

Analysis of the Ground-Level Enhancements on 14 July 2000 and 13 December 2006 Using Neutron Monitor Data

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Abstract On the basis of neutron monitor data, we estimate the energy spectrum, anisotropy axis direction, and pitch-angle distribution of solar energetic particles during two major ground-level enhancements (GLE 59 on 14 July 2000 and GLE 70 on 13 December 2006). For the analysis we used a newly computed neutron monitor yield function. The method consists of several consecutive steps: definition of the asymptotic viewing cones of neutron monitor stations considered for the data analysis by computing the cosmic ray particle propagation in a model magnetosphere with the MAGNETOCOSMICS code, computing the neutron monitor model responses, and deriving the solar energetic particle characteristics on the basis of inverse problem solution. The pitch-angle distribution and rigidity spectrum of high-energy protons are obtained as a function of time in the course of ground-level enhancements. A comparison with previously reported results is performed and reasonable agreement is achieved. A discussion of the obtained results is included.

Keywords Solar eruptive events · Neutron Monitor · Yield function

1. Introduction

A thorough analysis of solar energetic particle (SEP) events provides crucial information on particle scattering and transport in the interplanetary medium and for understanding their acceleration mechanisms (Debrunner *et al.*, 1988; Lockwood, Debrunner, and Flükiger, 1990; Kallenrode, Cliver, and Wibberenz, 1992; Reames, 1999). Some solar flares and eruptive events, such as coronal mass ejections (CMEs), can accelerate protons and other ions to high energies (Cliver, Kahler, and Reames, 2004; Dorman, 2006; Reames, 2009a,b; Aschwanden,

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2012, and references therein). These SEPs can sporadically enter the Earth atmosphere, with a greater probability during the maximum and declining phase of a solar activity cycle (*e.g.* Shea and Smart, 1990).

High-energy particles, mostly protons and α -particles of extra-solar origin that are known as Galactic cosmic rays (GCR) constantly hit the Earth's atmosphere. They induce a complicated atmospheric nuclear–electromagnetic–muon cascade (see Dorman, 2004; Bazilevskaya *et al.*, 2008 and references therein). The energy of SEPs is occasionally high enough (≥ 1 GeV/nucleon) to initiate a similar atmospheric cascade, leading to an enhancement in the count rate of ground-based detectors, specifically neutron monitors (NMs). This special class of SEP events is called ground-level enhancements (GLEs). The worldwide network of NMs (*e.g.* Mavromichalaki *et al.*, 2011) represents a multi-instrumental tool for continuous monitoring of the CR particle intensity and registration of GLEs (Simpson, Fonger, and Treiman, 1953; Hatton, 1971).

The NM stations are spread across the globe at multiple geographic locations to obtain a complete picture of cosmic rays in space, since their intensity is not uniform around the Earth (Bieber and Evenson, 1995). This is particularly important for GLEs, which possess an essential anisotropic part, specifically during the event onset (Debrunner *et al.*, 1988; Shea and Smart, 1990; Vashenyuk *et al.*, 2006b; Bütikofer *et al.*, 2009). Therefore, measurements performed by the worldwide network of NMs form the basis from which the spectral and angular characteristics of SEPs near Earth can be assessed. In addition, it was recently shown that spectral and angular characteristics of SEPs derived using NM data are model dependent (Bütikofer and Flückiger, 2013) mainly because of assumed NM yield function(s) and magnetospheric model(s) (for details see Bütikofer *et al.*, 2013). In this study we use an established method for the analysis of GLEs based on NM data, but apply a newly computed neutron monitor yield function (Mishev, Kocharov, and Usoskin, 2014). We study two major events, namely GLE 59 on 14 July 2000 and GLE 70 on 13 December 2006.

2. Modelling the Neutron Monitor Response

To derive the SEPs characteristics, it is necessary to establish the relation between NM count rates and the primary particle flux, considering the full complexity of particle transport in the geomagnetosphere and in the Earth's atmosphere (Debrunner and Brunberg, 1968; Hatton, 1971; Smart, Shea, and Flückiger, 2000; Dorman, 2004; Desorgher *et al.*, 2009; Mishev and Usoskin, 2013). A convenient formalism for the relation between NM count rate and primary particle flux is based on the yield function (for details see *e.g.* Hatton, 1971; Clem and Dorman, 2000, and references therein). We here used a recently computed NM yield function, which considers the finite lateral extent of a cosmic-ray-induced atmospheric cascade and provides good agreement with experimental latitude surveys (Mishev and Usoskin, 2013; Mishev, Usoskin, and Kovaltsov, 2013).

An analysis of GLEs based on NM data consists of several consecutive steps: determining asymptotic viewing cones of the NMs by computing particle trajectories in a model magnetosphere; assuming an initial guess of the inverse problem; applying an optimization procedure (inverse method) to derive the energy spectrum of the primary SEPs and the anisotropy axis direction and pitch angle distribution. A detailed description of the method is given elsewhere (Mishev, Kocharov, and Usoskin, 2014). The method is similar to that used by Shea and Smart (1982), Humble *et al.* (1991), Cramp *et al.* (1997), Bombardieri *et al.* (2006), Vashenyuk *et al.* (2006b, 2008).

