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A New Version of the Neutron Monitor Based Anisotropic GLE Model: Application to GLE60

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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 · Methods: data analysis · Plasmas

1. Introduction

The Sun occasionally emits particles of sufficiently high energies to cause an 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

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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 except 20 January 2005 rank below 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; Bieber *et al.*, 2005a; Bombardieri *et al.*, 2008; Flückiger *et al.*, 2005; McCracken, Moraal, and Stoker, 2008; Plainaki *et al.*, 2007; Saiz *et al.*, 2005).

The GLE can be defined as a cosmic ray phenomenon in association with either X-class solar flares or fast ($>1000\ \mathrm{km\,s^{-1}}$) 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 may occur from multiple sources during a major solar eruption, such as coronal or CME-driven shocks, coronal sites associated with magnetic reconnection (*e.g.*, solar flares and current sheets) and/or 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, Parker, and Simpson, 1956; Dröge, 2000; Bieber *et al.*, 2002; Saiz *et al.*, 2008). Thus, comparing the signatures of accelerated solar particles at the Sun with the measurements of the relativistic particles at the Earth is a non-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 evolution are presently available (Shea and Smart, 1982; Humble *et al.*, 1991; Duldig, 1994; Cramp *et al.*, 1997; Belov *et al.*, 2005a, 2005b; Bieber *et al.*, 2005b; 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 (Flückiger and Kobel, 1990; Boberg *et al.*, 1995).

On the basis of the Coupling Coefficient Method (Dorman, 2004), the NMBANGLE model, which couples primary SCRs 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 analytical results of its application to the GLE69 and GLE70 were 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 in this text, we shall refer to it as the '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 SCRs 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 the behavior of solar particles under extreme solar conditions.

The NMBANGLE PPOLA model assumes a slightly different expression of the SCR rigidity spectrum to that assumed in the NMBANGLE model; whereas the NMBANGLE model uses a quasi-power law dependence on rigidity, the NMBANGLE PPOLA model uses a pure power law. This main difference between the two models is described in detail below.

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, 2005b; Plainaki *et al.*, 2007):

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

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, $\gamma(t)$ 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 vertical asymptotic directions as defined in Plainaki *et al.* (2007) and applied in various GLEs (Plainaki *et al.*, 2007, 2009b), R_u is the upper limit for the rigidity of the primary SCR particles, taken to be 8 GV in this study. The parameter $b(t)$, inside Equation (1), is considered rigidity independent and defined as follows:

$$b(t) = b_1(R, t)/I_0(R, t_0) \tag{2}$$

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 $b_1(t) \circ R^{\gamma(t)}$, where $b_1(t)$ is rigidity independent. Therefore, the basic equation of the NMBANGLE PPOLA model becomes

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

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. In this analysis the trajectories calculated in order to define the NM asymptotic directions, correspond to vertical incidence. This consideration can imply limitations in case of highly anisotropic events (such as those in September 1989 and in February 1956) when a non-vertical arrival can produce a response in a monitor where a vertical incidence would not (Cramp, Duldig, and Humble, 1995). In such events the east – west asymmetry becomes important for the high cutoff monitor observations. However, low cut-off rigidities (below 5 GV) do not depend on the direction of arrival of particles (Dorman *et al.*, 2008). Moreover, Bazilevskaya *et al.* (1996) have found that the low rigidity protons arriving from different zenith and azimuthal directions at a given time have very close asymptotic directions. Therefore, since the majority of the stations used for the analysis of this event are low and middle cut-off rigidity stations, we assume that the consideration of explicitly vertical incidence proton directions does not compromise the results presented here. The scope of the NMBANGLE PPOLA 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.

