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# 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 at cruise flight altitude in the Earth atmosphere, related to ground level enhancement (GLE) events is created under VarSiTi/SCOSTEP support and incorporated to the International ground level enhancement (GLE) database ([gle.oulu.fi](http://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 (10,668 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.

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**Keywords:** 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 (GLEs) is an important 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 appeared, where the exposure of flying personnel to the cosmic radiation is advised to be regarded as occupational ([ICRP, 1991, 2007](#)). Accordingly, it was suggested in the EU, to assess the individual

accumulated doses of cockpit and cabin crew ([EURATOM, 1996](#); [EURATOM, 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 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

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of heavier nuclei (e.g. [Gaisser and Stanev, 2010](#), and references therein). Primary energetic CR particles enter the atmosphere, collide with nuclei of the ambient air and produce a 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](#)). Developed over the years by the research community e.g. L. Gentile, M. Shea, D. Smart, M. Duldig, J. Humble, H. Moraal, A. Belov, E. Eroshenko, V. Yanke, database provides information of NM count rates around the globe during GLEs, presently hosted by the University of Oulu ([Usoskin et al., 2015](#)).

Both GCR and SEPs, producing large diversity of secondary particles, determine the complex radiation field at flight altitudes. GLEs could enhance considerably the radiation exposure at flight altitudes (e.g. [Spurny et al., 2002](#)). Besides, GLEs 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, assessments of the radiation exposure of aircrew due to SEP events are usually performed retrospectively on the basis of retrieved information from 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 GLEs, it is necessary to possess precise and correct information about their energy and angular distribution. It was shown that the radiation exposure at aviation altitudes can be estimated using Monte Carlo simulations and/or transport models. As a result, several models have been developed (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 GLEs, where the information is available, at a cruise flight altitude of 35 kft (10,668 m) in a

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

region with low cut-off rigidity, namely with  $R_c < 1$  GV. We employed a recently developed model for computation of effective dose (Mishev and Usoskin, 2015).

## 2. Model for computation of effective dose rate at aviation altitudes

Herein we employed a numerical model for computation of the effective dose at aviation altitudes. The full description of the model with the corresponding look-up tables and comparison with reference data Menzel (2010) is given elsewhere (Mishev and Usoskin, 2015).

The model is based on pre-computed effective dose yield functions, which provide effective dose caused by monoenergetic unit flux of primary particle entering the Earth's atmosphere, derived with high statistics Monte Carlo simulations. The effective dose rate at a given altitude  $h$  induced by primary CR particles is computed using the expression:

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

where  $h$  is the altitude above sea level,  $R_c$  is the local cut-off rigidity,  $\theta$  and  $\phi$  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 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 expression:

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

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

Accordingly, the yield function  $Y_i$  is defined as:

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

where  $C_j(T^*)$  is the fluence-to-effective dose conversion coefficient for a secondary particle of type  $j$  (neutron, proton,  $\gamma, e^-, e^+, \mu^-, \mu^+, \pi^-, \pi^+$ ) with energy  $T^*$ ,  $F_{i,j}(h, T', T^*, \theta, \phi)$  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 Eqs. (1)–(3) lead to

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

The latter equation possess two integral terms, first describing the contribution of CR protons, while the second accounts for  $\alpha$ -particles and includes also heavier nuclei

similarly to Usoskin and Kovaltsov (2006) and Mishev and Velinov (2011). In case of GLEs, the effective dose is a superposition of GCR contribution (both integrands of Eq. 4) and SEPs contribution using only the first term in Eq. 4, assuming the corresponding GLE particles spectra. Note, that here we consider GLE spectra derived mostly on the basis of NM records (Table 1), which is an integral detector and does not provide information about the mass composition of SEPs. 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:

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

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  $\phi$  given in units of MV, which explicitly accounts for

Table 2

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

GLE	Date	Max. $E$ [ $\mu\text{Sv h}^{-1}$ ]	$E_{GCR}$ [ $\mu\text{Sv h}^{-1}$ ]	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

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 a conservative approach for GLE particles in sense of radiation exposure.

### 3. Assessment of effective dose rate at aviation altitude during GLEs

There are 72 GLEs so far, the most recent 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 SEP spectra and employing the model described in Section 2. The computations are performed for illustration, for a typical cruise flight altitude of 35 kft (10,668 m), which can be used as a reference, 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](#).

