Upgrade of GLE database: assessment of effective dose rate at flight altitude

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Abstract

A new database for assessment of radiation doses in the Earth atmosphere, related to GLE events is created under VarSiTi/SCOSTEP support and incorporated to the International ground level enhancement (GLE) database (`gle.oulu.fi`). The upgraded database provides, for each GLE event, where possible, information on the estimated energy/rigidity spectra of solar energetic particles and the corresponding computed effective doses at cruise flight altitude of 35 kft (10668 m above sea level). The computations are performed for various reconstructions of solar energetic particles spectra, available in literature, thus for some events there are several results. Computations were performed using a recent model for assessment of effective dose due to cosmic ray particles, applied specifically in the polar region, where the exposure is maximal. This upgrade allows one to estimate the radiation effects at cruise flight altitude caused by major GLE events over several decades.

Key words: Solar energetic particles, GLE events, GLE database, radiation environment

1 Introduction

The assessment of aircrew exposure to radiation due to cosmic rays (CRs), specifically during ground level enhancement (GLE) events is an important

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topic in the field of space weather (e.g. Baker, 1998; Lilensten and Bornarel, 2009; Vainio et al., 2009, and references therein). **Thus, several recommendations and regulations appeared, where the exposure of flying personnel to the cosmic radiation is recommended to be regarded as an occupational (ICRP, 1991, 2007). Accordingly in EU, it was suggested to assess the individual accumulated doses of cockpit and cabin crew (EURATOM, 1996, 2013).**

The assessment of the radiation exposure at typical flight altitudes due to CR of galactic and/or solar origin is not a simple task, because it depends on a geographic position and altitude (the intensity and energy distribution of the secondary CR particles), solar activity, geomagnetic conditions as well as on the eventual occurrence of solar energetic particle (SEP) events (Spurny et al., 1996, 2002; Shea and Smart, 2000). Moreover, the latter posses random occurrence and large variability. It is known that the main source of particles determining the radiation field at flight altitudes are CRs, specifically those originating from the Galaxy (e.g. O'Brien, 1970). According to the current knowledge, the majority of CRs originate from the Galaxy, the bulk are protons and $\alpha-$ particles with small abundance of heavier nuclei (e.g. Gaisser and Stanev, 2010, and references therein). Primary energetic CR particles enter in the atmosphere, collide with nuclei of the ambient air and produce certain number of secondary particles, which are eventually stopped and/or also collide, thus leading to the development of an extensive air shower. Occasionally, the Sun emits high energy particles (e.g. Reames, 2013; Klein and Dalla, 2017, and references therein). In some cases the energy of SEPs is GeV/nucleon, which is enough to produce an atmospheric shower registered by ground based detectors, specifically neutron monitors (NMs), an event known as GLE (e.g. Shea and Smart, 1982; Desai and Giacalone, 2016). **A developed over the years database provides information of NM count rates around the globe during GLEs. It was developed by the research community e.g. L. Gentile, M. Shea and D. Smart, M. Duldig, presently hosted by the University of Oulu.**

Both, GCR and SEPs, producing large diversity of secondary particles, determine the complex radiation field at flight altitudes. It is obvious that GLE events could enhance considerably the radiation exposure at flight altitudes (e.g. Spurny et al., 2002). Besides, GLE events differ from each other in spectra, angular distribution and duration as well as dynamics of characteristics governing the radiation exposure (Gopalswamy et al., 2012; Moraal and McCracken, 2012). **Therefore, the assessment of the radiation exposure of aircrew due to SEP event is normally performed retrospectively on the basis of retrieved information form ground based detectors, e.g. NMs or rarely from in-situ measurements (e.g. Spurny and Dachev, 2001; Getley, 2004).**

In order to assess the radiation exposure hazard due to CRs, specifically during GLE events, it is necessary to possess precise and correct information about their energy and angular distribution. **It was recently shown that the radiation exposure at aviation altitudes can be estimated using Monte Carlo simulations and/or transport models. As a result several models appeared (e.g. Ferrari et al., 2001; Getley et al., 2005a; Sato et al., 2008; Matthiä et al., 2008; Latocha et al., 2009; Mertens et al., 2013; Al Anid et al., 2014; Kataoka et al., 2014; Mishev et al., 2014a; Copeland, 2017; Hands et al., 2017) and good agreement between several models is observed (Bottollier-Depois et al., 2009). Here we compute the effective dose rate during several GLE events, where the information is available, at cruise flight altitude of 35 kft (10668 m) in a region with low cut-off rigidity, namely with $R_c < 1$ GV. For the computations we employed a recently proposed model for computation of effective dose (Mishev and Usoskin, 2015).**

2 Model for computation of effective dose rate at aviation altitudes

Herein, we employed numerical model for computation of effective dose at aviation altitudes. The full description of the model with the corresponding look-up tables and comparison with reference data is given elsewhere (Mishev and Usoskin, 2015).