The relative count rate increase of a given NM can be expressed as

$$\frac{\Delta N(P_{\text{cut}})}{N} = \frac{\int_{P_{\text{cut}}}^{P_{\text{max}}} J_{\parallel \text{sep}}(P, t) Y(P) G(\alpha(P, t)) dP}{\int_{P_{\text{cut}}}^{\infty} J_{\text{GCR}}(P, t) Y(P) dP}, \quad (1)$$

where $J_{\parallel \text{sep}}$ is the rigidity spectrum of the primary solar particles in the direction of the highest flux, $J_{\text{GCR}}(P, t)$ is the rigidity spectrum of the GCR at a given time t with the corresponding modulation, $Y(P)$ is the NM yield function, $G(\alpha(P, t))$ is the pitch angle distribution of SEPs, N is the count rate of the GCR, $\Delta N(P_{\text{cut}})$ is the count rate increase due to solar particles, P_{cut} is the minimum rigidity cut-off of the station, and accordingly P_{max} is the highest rigidity of SEPs considered in the model, assumed to be 20 GV, which is sufficiently high for SEPs. The fractional increase of the count rate of an NM station represents the ratio between the NM count rates due to SEPs and GCR averaged over two hours before the event onset. In our model we assume a modified power-law rigidity spectrum of SEPs similar to that of Cramp, Humble, and Duldig (1995), Cramp *et al.* (1997), Bombardieri *et al.* (2006), Vashenyuk *et al.* (2008):

$$J_{\parallel}(P) = J_0 P^{-(\gamma + \delta\gamma(P-1))}, \quad (2)$$

where J_{\parallel} is particle flux arriving from the Sun along the symmetry axis, whose direction is defined by the geographic coordinate angles Ψ and Λ , γ is the power-law spectral exponent at rigidity $P = 1$ GV, and $\delta\gamma$ is the rate of the spectrum steepening. The pitch angle distribution is assumed to be a Gaussian:

$$G(\alpha(P)) \sim \exp(-\alpha^2/\sigma^2), \quad (3)$$

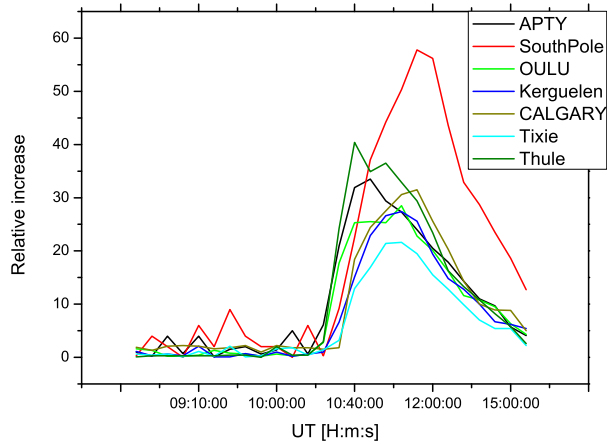
where α is the pitch angle, and σ is parameter corresponding to the width of the pitch angle distribution. The pitch angle is defined as the angle between the asymptotic direction and the axis of anisotropy. Therefore, according to Equations (1) to (3), six parameters have to be determined: J_0 , γ , $\delta\gamma$, Ψ , and Λ , σ .

To compute rigidity cut-offs and asymptotic directions of the allowed trajectories (Cooke *et al.*, 1991), we combined the International Geomagnetic Reference Field (IGRF) geomagnetic model (epoch 2010) as the internal field model (Langel, 1987) with the Tsyganenko 89 model as external field (Tsyganenko, 1989). This combination provides the most efficient computation of asymptotic directions and also a balance between simplicity and realism (Kudela and Usoskin, 2004; Kudela, Bučik, and Bobik, 2008; Nevalainen, Usoskin, and Mishev, 2013). All computations of the particle transport in the geomagnetic field were performed with the MAGNETOCOSMICS code (Desorgher *et al.*, 2005).

For the GCR spectrum we applied a parametrisation based on the force-field model (Gleeson and Axford, 1968; Caballero-Lopez and Moraal, 2004). Full details of the application of the model are given elsewhere (Usoskin *et al.*, 2005). The solar modulation parameter was taken from Usoskin, Bazilevskaya, and Kovaltsov (2011). To solve the inverse problem, we used the Levenberg–Marquardt algorithm (LMA) (Levenberg, 1944; Marquardt, 1963) with the Minpack code (More, Garbow, and Hillstom, 1980). The optimization was performed by minimizing the difference between the modelled NM responses and the measured NM responses, *i.e.* by optimizing the functional \mathcal{F} over the vector of unknowns and m NM stations:

$$\mathcal{F} = \sum_{i=1}^m \left[\left(\frac{\Delta N_i}{N_i} \right)_{\text{mod.}} - \left(\frac{\Delta N_i}{N_i} \right)_{\text{meas.}} \right]^2. \quad (4)$$

Figure 1 Profile of the time variation of Apatity, Calgary, Kerguelen, South Pole, Oulu, Thule, and Tixie NMs relative increase during GLE 59 on 14 July 2000.