During GLEs the assessed effective dose rate varies from several  $\mu\text{Sv h}^{-1}$ , dominated by GCR contribution, to tens and/or hundreds  $\mu\text{Sv h}^{-1}$  and even few  $\text{mSv h}^{-1}$ ,



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 (10,668 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.

dominated by SEPs contribution. During the strongest recorded events (e.g. GLE 5 and GLE 69) the estimated dose rate reached  $3.5 \text{ mSv.h}^{-1}$  (Table 2). The described computations are released as a database for assessment of radiation exposure in the Earth atmosphere, related to GLEs, which is supplementary and now linked to the International GLE database.

<http://gle.oulu.fi/#/dose>. Hence, the new database provides, for each GLE, where possible, an information on 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 there are three different sets of derived SEP spectra (as referred in the bottom of the plot), resulting in three different sets of the computed effective dose. Some examples of the used SEP spectra are shown in Fig. 4 corresponding to set 3 (Mishev and Usoskin, 2016) and set 1 (Bombardieri et al., 2006). For GLE 60, there is only one set of SEP spectra shown in Fig. 5 (Bombardieri et al., 2007), while for GLE 70 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 highest maximum dose rate found in Table 2 results from one of the hardest SEP spectra currently in the data set (Fig. 7), which occurs during GLE 69 (Bombardieri et al., 2008). For several events the time interval over which the spectra are integrated is given, e.g. set 3 (Fig. 4a) for GLE 59 (Fig. 1). When the time interval is uncertain or not available, the end of the interval is not given. For all events the contribution of GCRs to the effective dose is also

computed using the corresponding modulation potential, excluding Forbush decrease, which leads to 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. We note, that the computed effective doses differ from each other even for the same event assuming different derived spectra as reported by Bütkofer 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 GLEs, passengers and aircrew may receive radiation exposure doses well 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. Usually it is assessed retrospectively, when the necessary GLE particles characteristics became available by reconstructions. Obviously a systemic study of the radiation exposure during GLEs is

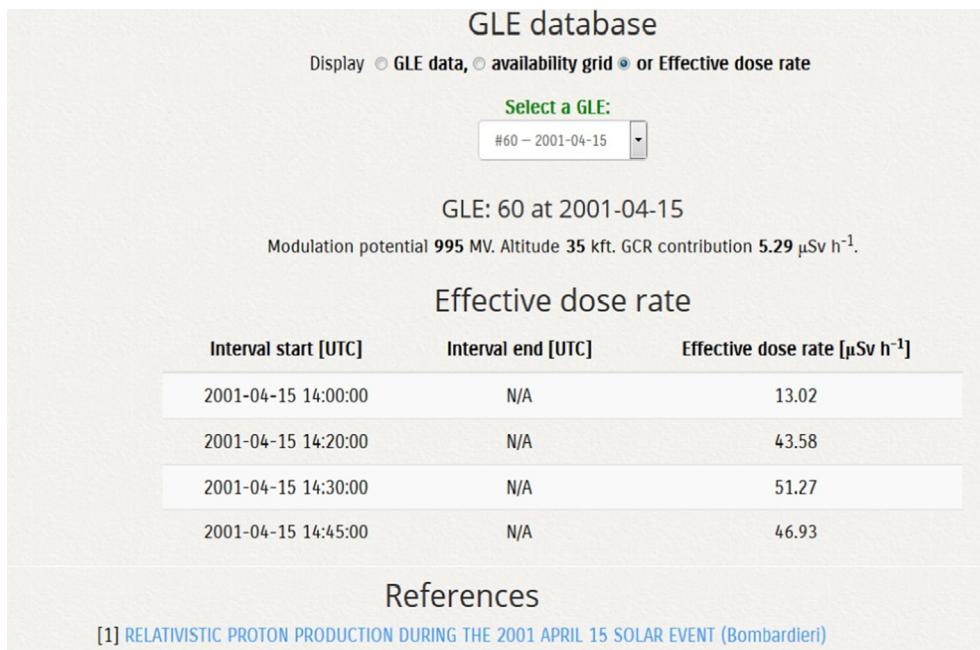


Fig. 2. Screen shot of the stored information about GLE 60 on 15 April 2001 in <http://gle.oulu.fi/#/dose>, namely the computed radiation doses at the cruise flight altitude of 35 kft (10,668 m) and the used bibliography (on the bottom).