The model is based on pre-computed effective dose yield functions, the latter is the response in the sense of effective dose, to the mono-energetic unit flux of primary particle entering the Earth's atmosphere, derived with high statistics Monte Carlo simulations. The effective dose rate at a given atmospheric depth h induced by primary CR particles is computed using the expression:

$$E(h, R_c, \theta, \varphi) = \sum_i \int_{E_{cut,i}(R_c)}^{\infty} \int_{\Omega} J_i(T')Y_i(T', h)d\Omega dT', \tag{1}$$

where h is the altitude above sea level, R_c is the local cut-off rigidity, θ and φ are the angles of incidence of the arriving particle, $J_i(T')$ is the differential energy spectrum of the primary CR arriving at the top of the atmosphere for i component (proton and/or $\alpha-$particle) and Y_i is the effective dose yield function for the corresponding primary CR component. In Eq. (1) the integration is over the kinetic energy above $E_{cut}(R_c)$, which is defined by the local cut-off rigidity R_c for a nuclei of type i at a given geographic location by the

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expression:

$$E_{cut,i} = \sqrt{\left(\frac{Z_i}{A_i}\right)^2 R_c^2 + E_0^2} - E_0 \qquad (2)$$

where $E_0 = 0.938$ GeV/c^2 is the proton's rest mass.

Accordingly, the yield function Y_i is defined as

$$Y_i(T',h) = \sum_j \int_{T^*} F_{i,j}(h,T',T^*,\theta,\varphi)C_j(T^*)dT^* \qquad (3)$$

where $C_j(T^*)$ is the fluence to effective dose conversion coefficient for a secondary particle of type j (neutron, proton, γ, e^-, e^+, μ^-, μ^+, π^-, π^+) with energy T^*, $F_{i,j}(h,T',T^*,\theta,\varphi)$ is the secondary particle fluence of type j, produced by a primary particle of type i (proton and/or $\alpha-$particle) with a given primary energy T'. The conversion coefficients $C_j(T^*)$ are considered according to Petoussi-Henss et al. (2010).

For GCR Eq.1–3 lead to

$$E = 4\pi^2 \left[\int_{E_{cut}}^{\infty} J_p(T')Y_p(T')dT' + \int_{E_{cut}}^{\infty} J_\alpha(T')Y_\alpha(T')dT' \right]. \qquad (4)$$

The latter equation possess two integral terms, first describing the contribution of CR protons, while the second accounts $\alpha-$particles and includes also heavier nuclei similarly to Usoskin and Kovaltsov (2006); Mishev and Velinov (2011). In case of GLE events, the effective dose is a superposition of GCR contribution (both integrands of Eq.4) and SEPs, the latter is computed using only the first term in Eq.4, assuming the corresponding SEP spectra. Note, that here we consider GLE spectra derived mostly on the basis of NM records (Table 1), the latter being an integral detector and not providing information about the mass composition. For GCRs we employ the force field model (Gleeson and Axford, 1968; Burger et al., 2000; Usoskin et al. , 2005) with the corresponding parametrization of local interstellar spectrum according to Usoskin and Kovaltsov (2006).

The differential intensity $J_i(T')$ of cosmic ray nuclei of type i at 1 AU is given as

$$J_i(T',\phi) = J_{LIS,j}(T' + \Phi_j)\frac{(T')(T' + 2T_r)}{(T' + \Phi_j)(T' + \Phi_j + 2T_r)} \qquad (5)$$

where T' is the kinetic energy per nucleon of primary CR with charge Z and atomic mass A and $\Phi_i = (Z_i e/A_i)\phi$. The only parameter of this model is the modulation potential ϕ given in units of MV, which explicitly accounts the solar activity. Herein, the modulation potential is considered according to Usoskin et al. (2011). The flux of incoming particles is assumed to be isotropic, which is conservative approach for GLE particles in sense of radiation exposure.