3. Results of the Analysis

Sixteen GLEs in total were observed during Solar Cycle 23 (Andriopoulou *et al.*, 2011a,b; Gopalswamy *et al.*, 2012). The strongest event, namely GLE 69 on 20 January 2005, was analysed elsewhere (Vashenyuk *et al.*, 2006a; Plainaki *et al.*, 2007; Bombardieri *et al.*, 2008; Perez-Peraza *et al.*, 2008; Bütikofer *et al.*, 2009; Bieber *et al.*, 2013). Here we focus on two major events: GLE 59 on 14 July 2000, which is also known as the Bastille Day event, and GLE 70 on 13 December 2006.

3.1. The Bastille Day GLE 59 on 14 July 2000

The second decade of July 2000 was characterized by intense solar activity extending from 10 to 15 July. During this period, three X-class flares (including the Bastille Day flare) and two halo CMEs were produced (Dryer *et al.*, 2001). The GLE 59 event was related to the Bastille day X5.8/3B solar flare and the associated full-halo CME. It started at 10:03 UT, reached a peak at 10:24 UT, and ended at 10:43 UT (Klein *et al.*, 2001). Accordingly, the GLE onset began between 10:30 and 10:35 UT at several stations (Figure 1). The strongest NM increases were observed at the South Pole (58.3 %) and SANA (54.4 %) compared to pre-increase levels. In general, the event was characterized by a high anisotropy in its initial phase (Bieber *et al.*, 2002; Bombardieri *et al.*, 2006; Vashenyuk *et al.*, 2006b).

An illustration of several computed asymptotic cones used for our analysis is shown in Figure 2. The full list of NMs used in this analysis is given below (Table 3). The computations were carried out with the MAGNETOCOSMICS code using the geomagnetic models of Tsyganenko 1989 (external field model) and the International Geomagnetic Reference Field (IGRF) (internal field model), adjusted to the measured K_p index and 2000 epoch. Here we present the asymptotic directions in the rigidity range from 1 to 5 GV to demonstrate the range of the strongest response, while in the analysis we used the 1–20 GV rigidity range.

For the analysis we considered five-minute NM data retrieved from the GLE database (Usoskin *et al.*, 2015). The derived rigidity spectra with the anisotropy characteristics of the high-energy SEP are presented in Figure 3. During the event onset, SEPs had a hard rigidity spectrum and strong anisotropy, as was observed by NM stations with small pitch-angles.

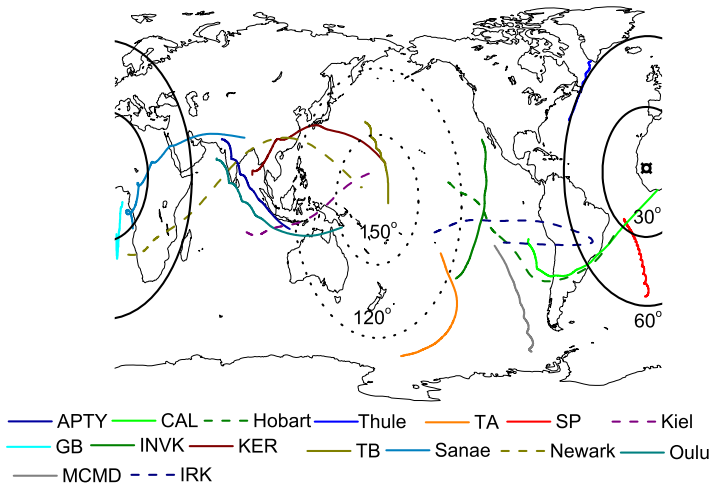


Figure 2 Calculated NM asymptotic directions during GLE 59 on 14 July 2000 at 10:30 UT. The small oval represents the derived apparent source position during the event onset. The lines of equal pitch angles relative to the derived anisotropy axis are plotted for 30°, 60°, 150°, and 120°. The asymptotic directions of polar NMs are plotted with solid lines, while mid-latitude NMs are plotted with dashed lines.