**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  $\mu\text{Sv h}^{-1}$ .

**Effective dose rate, series # 1**

Interval start [UTC]	Interval end [UTC]	Effective dose rate [ $\mu\text{Sv h}^{-1}$ ]
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 [ $\mu\text{Sv h}^{-1}$ ]
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 [ $\mu\text{Sv h}^{-1}$ ]
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 [ $\mu\text{Sv h}^{-1}$ ]
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 [ $\mu\text{Sv h}^{-1}$ ]
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 AT AVIATION 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 (10,668 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.

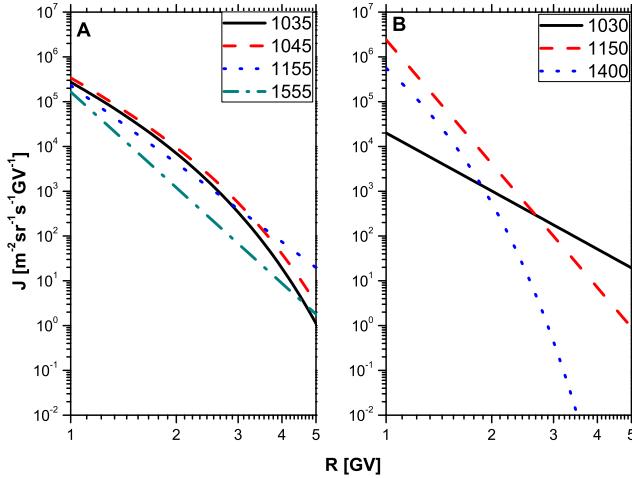


Fig. 4. SEP spectra used for computation of radiation doses at the cruise flight altitude of 35 kft (10,668 m) during GLE 59 on 14 July 2000. Panel A corresponds to set 3, while panel B corresponds to set 1.

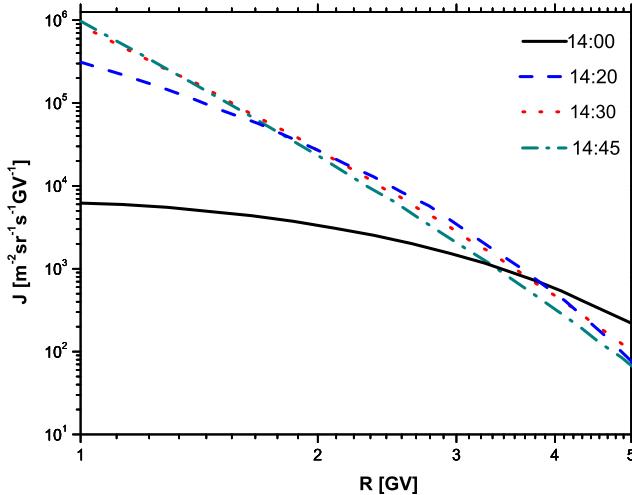


Fig. 5. SEP spectra used for computation of radiation doses at the cruise flight altitude of 35 kft (10,668 m) during GLE 60 on 15 April 2001.

necessary, specifically at polar region where it is expected to be maximal.

Herein, using a recent model for assessment of effective dose due to CRs at aviation altitude, we estimated the radiation exposure during GLEs and created the corresponding database. During the computations a conservative isotropic approach of SEPs angular distribution is assumed. The SEPs are assumed to be protons. Contribution of heavier nuclei can be straightforwardly assessed if appropriate information about SEP mass composition is available, similarly to Kapsos et al. (2007). However, taking into account the typical composition of SEPs and their energy range, the expected contribution of  $Z > 1$  particles to the radiation exposure at flight altitudes can be considered as marginal.

The new database is now linked to the existing GLE database <http://gle.oulu.fi/#/dose>. The database will be

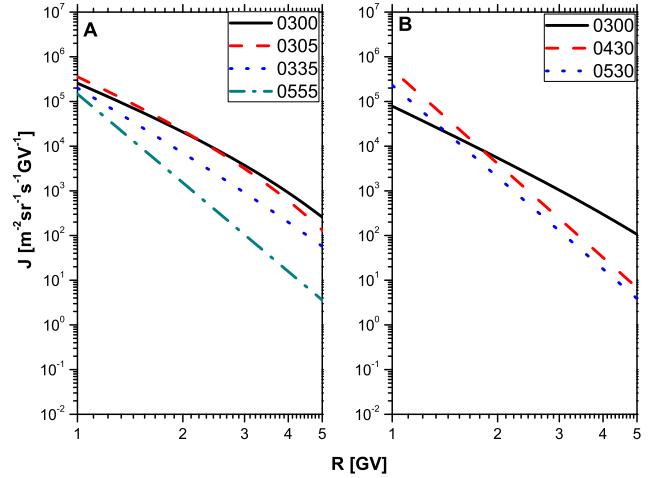


Fig. 6. SEP spectra used for computation of radiation doses at the cruise flight altitude of 35 kft (10,668 m) during GLE 70 on 13 December 2006. Panel A corresponds to set 4, while panel B corresponds to set 3.