3 Assessment of effective dose rate at aviation altitude during GLEs

There are 72 GLE events so far, the last recorded by the global NM network on 10 September 2017. **Their occurrence rate is roughly one per year (Shea and Smart, 1990; Stoker, 1995; Gopalswamy et al., 2012). Here we compute the effective dose rate for each GLE event, where possible, using various sets of derived energy/rigidity spectra and employing the model described in Section 2. The computations are performed for illustration, at typical cruise flight altitude of 35 kft (10668 m), which can be used as a reference, and in a region with low cut-off rigidity $R_c < 1$ GV, where the radiation exposure is maximal.** The results are shown for various reconstructions of SEPs spectra, available in literature, thus for some events there are several results. The full list of the events considered in this study with the corresponding bibliography is given in Table 1.

The assessed effective dose rate varies from several μSv.h^{-1}, with small contribution of SEPs to tens and/or hundreds μSv.h^{-1}. During the strongest recorded events (e.g. GLE 5 and GLE 69) the estimated dose rate is about a 1–3.5 mSv.h^{-1} (Table 2). Therefore, during the strongest events it would be possible to receive over one hour flight in the polar region, an exposure comparable to the annual recommended for the population (EURATOM, 2013). The described computations are released as a new database for assessment of radiation exposure in the Earth atmosphere, related to GLE events, which is supplementary and now linked to the International GLE database `gle.oulu.fi` (Usoskin et al., 2015). Hence, the new database provides, for each GLE event, where possible, an illustrative information for the energy/rigidity spectra of solar energetic particles and the corresponding computed effective doses for several periods of the event. Examples are shown for GLE 59 (Fig.1), GLE 60 (Fig.2) and GLE 70 (Fig.3). One can see that for GLE 59 are three different sets of derived spectra (the references given at the bottom), resulting on three different sets of computed effective dose.

An example of the used SEP spectra is given in Fig.4a, which corresponds to set 3 (Mishev and Usoskin, 2016), accordingly Fig.4b, which corresponds to set 1 (Bombardieri et al., 2006). For GLE 60, there is only one set of SEP spectra (Fig. 5) (Bombardieri et al., 2007), while for GLE 70 (Fig.3) there are five different sets. An example for the used SEP spectra in the latter case is given in Fig.6a (set 4) and Fig.6b (set 3). The hardest SEP spectra resulting on a maximum peak exposure during GLE 69 are shown in Fig. 7 (Bombardieri et al., 2008). For several events is given the time interval over the spectra are integrated, e.g. set 3 (Fig.4a) for GLE 59 (Fig. 1). When the time interval is uncertain or not available, the interval end is not given. For all events is also computed the contribution of GCRs to the effective dose using the corresponding modulation potential, without considering possible Forbush decrease, which can be neglected during GLEs as a conservative approach. Details of the peak effective dose rates, contribution of GCRs to the exposure and the corresponding modulation potential are given in Table 2. Note, that the computed effective doses differ from each other for the same event assuming different derived spectra as reported in Bütikofer and Flückiger (2013, 2015). This is due to differences in GLE reconstructions, specifically the particle intensity as well as rigidity and spectral shapes. A detailed study of the impact of various sets of SEP spectra within one event on radiation exposure at flight altitude is beyond the scope of this work. The full list of computations is available in `http://gle.oulu.fi/#/dose`.

4   Discussion and Summary

During strong GLE events, passengers and aircrew may receive radiation exposure doses above the background level due to GCR. Therefore, since the exposure of flying personnel to cosmic radiation is regarded as occupational, it should be assessed and monitored. While the background radiation at aviation altitudes could be routinely monitored nowadays and/or easy to assess by computations and/or using data sets with corresponding measurements, the estimation of radiation doses due to SEPs poses a significant challenge because of their random occurrence and large variability. **Normally it is assessed retrospectively, when the necessary GLE particles characteristics are available. Obviously a systemic study of the radiation exposure during GLE events is necessary, specifically at polar region where it would be maximal.**

Herein, we performed computations using a recent model for assessment of effective dose due to CRs at aviation altitude, we esti-

mated the radiation exposure during GLE events and created the corresponding database. During the computations a conservative approach of SEPs angular distribution is assumed, namely an isotropic. The mass composition of SEPs is assumed to be protons. The contribution of heavier nuclei can be assessed, when the appropriate information about SEP mass composition is available, similarly to Xapsos et al. (2007). However, taking into account the typical mass composition of SEPs and their energy range, the contribution of heavier than proton particles to the radiation exposure at flight altitudes can be quantitatively considered as marginal.