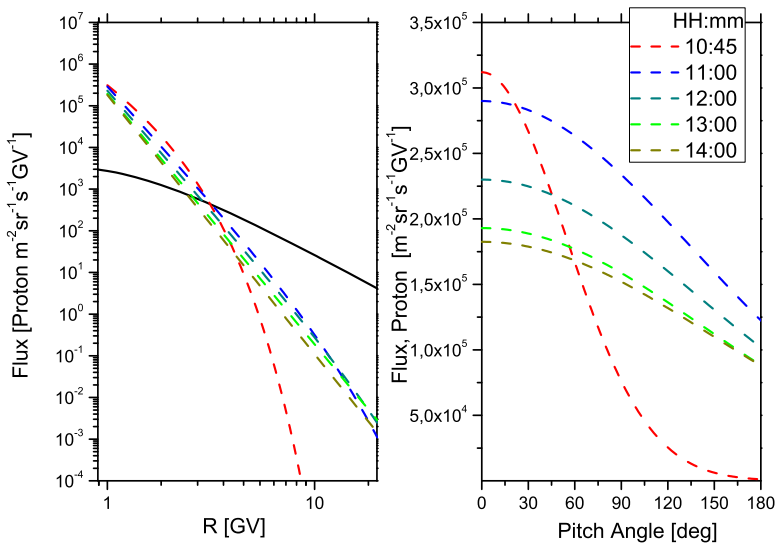


Figure 3 Derived rigidity spectra and pitch angle distributions of SEPs during GLE 59. The SEP flux $J_{||}$ is according to Equation (2) *i.e.* flux arriving from the Sun along the axis of symmetry. Time (UT) refers to the end of the corresponding five-minute interval. The solid line in the left panel denotes the GCR flux.

The left-hand panel of Figure 3 demonstrates the obtained rigidity spectrum during various stages of the event. The corresponding pitch angle distributions are presented in the right-hand panel of Figure 3. The rigidity spectrum gradually softened throughout the event. The steepening $\delta\gamma$ varied throughout the event. It resulted in a moderate steepening of the spectrum during the early phase and only a slight steepening during the late phase of the

Table 1 Derived spectral and angular characteristics for GLE 59 on 14 July 2000.

Integration interval [UT]	J_0 [$\text{m}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GV}^{-1}$]	γ	$\delta\gamma$	σ^2 [rad^2]	Ψ [degrees]	Λ [degrees]
10:35 – 10:40	273000	4.47	0.81	1.25	12.61	–6.31
10:40 – 10:45	312000	4.25	0.8	1.75	14.32	–8.02
10:45 – 10:50	340100	4.49	0.68	2.5	15.46	–14.32
10:50 – 10:55	328200	4.87	0.41	4.5	20.62	–14.89
10:55 – 11:00	290000	5.51	0.05	11.5	10.88	–12.65
11:25 – 11:30	272000	5.52	0.05	11.8	14.32	–16.04
11:55 – 12:00	230000	5.74	0.02	12.1	6.3	–21.19
12:25 – 12:30	195200	5.83	0.03	12.5	8.59	–23.49
12:55 – 13:00	193000	6.01	0.0	12.6	6.28	–25.78
13:25 – 13:30	187100	6.15	0.0	13.1	6.87	–29.22
13:55 – 14:00	182500	6.22	0.0	13.5	6.91	–32.65
14:55 – 15:00	178500	6.5	0.0	14.2	8.59	–35.52
15:55 – 16:00	165000	7.1	0.0	15.0	5.72	–38.39

event. Moreover, $\delta\gamma$ vanished after 13:00 UT so that the derived rigidity spectra can be described by a pure power law. The derived anisotropy was high during the event onset. It rapidly dropped to a low, relatively steady level so that the SEPs' angular distribution considerably broadened after the initial phase of the event. We can conclude that the event was isotropised very fast, leading to a nearly isotropic SEP flux after 11:00 UT. The derived spectral and anisotropy characteristics are summarized in Table 1.

The quality of the modelling is demonstrated by comparison between the modelled and observed responses of NMs during GLE 59. Here we present a comparison for several NM stations (Figure 4), but the quality of the fit is similar for the other NM stations. Since there is no dramatic change of the derived SEP characteristics after 11:00 UT (gradual softening of the rigidity spectrum and isotropic phase), the X axis (time) in Figure 4 is not uniform so that we can present detailed information for the whole event.

A detailed analysis of confidence limits of the derived model parameters is rather difficult because of strong non-linearity and complexity of the model and because the fit parameters are significantly correlated (Dennis and Schnabel, 1996; Aster, Borchers, and Thurber, 2005). We examine the squared difference between the observed and calculated increases. We achieve a relative difference smaller than 5 % between modelled and observed NM relative increases. We note that in the analysis we employed a natural initial guess similarly to Bombardieri *et al.* (2006), which was that the apparent source position is located along the interplanetary magnetic field (IMF) line derived from the ACE satellite measurements (otherwise the initial guess is similar to that of Cramp, Humble, and Duldig, 1995). According to our analysis, a small variation of the input (initial guess) does not alter the solution. When the initial guess is far from the local minimum (the LMA converges to the global minimum only if the initial guess is close to the final solution (Dennis and Schnabel, 1996)), the derived solution of the inverse problem possesses a greater residual than that with a natural initial guess, or it is not physical.