3. Model Application to GLE60 – Results

On 15 April 2001 a strong flare (X14.4/2B) was observed at the west limb of the Sun at S20W85. This flare, associated with a fast CME ($>$1200 km s^{-1}) has been the largest of a series of solar eruptions that occurred within 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 a 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 the *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, with the High Energy Proton and Alpha Detector on board, the 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 in 5-min data starting at about 13:50 UT. The SCR intensity – time profiles registered at NMs of different cut-off rigidities are presented in Figure 1, where the pre-increase baseline period used for deriving the percentage 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 R_c) registered it also; the Potchefstroom NM ($R_c \sim 7.30$ GV) recorded a peak at 13:50 UT whereas the Athens NM ($R_c \sim 8.53$ GV) did not register any significant increase. This implies that solar protons with rigidity significantly higher than 7.3 GV must have been present at 1 AU,

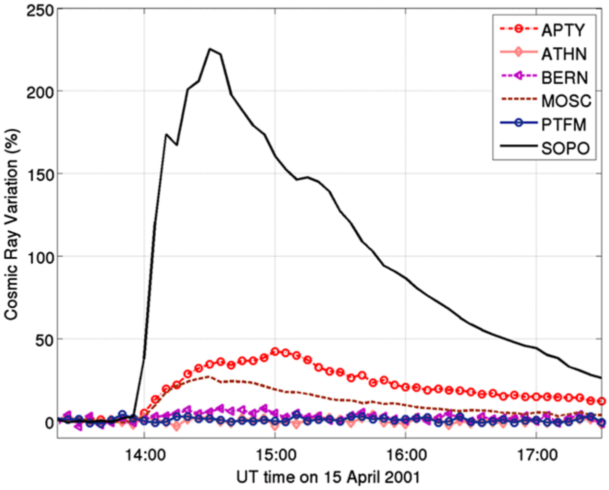


Figure 1 SCR intensity – time profiles at 15 April 2001, as recorded at Apatity (APTY, $R_c \sim 0.57$ GV), Athens (ATHN, $R_c \sim 8.53$ GV), Bern (BERN, $R_c \sim 4.49$ GV), Moscow (MOSC, $R_c \sim 2.43$ GV), Potchefstroom (PTFM, $R_c \sim 7.30$ GV), South Pole (SOPO, $R_c \sim 0.11$ GV) NMs.

during the event of 15 April 2001. We underline that in this analysis, the GLE was considered to result solely from solar protons and not in combination with solar neutrons, as stated by Muraki *et al.* (2008). 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. Of crucial importance for this large GLE response registered at the South Pole NM station has been the fact that its asymptotic cone of view intersected the peak in the particle arrival.

In general a GLE may 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, Balabin, and Gvozdevsky (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. Bombardieri *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 five minutes between 13:45 UT and 14:55 UT. Each indicated time represents the start of a five-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 four. The NM vertical asymptotic directions of viewing, on 15 April 2001 at 14:00 UT, are presented in Figure 2. Comparing the increases registered at NMs of almost the same cut-off rigidities but of different asymptotic directions of viewing, some first estimation on the preferred arrival direction of the SCR particles can be made. For example (Figure 3), the Fortsmith NM ($R_c \sim 0.30$ GV, *altitude* $\sim$ sea level) registers, for the first three hours of the event, a bigger enhancement than that recorded at the Apatity polar NM ($R_c \sim 0.65$ GV, effectively $\sim$1 GV because of the atmospheric cut-off, *altitude* $\sim$177 m). This difference can be attributed to

Table 1 Characteristics of the NMs used in this analysis (Data derived from the NMDB Database, http://cosmicrays.oulu.fi/nmdbinfo/).

Station	Latitude (deg)	Longitude (deg)	R_c (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
Newark	39.68	−75.75	1.97	50
Norilsk	69.26	88.05	0.63	0
Novosibirsk	54.8	83	2.91	163
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

the fact that the asymptotic cone of view of the FSMT NM was closer to the average direction of the negative Interplanetary Magnetic Field (IMF) at that time (*i.e.* −60° in GEO coordinates, according to the *Advance Composition Explorer* (ACE) measurements).

3.1. NMBANGLE Model Results

In order to check the validity of the NMBANGLE model we calculate the correlation coefficient between the modeled and the observed values of the NM intensity variations. The correlation coefficient, denoted in this text by C, is a measure of the strength of the linear relationship between these two quantities. The closer to 1 (100%) is the value of C, the closer to a perfect linear relationship is their correlation. Therefore, C can characterize the goodness of the NMBANGLE model by comparing the modeled NM intensities with the registered ones; consequently, the values of C indicate the time period that the model appli-