The new database is now linked to the existing GLE database `http://gle.oulu.fi/#/dose`. The database will be kept updated when new events occur and/or new information for historical events is retrieved as well as improvement of the model computations. Hence, the new database provides, for each observed GLE event where data are available, information on the spectral properties of SEPs and the corresponding effective doses at typical cruise altitude of 35 kft. This allows one to estimate the radiation effects during GLE events over several solar cycles and give good basis for subsequent comparison between models and measurements (Getley et al., 2005b; Beck et al., 2006; Ploc et al., 2013). A more detailed computation, namely at several flight altitudes, time intervals, considering anisotropy affects is planified as forthcoming work.

5   Acknowledgements

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Table 1

List of GLE events used for the upgrade of the GLE database `gle.oulu.fi` with the corresponding date and bibliography.

GLE	Date	Bibliography
5	23.02 1956	(Belov et al., 2005; Vashenyuk et al., 2008, 2011)
8	04.05 1960	(Deeley et al., 2002; Vashenyuk et al., 2011)
10	12.11 1960	(Vashenyuk et al., 2011)
11	15.11 1960	(Vashenyuk et al., 2011)
13	18.07 1961	(Vashenyuk et al., 2011)
16	28.01 1967	(Vashenyuk et al., 2011)
19	18.11 1968	(Vashenyuk et al., 2011)
22	14.01 1971	(Vashenyuk et al., 2011)
25	07.08 1972	(Vashenyuk et al., 2011)
29	24.09 1977	(Vashenyuk et al., 2011)
30	22.11 1977	(Debrunner et al., 1984; Vashenyuk et al., 2011)
31	07.05 1978	(Debrunner and Lockwood, 1980; Debrunner et al., 1984; Lockwood et al., 1990; Vashenyuk et al., 2006b, 2011)
32	23.09 1978	(Vashenyuk et al., 2011)
38	08.12 1982	(Cramp et al., 1997b; Vashenyuk et al., 2006b, 2011)
39	16.02 1984	(Vashenyuk et al., 2006b, 2011)
41	16.08 1989	(Vashenyuk et al., 2011)
42	29.09 1989	(Humble et al., 1991; Cramp et al., 1993; Vashenyuk et al., 2006b, 2011)
43	19.10 1989	(Bieber and Evenson, 1991; Vashenyuk et al., 2006b, 2011)
44	22.10 1989	(Cramp et al., 1997a; Vashenyuk et al., 2006b, 2011)
45	24.10 1989	(Cramp et al., 1995; Lovell et al., 1998; Vashenyuk et al., 2011)
47	21.05 1990	(Vashenyuk et al., 2011)
48	24.05 1990	(Vashenyuk et al., 2011)
51	11.06 1991	(Smart and Shea, 1994; Vashenyuk et al., 2011)
52	15.06 1991	(Smart et al., 1993; Vashenyuk et al., 2011)
55	06.11 1997	(Lovell et al., 2002; Vashenyuk et al., 2011; Kravtsova and Sdobnov, 2016)
59	14.07 2000	(Bombardieri et al., 2006; Vashenyuk et al., 2006b, 2011; Mishev and Usoskin, 2016)
60	15.04 2001	(Bombardieri et al., 2007; Vashenyuk et al., 2006b, 2011)
61	18.04 2001	(Vashenyuk et al., 2011)
65	28.10 2003	(Miroshnichenko et al., 2005; Vashenyuk et al., 2006b, 2011)
67	02.11 2003	(Vashenyuk et al., 2006b, 2011; Kocharov et al., 2017)
69	20.01 2005	(Vashenyuk et al., 2006b,a; Bombardieri et al., 2008; Bütikofer et al., 2009)
		(Matthiä et al., 2009a; Vashenyuk et al., 2011; Bieber et al., 2013)
70	13.12 2006	(Bütikofer et al., 2009; Matthiä et al., 2009b; Vashenyuk et al., 2011; Mishev and Usoskin, 2016),(nmdb.eu)
71	17.05 2012	(Mishev et al., 2014b; Plainaki et al., 2014),(nmdb.eu)

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Table 2
GLE events, peak effective dose rate and contribution of GCRs to the exposure with the corresponding modulation potential.