3.2. GLE 70 on 13 December 2006

The second event considered for analysis in this study is one of the strongest events of Solar Cycle 23. The month of December 2006 was at the declining phase of the solar cycle close

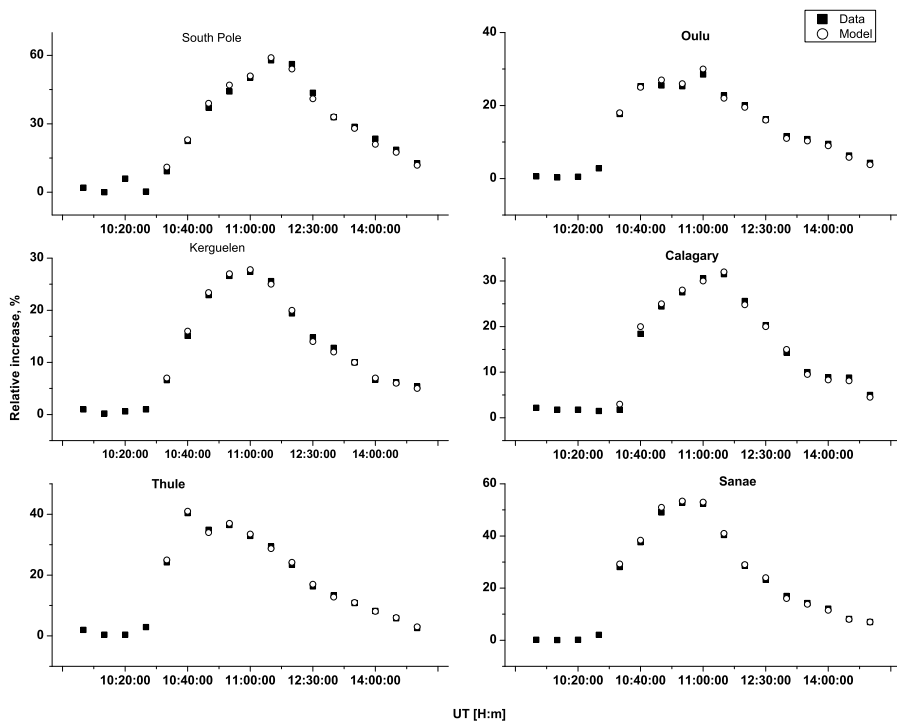


Figure 4 Modelled and observed responses of several NM stations during GLE 59 on 14 July 2000. The quality of the fit for other stations is of the same order.

to the minimum. However, on 13 December 2006, NOAA Active Region 10930, located at S06W26, triggered an X3.4/4 B solar flare that reached maximum at 2:40 UT. It was associated with Type II and Type IV radio bursts and a fast full-halo CME accompanied by a strong solar proton event (for details see *e.g.* Gopalswamy *et al.*, 2012; Moraal and McCracken, 2012, and references therein). The worldwide network of NMs recorded the event, with the maximum seen at Oulu NM ~ 90 % in the five-minute data (Figure 5). It was classified as GLE 70.

Similarly to some other events, it was characterized by a high anisotropy in the initial phase (Bütikofer *et al.*, 2009; Vashenyuk *et al.*, 2008; Plainaki *et al.*, 2009). Here for the analysis we consider five-minute NM data retrieved from the GLE database (Usoskin *et al.*, 2015). An illustration of several computed asymptotic cones of NMs used for the analysis is shown in Figure 6. The full list of NMs used in this analysis is given in Table 3. Similarly to the previous case, the computations were carried out with the MAGNETOCOSMICS code using the geomagnetic models of Tsyganenko 1989 (external field model) and IGRF (internal field model), adjusted to the measured K_p index and 2000 epoch. The derived rigidity spectra with the corresponding anisotropy characteristics are shown in Figure 7. During the event onset, SEPs had a hard spectrum and the strong anisotropy of a beam-like SEP flux, which have been observed by NM stations with small pitch-angles. As an example, Oulu and Barentsburg NMs showed very different responses despite their close geographic location and rigidity cut-offs. A summary of the derived spectral and angular characteristics for GLE 70 on 13 December 2006 and the NM integration period and apparent source position are given in Table 2.

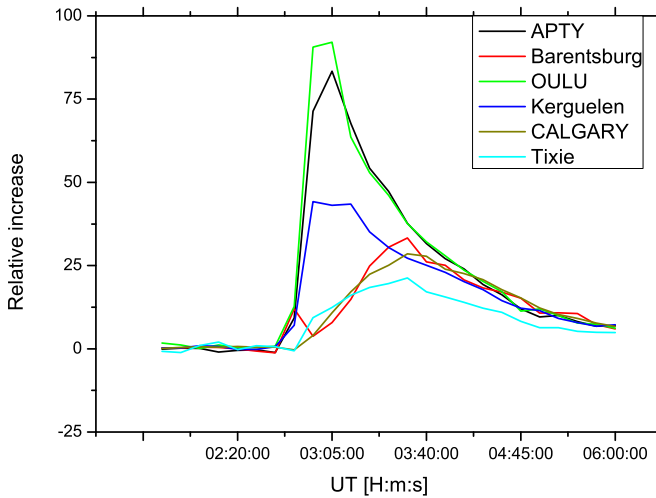


Figure 5 Time variation of ten-minute data in Apatity, Barentsburg, Calgary, Kerguelen, Oulu, and Tixie NMs relative increase during GLE 70 on 13 December 2006.