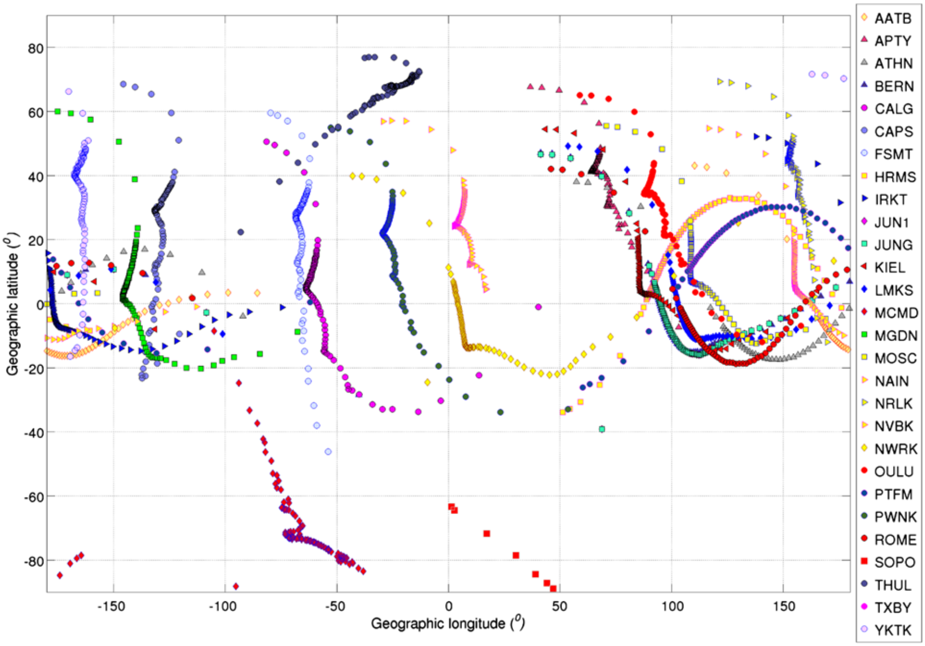
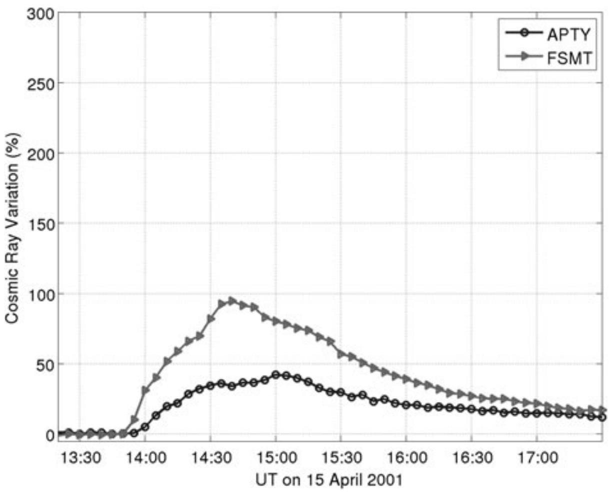


Figure 2 NM vertical asymptotic directions of viewing, on 15 April 2001, at 14:00 UT. Geomagnetic conditions were slightly disturbed ($K_p = 4$). The calculation step in rigidity scale was taken as 0.1 GV. Station abbreviations are: AATB (Alma Ata B), APTY (Apatity), Athens, (ATHN), Bern (BERN), Calgary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

Figure 3 SCR intensity – time profiles at 15 April 2001, as recorded at Apatity (APTY, $R_c \sim 0.57$ GV, altitude ~177 m) and Fortsmith (FSMT, $R_c \sim 0.30$ GV, *altitude* ~ sea level).