GLE	Date	max. E [μSv.h^{-1}]	E_{GCR} [μSv.h^{-1}]	Modulation potential [MV]
5	23.02 1956	2977	6.9	551
8	04.05 1960	57.3	5.0	1109
10	12.11 1960	12.1	5.2	1024
11	15.11 1960	140.5	5.2	1024
13	18.07 1961	13.7	5.4	956
16	28.01 1967	15.8	6.4	632
19	18.11 1968	11.4	5.3	985
22	14.01 1971	25.1	6.2	717
25	07.08 1972	7.8	6.4	636
29	24.09 1977	8.8	7.3	475
30	22.11 1977	15.5	7.7	408
31	07.05 1978	35.4	6.4	669
32	23.09 1978	8.1	7.2	495
38	08.12 1982	22.4	4.7	1256
39	16.02 1984	13.5	6.1	736
41	16.08 1989	10.8	5.0	1114
42	29.09 1989	92.7	4.8	1195
43	19.10 1989	41.9	4.5	1356
44	22.10 1989	92.5	4.5	1356
45	24.10 1989	61.0	4.5	1356
47	21.05 1990	12.0	4.3	1452
48	24.05 1990	17.0	4.3	1452
51	11.06 1991	6.0	3.5	2016
52	15.06 1991	11.2	3.5	2016
55	06.11 1997	19.9	7.5	439
59	14.07 2000	48.1	4.9	1167
60	15.04 2001	51.3	5.3	995
61	18.04 2001	9.0	5.3	995
65	28.10 2003	12.4	5.4	963
67	02.11 2003	15.6	4.6	1281
69	20.01 2005	3592	5.9	788
70	13.12 2006	78.2	7.4	467
71	17.05 2012	32.9	7.2	494

Figure captions:

Fig.1 Screen shot of the stored information about GLE 59 on 14 July 2000 in `http://gle.oulu.fi/#/dose`, namely the computed radiation doses at the cruise flight altitude of 35 kft (10668 m) for several different sets of derived spectra and the used bibliography. The numbering of the sets corresponds to the used references given on the bottom.

Fig.2 Screen shot of the stored information about GLE 60 on 15 April 2001 in `http://gle.oulu.fi/#/dose`, namely the computed radiation doses at the cruise flight altitude of 35 kft (10668 m) and the used bibliography (on the bottom).

Fig.3 Screen shot of the stored information about GLE 70 on 13 December 2006 in `http://gle.oulu.fi/#/dose`, namely the computed radiation doses at the cruise flight altitude of 35 kft (10668 m) for several different sets of derived spectra and the used bibliography. The numbering of the sets corresponds to the used references given on the bottom.

Fig.4 SEP spectra used for computation of radiation doses at the cruise flight altitude of 35 kft (10668 m) during GLE 59 on 14 July 2000. Panel A corresponds to set 3, while panel B corresponds to set 1.

Fig.5 SEP spectra used for computation of radiation doses at the cruise flight altitude of 35 kft (10668 m) during GLE 60 on 15 April 2001.

Fig.6 SEP spectra used for computation of radiation doses at the cruise flight altitude of 35 kft (10668 m) during GLE 70 on 13 December 2006. Panel A corresponds to set 4, while panel B corresponds to set 3.

Fig.7 Hardest SEP spectra used for computation of radiation doses at the cruise flight altitude of 35 kft (10668 m) during GLE 59 on 20 January 2005. The spectra correspond to set 2 in the database.

GLE database

Display ○ GLE data, ○ availability grid ◉ or Effective dose rate

Select a GLE:

#59 — 2000-07-14

GLE: 59 at 2000-07-14

Modulation potential **1167** MV. Altitude **35** kft. GCR contribution **4.86** μSv h⁻¹.

Effective dose rate, series # 1

Interval start [UTC]	Interval end [UTC]	Effective dose rate [μSv h⁻¹]
2000-07-14 10:30:00	N/A	6.94
2000-07-14 11:50:00	N/A	48.16
2000-07-14 14:00:00	N/A	14.53

Effective dose rate, series # 2

Interval start [UTC]	Interval end [UTC]	Effective dose rate [μSv h⁻¹]
2000-07-14 11:05:00	N/A	4.87
2000-07-14 12:00:00	N/A	5.48
2000-07-14 14:10:00	N/A	6.43
2000-07-14 14:40:00	N/A	7.45
2000-07-14 16:00:00	N/A	6.27

Effective dose rate, series # 3

Interval start [UTC]	Interval end [UTC]	Effective dose rate [μSv h⁻¹]
2000-07-14 10:35:00	2000-07-14 10:40:00	18.51
2000-07-14 10:45:00	2000-07-14 10:50:00	22.68
2000-07-14 11:55:00	2000-07-14 12:00:00	14.92
2000-07-14 15:55:00	2000-07-14 16:00:00	9.47