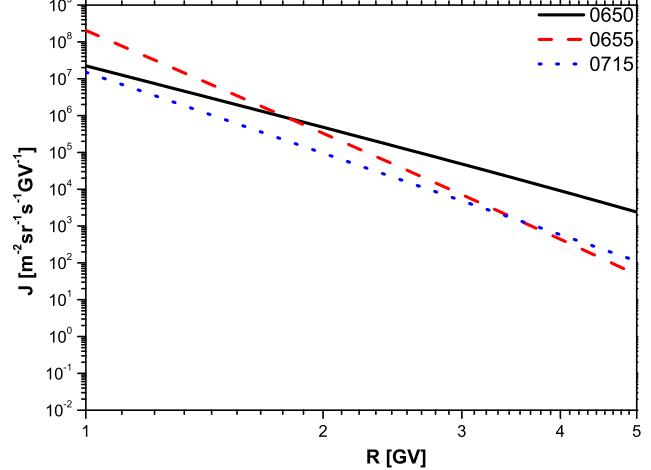


Fig. 7. Hard SEP spectra used for computation of radiation doses at the cruise flight altitude of 35 kft (10,668 m) during GLE 59 on 20 January 2005. The spectra correspond to set 2 in the database.

kept updated when new events occur and/or new information for historical events is retrieved as well as improvement of the model computations made. Hence, the new database provides, for each observed GLE 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 GLEs over several solar cycles and provides solid basis for subsequent comparison between models and measurements (Getley et al., 2005b; Beck et al., 2006; Ploc et al., 2013). However, as based on various studies with uneven and not always well-defined accuracy, the results should be regarded only as approximative and considered with caveats. A more detailed computation, namely at several flight altitudes, time intervals, considering anisotropy effects is planned as forthcoming work.