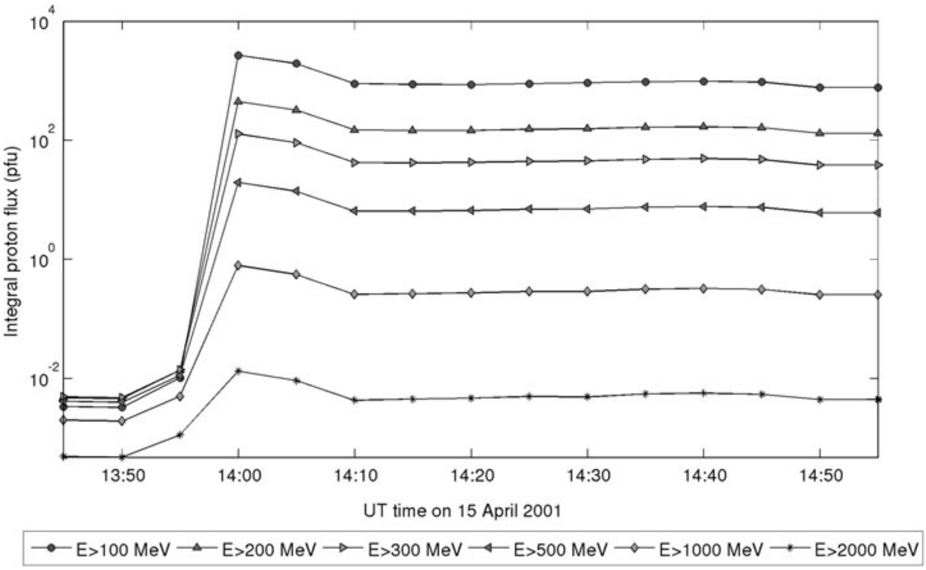


Figure 4 SCR integral proton fluxes on 15 April 2001, as obtained by the NMBANGLE model.

cation is most reliable. Specifically, for GLE60, the NMBANGLE model results are most reliable from 14:00 UT (of 15 April 2001) and afterwards, since C takes values between 0.8 and 0.85, whereas during the initial GLE period, C becomes smaller than 0.35. Therefore, we largely confine our discussion of the model outputs to times after 14:00 UT.

The percentage error, $r(t)$, in the calculation of each modeled GLE parameter (*e.g.* spectral index, latitude of the anisotropy source *etc.*), $p(t)$, can de derived by the following formula:

$$r(t) = \left[\left(p(t) - \delta p(t)\right)/p(t)\right] \times 100, \tag{4}$$

where $\delta p(t)$ is the standard error of parameter $p(t)$, at some specific time t. The error $\delta p(t)$ is calculated assuming a t-distribution, inside 95% confidence intervals for the non-linear least-squares parameter $p(t)$. For the time period after 14:00 UT, the values of $r(t)$ corresponding to the spectral index parameter, are [334?] 1%. For the same time period, the error corresponding to the anisotropic parameter $n_a(t)$ (as defined in Plainaki *et al.* (2007)), ranges between 5% and 35%. As much as the error in the calculation of the location of the anisotropy source is considered, the NMBANGLE model gives values ranging between *i*) 13° and 51°, for the GSE latitude, and *ii*) 28° and 167° for the GSE longitude. From the above one can see that the model seems to be less reliable in defining the position of the anisotropy source, in respect to the definition of other parameters, such as the spectral index. On the other hand, the NMBANGLE model seems to be reliable in defining the energy spectrum of the arriving solar particles.

At 14:00 UT the spectral index is -6.8 ± 0.3, whereas later it remains more or less constant. These results 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 Figure 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 mean integral flux of particles of energy

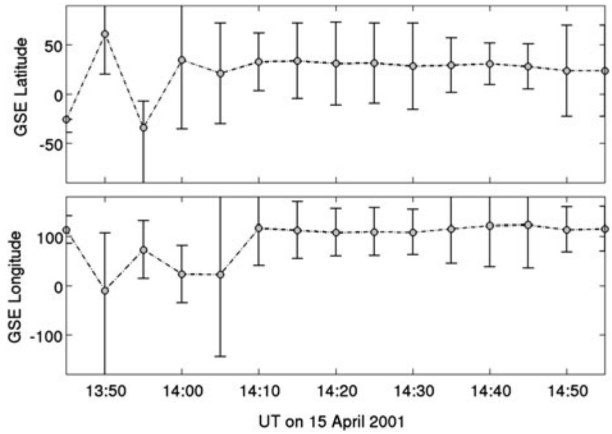


Figure 5 Location of the anisotropy source in GSE coordinates, on 15 April 2001, as obtained by the NMBANGLE model.