References

[1] RELATIVISTIC PROTON PRODUCTION DURING THE 2000 JULY 14 SOLAR EVENT: THE CASE FOR MULTIPLE SOURCE MECHANISMS (Bombardieri)
[2] Relativistic Solar proton Dynamics in Large GLE of 23rd Solar Cycle (Vashenyuk)
[3] Analysis of the Ground-Level Enhancements on 14 July 2000 and 13 December 2006 Using Neutron Monitor Data (Mishev)

Fig. 1. Screen shot of the stored information about GLE 59 on 14 July 2000 in `http://gle.oulu.fi/#/dose`, namely the computed radiation doses at the cruise flight altitude of 35 kft (10668 m) for several different sets of derived spectra and the used bibliography. The numbering of the sets corresponds to the used references given on the bottom.

Fig. 2. Screen shot of the stored information about GLE 60 on 15 April 2001 in `http://gle.oulu.fi/#/dose`, namely the computed radiation doses at the cruise flight altitude of 35 kft (10668 m) and the used bibliography (on the bottom).

GLE database

Display ○ **GLE data,** ○ **availability grid** ● **or Effective dose rate**

Select a GLE:

[#70 − 2006-12-13 ▾]

GLE: 70 at 2006-12-13

Modulation potential **467** MV. Altitude **35** kft. GCR contribution **7.36** μSv h^{-1}.

Effective dose rate, series # 1

Interval start [UTC]	Interval end [UTC]	Effective dose rate [μSv h^{-1}]
2006-12-13 02:58:00	N/A	40.34
2006-12-13 03:38:00	N/A	19.58
2006-12-13 04:38:00	N/A	13.65
2006-12-13 06:38:00	N/A	9.41

Effective dose rate, series # 2

Interval start [UTC]	Interval end [UTC]	Effective dose rate [μSv h^{-1}]
2006-12-13 02:57:00	N/A	21.84
2006-12-13 03:20:00	N/A	67.3
2006-12-13 04:00:00	N/A	78.16

Effective dose rate, series # 3

Interval start [UTC]	Interval end [UTC]	Effective dose rate [μSv h^{-1}]
2006-12-13 03:00:00	N/A	17.55
2006-12-13 04:30:00	N/A	21.98
2006-12-13 05:30:00	N/A	4.43

Effective dose rate, series # 4

Interval start [UTC]	Interval end [UTC]	Effective dose rate [μSv h^{-1}]
2006-12-13 03:00:00	2006-12-13 03:05:00	42.14
2006-12-13 03:05:00	2006-12-13 03:10:00	43.54
2006-12-13 03:35:00	2006-12-13 03:40:00	14.37
2006-12-13 05:55:00	2006-12-13 06:00:00	9.4

Effective dose rate, series # 5

Interval start [UTC]	Interval end [UTC]	Effective dose rate [μSv h^{-1}]
2006-12-13 00:00:00	N/A	52.02

References

[1] THE GROUND LEVEL EVENT 70 ON DECEMBER 13TH, 2006 AND RELATED EFFECTIVE DOSES ATAVIATION ALTITUDES (Matthia)
[2] The GLE of December 13, 2006 according to the ground level and balloon observations (Vashenyuk)
[3] pgia.ru
[4] Analysis of the Ground-Level Enhancements on 14 July 2000 and 13 December 2006 Using Neutron Monitor Data (Mishev)
[5] The solar cosmic ray ground-level enhancements on 20 January 2005 and 13 December 2006 (Butikofer)