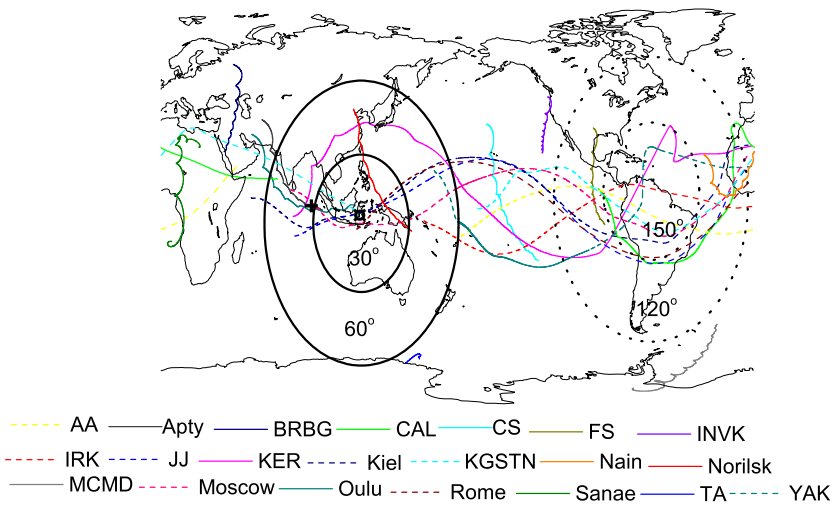


Figure 6 Calculated NM asymptotic directions during GLE 70 on 13 December 2006 at 03:00 UT. The cross represents the direction of the interplanetary magnetic field (IMF) derived from the ACE satellite measurements at 03:00 UT. The small oval represents the derived apparent source position. The lines of equal pitch angles relative to the derived anisotropy axis are plotted for 30°, 60°, 120°, and 150°. The asymptotic directions of polar NMs are plotted with solid lines, while mid-latitude NMs are plotted with dashed lines.

The quality of the modelling is demonstrated in Figure 8, where the model and observed responses of several NMs are compared. The quality of the fit is similar for the other NM stations. Similarly to Figure 4, the X axis (time) in Figure 8 is not uniform.

An analysis similar to the previous one shows an achieved largest relative difference of about 3–6 % between modelled and observed NM relative increases. The full list of NMs used for the analysis of both events is given in Table 3.

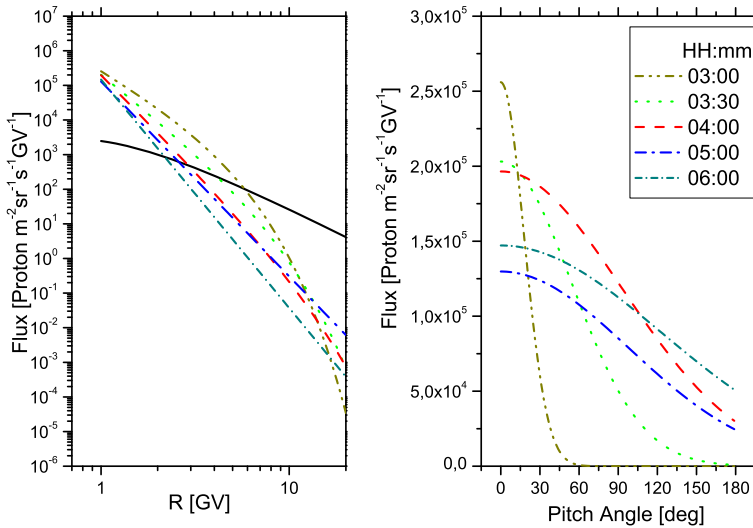


Figure 7 Derived rigidity spectra and pitch angle distributions of SEPs during GLE 70. The SEP flux is derived according to Equation (2), *i.e.* flux arriving from the Sun along the axis of symmetry. Time (UT) refers to the end of the corresponding five-minute interval. The solid line in the left panel denotes the GCR flux.