>100 MeV has a maximum of the order of 10^3 pfu (1 pfu is equal to 1 proton $cm^{-2}\,s^{-1}\,sr^{-1}$), at 14:00 UT, whereas later it falls at some 10^2 pfu. The direction of the apparent source of solar particles direction, a quantity that in general 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.*, 2007). 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, 2009b). The time-dependent variation of the position of the maximum anisotropy source near Earth, in GSE coordinates, is demonstrated in Figure 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 $21.4° \pm 51.3°$ and $34.3° \pm 38.3°$. In the same time period the GSE longitude of the source does not vary significantly; after 14:10 stabilizes at 107.9°–116.8°. The model-derived latitude and longitude of the apparent SCR source direction at the time period 14:00 – 14:55 UT differ significantly from the latitude of the negative IMF, measured by ACE and presented in the paper of Bombardieri *et al.* (2007). However, according to Bieber *et al.* (2002), there is no reason that the magnetic field measured by a satellite at some point should be the same as the average field sampled by the particle over its orbit, given that the Larmor radius is on the order of the coherence length of interplanetary magnetic turbulence (Bieber *et al.*, 2002; Bombardieri *et al.*, 2007). Therefore, the apparent source vectors derived from the model do not need to be aligned with the measured magnetic field vectors. For example, in the work of Bieber *et al.* (2002) on the GLE of 14 July 2000 the derived GSE latitude of anisotropy deviated from the IMF latitude up to almost 100° (opposite hemisphere) during the event maximum. Moreover, in the work of Bombardieri *et al.* (2006) on the same event of 2000, considerable differences between the modeled anisotropy latitude and the measured IMF ones are noticed. Nevertheless, the NMBANGLE model results on the position of the apparent SCR source differ significantly from other determinations (see, *e.g.*, Bombardieri *et al.* (2007)). This can be due to either the different GLE models used or the under-representation of southern viewing direction data in our analysis, forcing the model to solve for northern biased data. However, it should be noted that differences between derived apparent source directions and IMF ones exist also in analyses realized using data from NMs equivalently distributed in the Earth's hemispheres (*e.g.* in the work of Bieber *et al.* (2002) on the GLE of 14 July 2000, where data from four northern and five southern stations were used, the modeled latitude of the anisotropy differed significantly from the latitude of the IMF). Nevertheless, in the future we intend to realize studies on GLE modeling using data from more NMs, possibly distributed even more widely in the world.

3.2. 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 various GLE parameters are still quite large. At later phases (>14:00 UT) C ranges between 57% and 70%. The time evolution of the spectral index is presented in Figure 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 at the beginning has also been derived by other researchers (for example see Vashenyuk, Balabin, and Gvozdevsky, 2003), using a power law SCR spectrum. Most GLEs exhibit a harder onset and peak spectrum which softens during the declining phase. This is what also happens in the case of GLE60. At the time period after 14:00 UT the model becomes more reliable and the value of the spectral index ranges around -5.5 ± 0.3.

The behavior of the mean integral SCR fluxes of energy above 100 MeV, 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 Figure 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 -34.50 ± 80.50 and 21.50 ± 117.30. After 14:00 UT the GSE latitude stabilizes at about 48° and the GSE longitude at about 25°. Also in the case of the application of the NMBANGLE PPOLA model, we note differences between the modeled direction of the apparent SCR source and the measured direction of the IMF. Moreover, the NMBANGLE PPOLA model results on the position of the apparent SCR source differ significantly from other determinations (see,

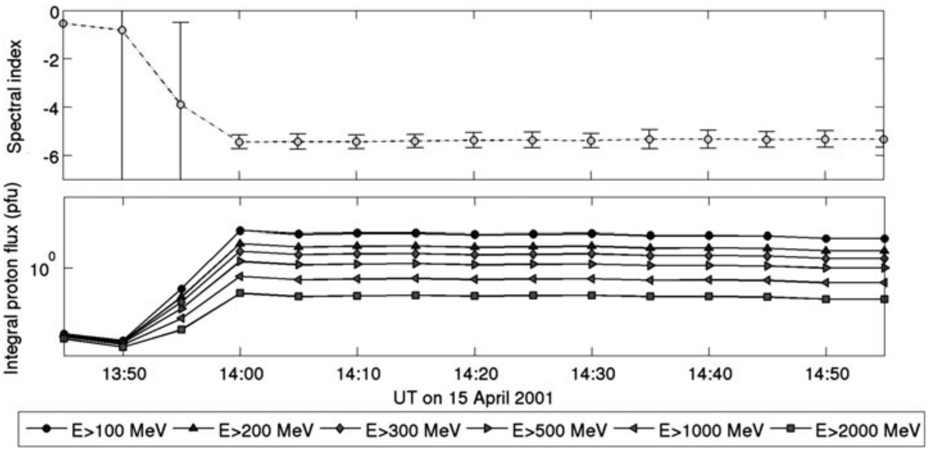


Figure 6 Time evolution of the spectral index together with SCR integral proton fluxes, on 15 April 2001, as obtained by the NMBANGLE PPOLA model.