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## References

- Al Anid, H., Lewis, B., Bennett, L., Takada, M., Duldig, M., 2014. Aircrew radiation dose estimates during recent solar particle events and the effect of particle anisotropy. *Radiat. Prot. Dosimetry* 158 (3), 355–367.
- Baker, D., 1998. What is space weather? *Adv. Space Res.* 22 (1), 7–16.
- Beck, P., Bartlett, D., Lindborg, L., McAulay, I., Schnuer, K., Schraube, H., Spurny, F., 2006. Aircraft crew radiation workplaces: comparison of measured and calculated ambient dose equivalent rate data using the eurados in-flight radiation data base. *Radiat. Prot. Dosimetry* 118 (2), 182–189.
- Belov, A., Eroshenko, E., Mavromichalaki, H., Plainaki, C., Yanke, V., 2005. Solar cosmic rays during the extremely high ground level enhancement on 23 February 1956. *Ann. Geophys.* 23 (6), 2281–2291.
- Bieber, J., Clem, J., Evenson, P., Pyle, R., Siz, A., Ruffolo, D., 2013. Giant ground level enhancement of relativistic solar protons on 2005 January 20. I. Spaceship earth observations. *Astrophys. J.* 771 (2), 92.
- Bieber, J., Evenson, P., 1991. Determination of energy spectra for the large solar particle events of 1989. In: Proc. of 22th ICRC Dublin, Ireland, 11–23 August, 1991, vol. 3, pp. 129–132.
- Bombardieri, D., Duldig, M., Humble, J., Michael, K., 2008. An improved model for relativistic solar proton acceleration applied to the 2005 January 20 and earlier events. *Astrophys. J.* 682 (2), 1315–1327.
- Bombardieri, D., Duldig, M., Michael, K., Humble, J., 2006. Relativistic proton production during the 2000 July 14 solar event: the case for multiple source mechanisms. *Astrophys. J.* 644 (1), 565–574.
- Bombardieri, D., Michael, K., Duldig, M., Humble, J., 2007. Relativistic proton production during the 2001 April 15 solar event. *Astrophys. J.* 665 (1 Part 1), 813–823.
- Bottollier-Depois, J., Beck, P., Bennett, B., Bennett, L., Bütkofer, R., Clairand, I., Desorgher, L., Dyer, C., Felsberger, E., Flückiger, E., Hands, A., Kindl, P., Latocha, M., Lewis, B., Leuthold, G., Maczka, T., Mares, V., McCall, M., O'Brien, K., Rollet, S., Rühm, W., Wissmann, F., 2009. Comparison of codes assessing galactic cosmic radiation exposure of aircraft crew. *Radiat. Prot. Dosimetry* 136 (4), 317–323.
- Burger, R., Potgieter, M., Heber, B., 2000. Rigidity dependence of cosmic ray proton latitudinal gradients measured by the Ulysses spacecraft: implication for the diffusion tensor. *J. Geophys. Res.* 105, 27445–27447.
- Bütkofer, R., Flückiger, E., 2013. Differences in published characteristics of GLE 60 and their consequences on computed radiation dose rates along selected flight paths. *J. Phys. Conf. Ser.* 409 (1), 012166.
- Bütkofer, R., Flückiger, E., 2015. What are the causes for the spread of GLE parameters deduced from NM data? *J. Phys. Conf. Ser.* 632 (1).
- Bütkofer, R., Flückiger, E., Desorgher, L., Moser, M., Pirard, B., 2009. The solar cosmic ray ground-level enhancements on 20 January 2005 and 13 December 2006. *Adv. Space Res.* 43 (4), 499–503.
- Copeland, K., 2017. Cari-7a: development and validation. *Radiat. Prot. Dosimetry* 175 (4), 419–431.
- Cramp, J., Duldig, M., Flückiger, E., Humble, J., Shea, M., Smart, D., 1997a. The October 22, 1989, solar cosmic enhancement: ray an analysis the anisotropy spectral characteristics. *J. Geophys. Res.* 102 (A11), 24 237–24 248.
- Cramp, J., Duldig, M., Humble, J., 1993. The GLE of 29 September 1989. In: Proc. of 23th ICRC 19–30 July 1993, Calgary, Canada, vol. 3, pp. 47–50.
- Cramp, J., Duldig, M., Humble, J., 1997b. The effect of a distorted interplanetary magnetic field configuration on the December 7–8, 1982, ground level enhancement. *J. Geophys. Res. A: Space Phys.* 102 (A3), 4919–4925.
- Cramp, J., Humble, J., Duldig, M., 1995. The cosmic ray ground-level enhancement of 24 October 1989. In: Proceedings Astronomical Society of Australia, vol. 11, pp. 28–32.
- Debrunner, H., Flückiger, E., Lockwood, J., McGuire, R., 1984. Comparison of the solar cosmic ray events on May 7, 1978, and November 22, 1977. *J. Geophys. Res.* 89 (A2), 769–774.
- Debrunner, H., Lockwood, J.A., 1980. The spatial anisotropy, rigidity spectrum, and propagation characteristics of the relativistic solar particles during the event on May 7, 1978. *J. Geophys. Res.: Space Phys.* 85 (A12), 6853–6860.
- Deeley, K., Duldig, M., Humble, J., 2002. Re-analysis of the cosmic ray ground level enhancement of 4 May 1960. *Adv. Space Res.* 30 (4), 1049–1052.
- Desai, M., Giacalone, J., 2016. Large gradual solar energetic particle events. *Liv. Rev. Sol. Phys.* 13 (1), 3.
- EURATOM, 1996. Council directive 96/29/EURATOM of 13 May 1996 laying down basic safety standards for protection of the health of workers and the general public against the dangers arising from ionising radiation. *Off. J. Eur. Commun.* 39 (L159).
- EURATOM, 2013. Council Directive 2013/59/EURATOM of 5 December 2013 Laying Down Basic Safety Standards for Protection Against the Dangers Arising from Exposure to Ionising Radiation, and Repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom (L13).
- Ferrari, A., Pelliccioni, M., Rancati, T., 2001. Calculation of the radiation environment caused by galactic cosmic rays for determining air crew exposure. *Radiat. Prot. Dosimetry* 93 (2), 101–114.
- Gaisser, T.K., Stanev, T., 2010. Cosmic rays. In: Nakamura, K.N., et al., *Review of Particle Physics*. Journal of Physics G, vol. 37, pp. 269–275.
- Getley, I., Duldig, M., Smart, D., Shea, M., 2005a. The applicability of model based aircraft radiation dose estimates. *Adv. Space Res.* 36 (9), 1638–1644.
- Getley, I.L., 2004. Observation of solar particle event on board a commercial flight from Los Angeles to New York on 29 October 2003. *Space Weather* 2 (5), S05002.
- Getley, I.L., Duldig, M.L., Smart, D.F., Shea, M.A., 2005b. Radiation dose along north American transcontinental flight paths during quiescent and disturbed geomagnetic conditions. *Space Weather* 3 (1), S01004.
- Gleeson, L., Axford, W., 1968. Solar modulation of galactic cosmic rays. *Astrophys. J.* 154, 1011–1026.
- Gopalswamy, N., Xie, H., Yashiro, S., Akiyama, S., Mäkelä, P., Usoskin, I., 2012. Properties of ground level enhancement events and the associated solar eruptions during solar cycle 23. *Space Sci. Rev.* 171 (1–4), 23–60.
- Hands, A., Lei, F., Ryden, K., Dyer, C., Underwood, C., Mertens, C., 2017. New data and modelling for single event effects in the stratospheric radiation environment. *IEEE Trans. Nucl. Sci.* 64 (1), 587–595.
- Humble, J., Duldig, M., Smart, D., Shea, M., 1991. Detection of 0.515 GeV solar protons on 29 September 1989 at Australian stations. *Geophys. Res. Lett.* 18 (4), 737–740.
- ICRP, 1991. ICRP publication 60: 1990 recommendations of the international commission on radiological protection. *Ann. ICRP* 21(1–3).