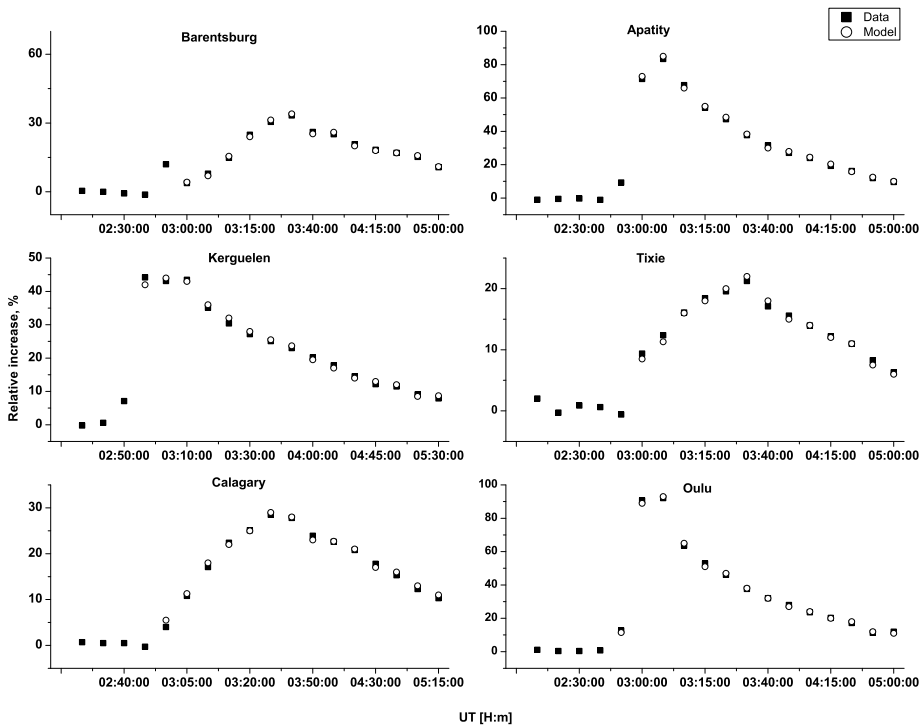


Figure 8 Modelled and observed responses of six NM stations during GLE70 on 13 December 2006. The quality of the modelled responses for other stations is of the same order.

Table 2 Derived spectral and angular characteristics for GLE 70 on 13 December 2006.

Integration interval [UT]	J_0 [$\text{m}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GV}^{-1}$]	γ	$\delta\gamma$	σ^2 [rad^2]	Ψ [degrees]	Λ [degrees]
03:00–03:05	256000	3.41	0.22	0.19	−17	148
03:05–03:10	356500	3.71	0.3	0.28	−16	154
03:10–03:15	216800	4.25	0.2	0.3	−14	145
03:15–03:20	206000	4.31	0.1	0.85	−13	160
03:20–03:25	205000	4.32	0.2	1.2	−13	137
03:25–03:30	203100	4.43	0.11	1.77	−11	131
03:30–03:35	200000	4.5	0.1	1.81	−10	126
03:35–03:40	200000	4.75	0.08	1.85	−10	128
03:40–03:45	204900	5.2	0.1	2.01	−7	122
03:45–03:50	202500	5.46	0.12	2.3	−5	120
03:50–03:55	201800	5.48	0.1	3.5	−5	117
03:55–04:00	196500	5.52	0.05	5.19	−1	120
04:10–04:15	185203	5.62	0.04	5.8	0.1	118
04:25–04:30	150000	5.69	0.001	5.68	5	115
04:40–04:45	135920	5.65	0	6.47	10	111
04:55–05:00	129800	5.63	0	5.87	13	110
05:10–05:15	145325	6.15	0	6.63	15	108
05:25–05:30	135320	6.12	0	6.68	14	107
05:40–05:45	125050	6.19	0	7.1	14	105
05:55–06:00	147150	6.6	0	9.2	15	95

4. Discussion and Conclusions

The two major events GLE 59 and GLE 70 considered for study in this work occurred at different solar activity conditions. They were also quite different in increase profiles. GLE 70 showed a very sharp impulsive-type increase, while GLE 59 had a wider time profile typical of gradual events. This feature may be explained by the position of the flare on the solar disk (Duldig *et al.*, 1995; Cramp *et al.*, 1997).

The events were characterized by relatively strong anisotropy during the initial phase, which decreased rapidly over the following 30 minutes for GLE 59 and in the following 50–60 minutes for GLE 70. The strong anisotropy of SEPs during both event onsets indicates focused transport conditions in the interplanetary medium. In addition, we studied the likelihood of bidirectional arrival of SEPs by modelling the NM response assuming a two-flux event and a complicated shape of pitch-angle distribution (see Mishev, Kocharov, and Usoskin, 2014) similarly to Vashenyuk *et al.* (2006a), who found a clear signature of bidirectional flux for GLE 69 on 20 January 2005. In this case study we found no evidence of particles arriving from other but sunward directions. The rapid increase of the NM response of stations in the anti-sunward direction such as Tixie for GLE 59 is most likely due to scattering processes (Bieber *et al.*, 2002).

The particle fluences (rigidity, time- and angle-integrated particle flux) of both events were compared (Figure 9a). The particle fluence during the Bastille Day event is greater than during the GLE 70 event. This is consistent with recent findings based on both satellite-borne and NM data analysis (Tylka and Dietrich, 2009). The fluence during the Bastille Day event was compared with recent estimations (Figure 9b) (Tylka and Dietrich, 2009). The observed

Table 3 Neutron monitors with corresponding geomagnetic rigidity cut-offs used in the analysis. The crosses (nulls) in the last columns denote NMs used (not used) for the analysis of the event.