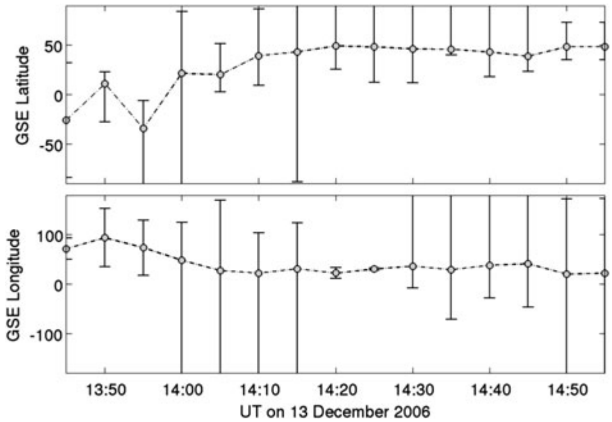


Figure 7 Location of the anisotropy source in GSE coordinates, on 15 April 2001, as obtained by the NMBANGLE PPOLA model.

e.g., Bombardieri *et al.* (2007)). As stated before, these differences can be due to either the different GLE models used or the under-representation of southern viewing direction data in our analysis. The latter forces our model to solve the inverse fitting problem for northern biased data (see also the discussion in the previous paragraph).

According to this version of the model, 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 an analytical definition of n_a) at 13:55 UT takes the value of $\sim$2.8, meaning a narrow SCR spatial distribution. It should be noted, however, that the model fit is less reliable at this time, so the above mentioned value should be considered as an indication and not be taken to be strictly quantitative. At later phases n_a descends to $\sim$1.

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 model versions (NMBANGLE and NMBANGLE PPOLA) at that phase leads to less reliable results, with the NMBANGLE PPOLA model being a little better (exhibiting a better correlation coefficient). After 14:00 UT both models become reliable.

4.1. SCR Spectrum

In Figure 8, we present the SCR rigidity spectrum derived by each model at 14:00 UT, when most NMs have already started registering the GLE. It is clearly seen that the NMBANGLE PPOLA model has a harder spectrum. Comparing the two, the NMBANGLE PPOLA spectrum, at 14:00 UT, is in better agreement with the spectrum calculated for the same GLE at the same time by Bombardieri *et al.* (2007), especially in the rigidity range above 2 GV. Moreover, the NMBANGLE PPOLA model, in the higher rigidity range (above 2 GV), gives high differential rigidity fluxes, which are in general in good agreement with the fluxes calculated during relative phases of other GLEs. For example, the rigidity spectrum (above 2 GV) of the GLE of 29 September 1989, as presented in the work of Lovell, Duldig, and Humble (1998), is in good agreement with that calculated applying the NMBANGLE PPOLA model. In the lower rigidity range, however, the spectrum of Lovell,

Figure 8 SCR rigidity spectrum at 14:00 UT derived by the two different models.

