, W. 2000, Space Sci.Rev.,93, 1/2, 121

Duldig, M.L. 1994, Proc. Astron. Soc. Australia 11, 110

Gopalswamy, N.; Lara, A.; Yashiro, S. et al. 2003, ApJ, 598, 1, L63

Humble, J.E., Duldig, M.L., Shea, M.A. et al. 1991, *Geophys. Res. Lett*., 18, 737

Lin, J., Ko, Y.-K., Sui, L. et al. 2003, ApJ, 622, 1251

Masson, S. Klein, K.-L., Bütikofer, R. et al. 2009, Solar Phys.,257, 2, 305

Meyer, P., Parker, E.N., & Simpson, J.A. 1956, Sp Phys. Rev., 104, 768

Muraki, Y., Matsubara, S., Masuda, S. et al. 2008, Astroparticle Phys., 29,229

Plainaki, C., Belov , A., Eroshenko, E. et al. 2007, J. Geophys. Res., 112, A04102, doi:10.1029/2006JA011926, 2007.

Plainaki, C., Mavromichalaki, H., Belov, A. et al. 2009a, AdSR, 43, 4, 474

Plainaki, C., Mavromichalaki, H., Belov, A. et al. 2009b, AdSR, 43, 4, 518

Reames, D.V. 1999, Space Sci. Rev., 90, 413

Sàiz, A., Ruffolo, D., Bieber, J.W. et al. 2008, ApJ, 672, 1, 650

Shea, M.A. & Smart, D.F. 1982, *Sp. Sci. Rev.* 32, 251

Tsyganenko, N.A. 1987, *Planet. Space Sci., 35, 11,* 1347

Tsyganenko, N.A. 1989, *Planet. Space Sci., 37,* 5

Vashenyuk, E.V., Balabin Y.V., % Gvozdevsky, B.B. 2003,Proc. 28th Int. Conf. Cosmic Rays, 3401