Station	Latitude [deg]	Longitude [deg]	P_c [GV]	Altitude [m]	GLE 59	GLE 70
Alma Ata (AA)	43.25	76.92	6.67	3340	x	x
Apatity (Apty)	67.55	33.33	0.48	177	x	x
Barentsburg (BRBG)	78.03	14.13	0	70	0	x
Calgary (Cal)	51.08	245.87	1.04	1128	x	x
Cape Schmidt (CS)	68.92	180.53	0.41	0	0	x
Forth Smith (FS)	60.02	248.07	0.25	0	0	x
Goose Bay (GB)	23.27	299.60	0.52	46	x	0
Hermanus (HRMS)	−34.42	19.22	4.90	26	x	x
Hobart (HBRT)	−42.92	147.24	1.88	0	x	0
Inuvik (INVK)	68.35	226.28	0.16	21	x	x
Irkutsk (IRK)	52.58	104.02	3.23	435	x	x
Jungfraujoch (JJ)	46.55	7.98	4.46	3476	x	x
Kerguelen (Ker)	−49.35	70.25	1.01	33	x	x
Kiel	54.33	10.13	2.22	54	x	x
Kingston (KGSTN)	−42.99	147.29	1.75	65	x	x
Lomnický Štít (LS)	49.2	20.22	3.72	2634	x	x
Magadan (MAG)	60.12	151.02	1.84	220	x	x
Mawson (MWSN)	−67.60	62.88	0.22	0	x	x
McMurdo (MCMD)	−77.85	166.72	0	48	x	x
Moscow (MOS)	55.47	37.32	2.13	200	x	x
Nain	56.55	298.32	0.28	0	0	x
Newark (NWRK)	39.70	284.30	1.97	50	x	0
Norilsk	69.26	88.05	0.52	0	0	x
Oulu	65.05	25.47	0.69	15	x	x
Peawanuck (PWNC)	54.98	274.56	0.16	52	0	x
Rome	41.86	12.47	6.19	60	0	x
Sanae	−71.67	357.15	0.56	856	x	0
South Pole (SP)	−90.00	0.0	0	2820	x	0
Terre Adelie (TA)	−66.67	140.02	0	45	x	x
Thule	76.60	291.2	0.1	260	x	0
Tixie (TB)	71.60	128.90	0.53	0	x	x
Yakutsk (YAK)	62.03	129.73	1.64	105	x	x

discrepancy is most likely due to different reconstruction methods and model assumptions. In Tylka and Dietrich (2009) a simplified analysis of NM data was used and a different spectral shape, namely a band function, was employed.

A reasonable agreement was achieved for the GLE 70 event (Figure 9c). In addition, Figure 9c compares the particle fluence using the reconstructions by Vashenyuk *et al.* (2008), where a discrepancy in particle fluence is observed, but not in the derived rigidity spectra.

We performed a detailed modelling of spectral and angular characteristics of high-energy SEPs in the vicinity of Earth during the Bastille Day 2000 (GLE 59) event and GLE 70 on 13 December 2006. The derived characteristics during the GLEs are useful for further

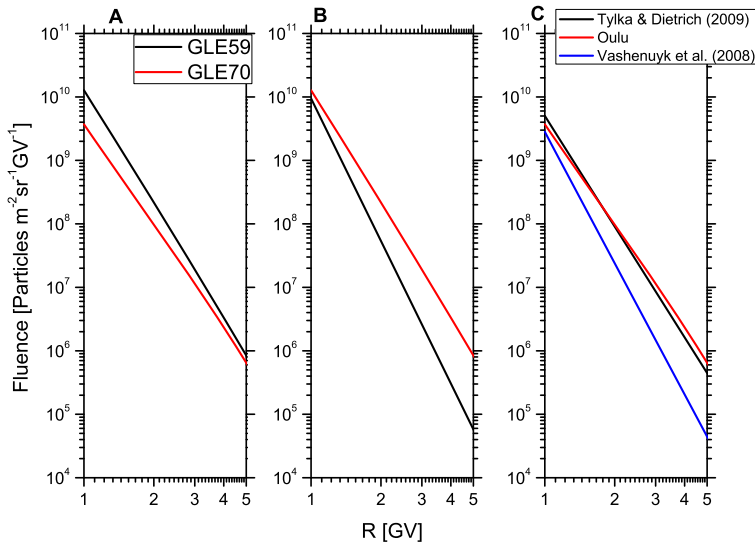


Figure 9 (a) Computed fluence of SEPs during GLE 59 on 14 July 2000 and GLE 70 on 13 December 2006 as denoted in the legend in panel A. The SEPs fluence is time- and angle-integrated throughout the event(s). (b) Computed fluence of SEPs during GLE 59 on 14 July 2000 compared with previous estimations (Tylka and Dietrich, 2009) as denoted in the legend in panel C. (c) Computed fluence of SEPs during GLE 70 on 13 December 2006 compared with previous estimations (Vashenyuk *et al.*, 2008; Tylka and Dietrich, 2009) as denoted in the legend in panel C.

space-weather and space-climate applications. The results presented in this work are a good basis for thorough studies related to changes in the Earth's polar atmosphere through enhanced ionization, similarly to *e.g.* Bazilevskaya *et al.* (2008); Usoskin *et al.* (2011); Žigman, Kudela, and Grubor (2014); Mishev and Velinov (2015).

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