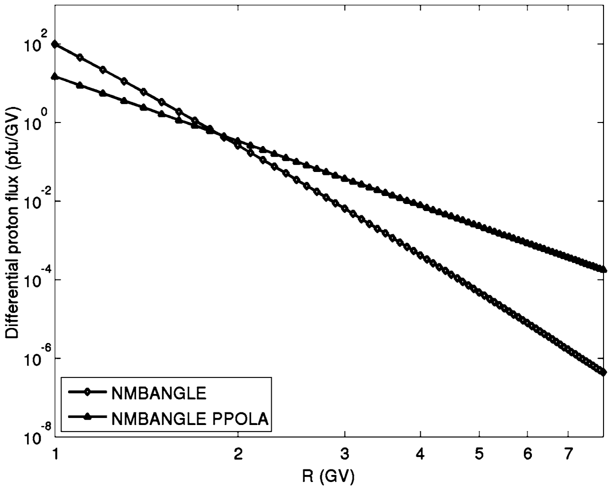
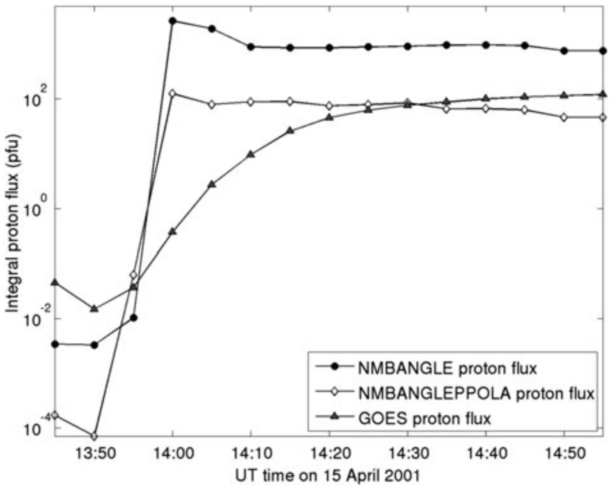


Figure 9 Modeled SCR integral fluxes (>100 MeV) together with those registered by GOES (GOES data were derived from http://spidr.ngdc.noaa.gov/spidr/).



Duldig, and Humble (1998) gives higher differential fluxes, probably due to the more intense GLE registered during that time. Summarizing, we hold the NMBANGLE PPOLA model spectrum to be more realistic than that calculated by the NMBANGLE model.

4.2. SCR Fluxes

The lower-energy (>100 MeV) SCR integral fluxes calculated by the two model versions differ at about 1 order of magnitude with those obtained by the NMBANGLE model, these 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 one order of magnitude. Moreover, the SCR fluxes (at all energies) calculated by the NMBANGLE model remain at a high level for at least ten minutes more than those calculated by the NMBANGLE PPOLA model (see Figure 4 in comparison with the lower panel of Figure 6).

In Figure 9 the modeled SCR integral flux (>100 MeV) is presented together with 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 two orders of magnitude) than those registered at the satellite. To explain this difference, one should consider the dispersion in the arrival times of SCR particles of different energies, which traverse longer or shorter path lengths, following the magnetic field line from the source to the Earth. A longer path length inside the IMF has consequences for slower particles, which must be accelerated before those of higher energy. Thus, for example, 10 MeV protons that travel about 1 AU hr^{-1} would take two hr to travel a path length of 2 AU (Reames, 2009). The first particles of a given velocity to arrive at the Earth from a source near the Sun are minimally scattered particles that have been focused into a narrow cone of pitch angle by the diverging magnetic field (Reames, 2009). The cone of pitch angles becomes wider as time goes by and the flux intensity rises towards a maximum. This pitch-angle scattering slows the rise in intensity and delays the apparent onset, a process that has been modeled in the past for large SEP events (see, *e.g.*, Saiz *et al.*, 2005). Moreover, during a SEP event, the intensity of the MeV-energy particle fluxes can exhibit a plateau of about 100 cm^2 s MeV, varying by a factor of two among different events (Reames and Ng, 1998). This phenomenon, known as the 'streaming limit' (Reames and Ng, 1998), can result in suppressing the low-energy particle arrival below the levels expected from higher-energy spectral responses. The physical mechanism, leading to the existence of a streaming limit, is a process of self-regulation of the particle intensity. Once the source intensity rises above that required to reach the streaming limit, additional particles are diffusively trapped near the expanding shock source. Thus, added acceleration only serves to increase the intensity at the peak and not at the early plateau, the visibility of which is modulated by the geometric effect of the connection longitude of the observer relative to the source (see, *e.g.*, Reames, Barbier, and Ng, 1996; Reames, 1997). 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 the derived SCR fluxes less accurate.