Fig. 3. Screen shot of the stored information about GLE 70 on 13 December 2006 in `http://gle.oulu.fi/#/dose`, namely the computed radiation doses at the cruise flight altitude of 35 kft (10668 m) for several different sets of derived spectra and the used bibliography. The numbering of the sets corresponds to the used references given on the bottom.
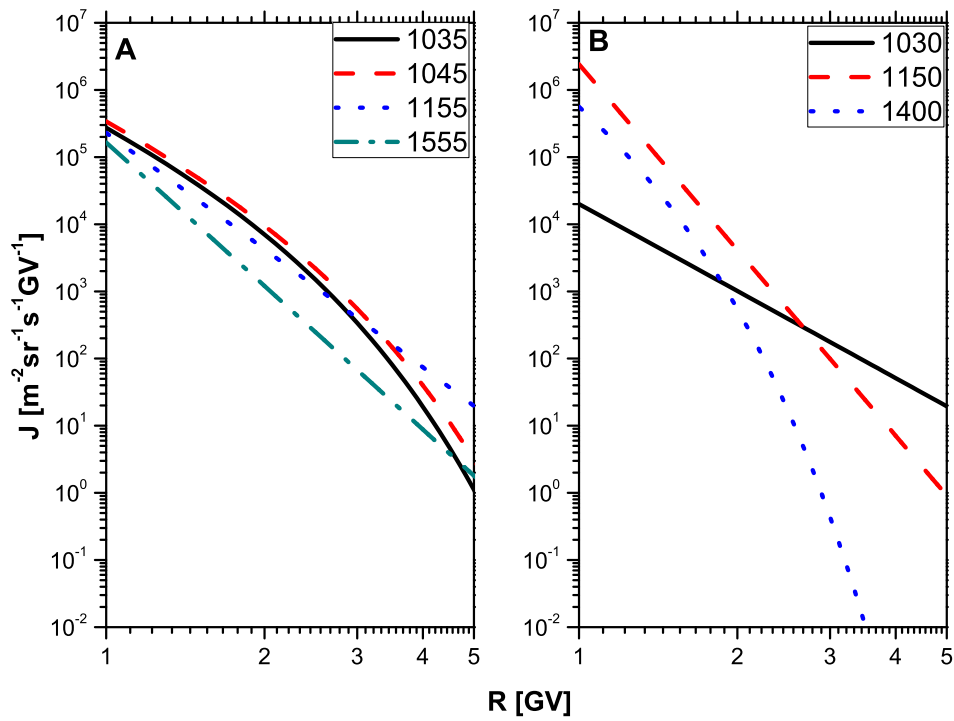
Fig. 4. SEP spectra used for computation of radiation doses at the cruise flight altitude of 35 kft (10668 m) during GLE 59 on 14 July 2000. Panel A corresponds to set 3, while panel B corresponds to set 1.
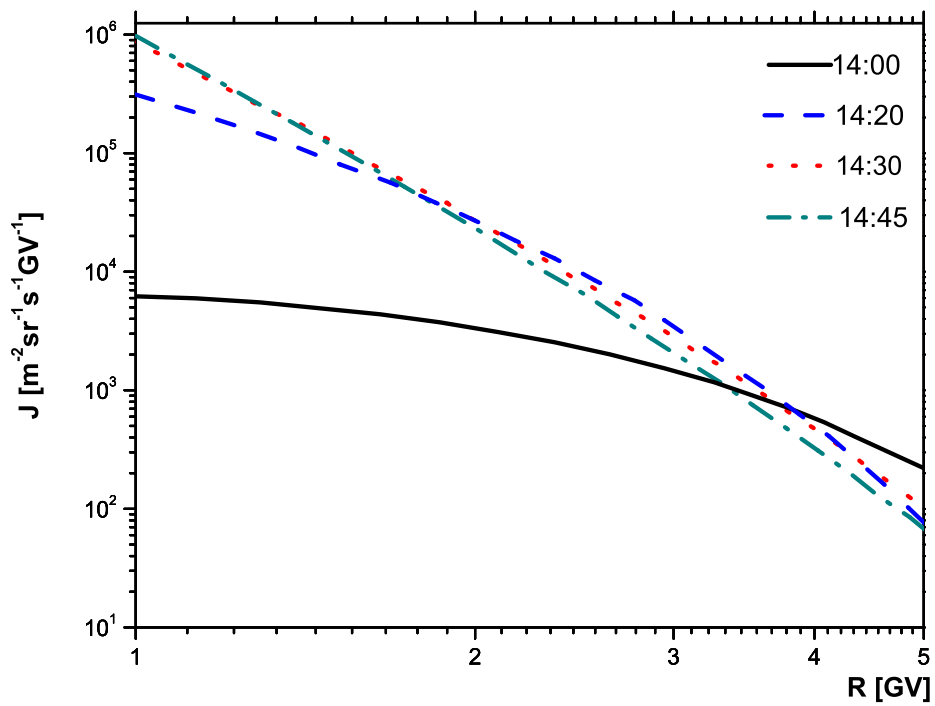