4.3. Location of the SCR Source Outside the Atmosphere

During the initial phase of the event, the GSE latitude of the apparent SCR source, as obtained 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 two main reasons: *i*) existence of small increases in the CR intensity, which render the modeling difficult and/or *ii*) 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 obtained from both model versions are very similar; both NMBANGLE and NMBANGLE PPOLA models place the source direction at a GSE latitude between $21° – 49°$. The differences in the calculated (by the two models) values of the apparent SCR source's GSE latitude are presented in Figure 10, where the y-axis corresponds to the quantity $\varphi_{\mathrm{NMBANGLE}} - \varphi_{\mathrm{NMBANGLEPPOLA}}$, 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; specifically, at 13:50 UT the difference in the

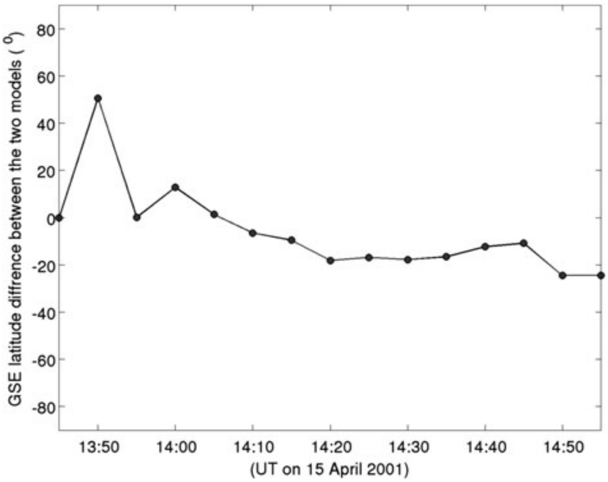


Figure 10 Differences in the calculated values of the apparent SCR source's GSE latitude, obtained by the NMBANGLE and NMBANGLE PPOLA models. The y-axis corresponds to the quantity $\varphi_{\text{NMBANGLE}} - \varphi_{\text{NMBANGLEPPOLA}}$, where φ is the GSE latitude of the source.

results obtained by the two models is maximum. At the time period after 14:00 UT, the results of the two models are similar.

An important reason that most models fail during the rising phase of a GLE is that the changes are too dynamic and the models would need data of sufficient statistical accuracy, with sampling times as short as a minute or less. These data are not always available, since many NM stations have registration systems with larger sampling times. Moreover, in the present analysis there is very poor representation of southern viewing directions with only three southern stations (and 24 northern stations). This fact seems to have affected the current results, especially those considering the position of the anisotropy source, which seems to be the less reliably modeled parameter. However, the availability of data from a well distributed set of NM stations for inclusion in the analysis is a problem for every model. Our results presented for arrival direction, are very different from those of (for example) Bombardieri *et al.* (2007) and this is most likely due to the above mentioned problem.

5. Conclusions

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

i) 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 very anisotropic particle propagation. After 14:00 UT both models become reliable.

ii) The SCR rigidity spectrum calculated using the NMBANGLE PPOLA model is harder. The NMBANGLE PPOLA spectrum, at 14:00 UT, however, is in better agreement with the spectrum calculated for the same GLE, in other studies, especially in the rigidity range above 2 GV. Moreover, the NMBANGLE PPOLA model, in this rigidity range, gives higher differential rigidity fluxes, which are in general in good agreement with the fluxes calculated during relative phases of other GLEs.

iii) The lower-energy (>100 MeV) SCR integral fluxes (extrapolated in both model cases) differ at about one order of magnitude, with those obtained by the NMBANGLE model, being the higher ones. In general the NMBANGLE PPOLA model simulates better the real SCR flux than the NMBANGLE model, since it is in closer agreement with the satellites' measurements. However, the differences between modeled fluxes and satellite measurements might be due to the 'streaming limit' phenomenon, which may result in suppressing the low-energy particle arrival below the levels expected from higher-energy spectral responses.

iv) At the time period after 14:00 UT, the NMBANGLE and the NMBANGLE PPOLA models present similar results on the location of the apparent SCR source. However, these results, at the time period 14:00 – 14:55 UT, differ significantly from the latitude of the negative IMF, measured by ACE. Of course, there is no reason that the magnetic field measured by a satellite at some point should be the same as the average field sampled by the particle over its orbit; hence, the apparent source vectors derived from the model do not need to be aligned with the measured magnetic field vectors.

v) The NMBANGLE and NMBANGLE PPOLA model results on the position of the apparent SCR source differ significantly from other determinations presenting SCR particle arrival directions in opposite hemispheres. This may be due to either different GLE models being used or an under-representation of the southern viewing direction data in our analysis, forcing the model to solve for northern biased data. In the future we intend to realize studies on GLE modeling using data from more NMs, possibly distributed even more widely in the world.

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