Fig. 5. SEP spectra used for computation of radiation doses at the cruise flight altitude of 35 kft (10668 m) during GLE 60 on 15 April 2001.
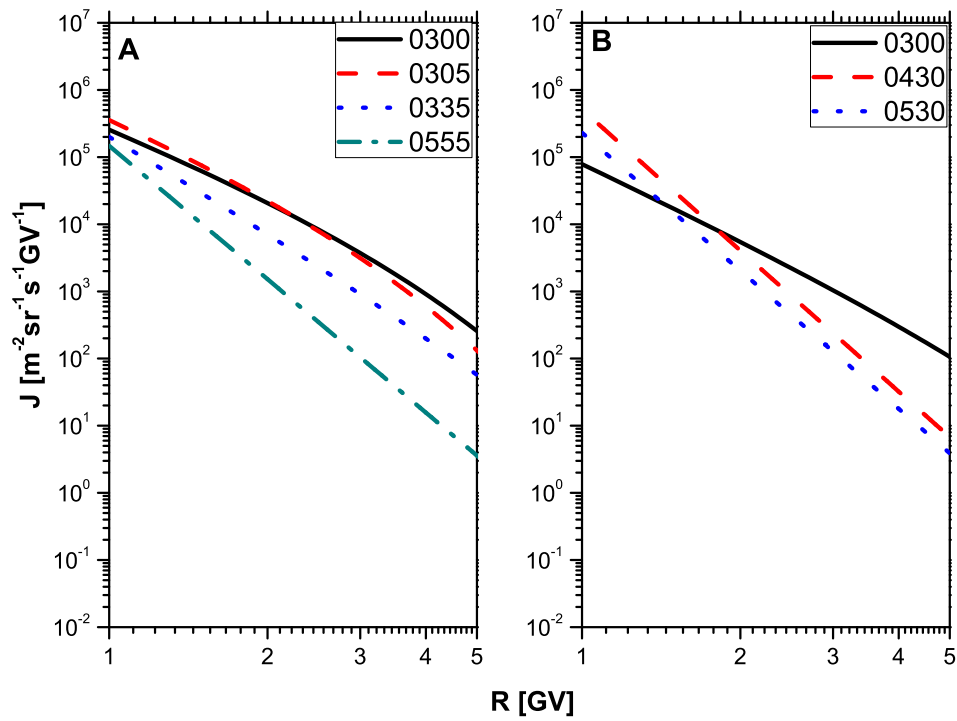
Fig. 6. SEP spectra used for computation of radiation doses at the cruise flight altitude of 35 kft (10668 m) during GLE 70 on 13 December 2006. Panel A corresponds to set 4, while panel B corresponds to set 3.
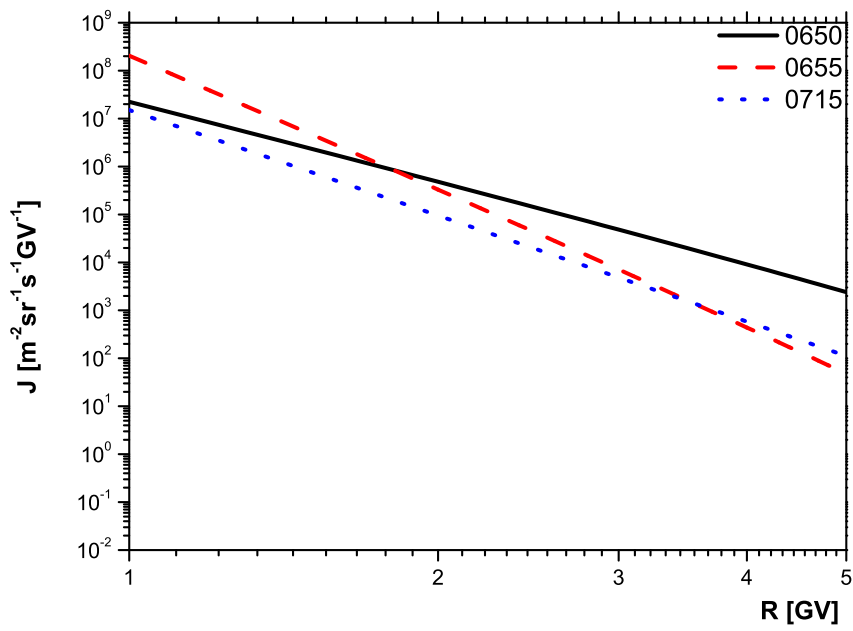
Fig. 7. Hardest SEP spectra used for computation of radiation doses at the cruise flight altitude of 35 kft (10668 m) during GLE 59 on 20 January 2005. The spectra correspond to set 2 in the database.