- ICRP, 2007. ICRP Publication 103: The 2007 Recommendations of the International Commission on Radiological Protection. Ann. ICRP 37 (2–4).
- Kataoka, R., Sato, T., Kubo, Y., Shiota, D., Kuwabara, T., Yashiro, S., Yasuda, H., 2014. Radiation dose forecast of Wasavies during ground-level enhancement. *Space Weather* 12 (6), 380–386.
- Klein, K.-L., Dalla, S., 2017. Acceleration and propagation of solar energetic particles. *Space Sci. Rev.* 212 (3–4), 1107–1136.
- Kocharov, L., Pohjolainen, S., Mishev, A., Reiner, M., Lee, J., Laitinen, T., Didkovsky, L., Pizzo, V., Kim, R., Klassen, A., Karlicky, M., Cho, K.-S., Gary, D., Usoskin, I., Valtonen, E., Vainio, R., 2017. Investigating the origins of two extreme solar particle events: proton source profile and associated electromagnetic emissions. *Astrophys. J.* 839 (2), 79.
- Kravtsova, M.V., Sdobnov, V.E., 2016. Ground level enhancement of cosmic rays on November 6, 1997: Spectra and anisotropy. *JETP Lett.* 103 (1), 8–14.
- Latocha, M., Beck, P., Rollet, S., 2009. Avidos – a software package for European accredited aviation dosimetry. *Radiat. Prot. Dosimetry* 136 (4), 286–290.
- Lilensten, L., Bornarel, J., 2009. *Space Weather. Environment and Societies*. Springer, Dordrecht.
- Lockwood, J., Debrunner, H., Flükiger, E., Grädel, H., 1990. Proton energy spectra at the sun in the solar cosmic-ray events on 1978 May 7 and 1984 February 16. *Astrophys. J.* 355 (1), 287–294.
- Lovell, J., Duldig, M., Humble, J., Shea, M., Smart, D., Flückiger, E., 2002. The cosmic ray ground level enhancement of 6 November 1997. *Adv. Space Res.* 30 (4), 1045–1048.
- Lovell, J.L., Duldig, M.L., Humble, J.E., 1998. An extended analysis of the September 1989 cosmic ray ground level enhancement. *J. Geophys. Res.: Space Phys.* 103 (A10), 23733–23742.
- Matthiä, D., Heber, B., Reitz, G., Meier, M., Sihver, L., Berger, T., Herbst, K., 2009a. Temporal and spatial evolution of the solar energetic particle event on 20 January 2005 and resulting radiation doses in aviation. *J. Geophys. Res.: Space Phys.* 114 (8).
- Matthiä, D., Heber, B., Reitz, G., Sihver, L., Berger, T., Meier, M., 2009b. The ground level event 70 on December 13th, 2006 and related effective doses at aviation altitudes. *Radiat. Prot. Dosimetry* 136 (4), 304–310.
- Matthiä, D., Sihver, L., Meier, M., 2008. Monte-Carlo calculations of particle fluences and neutron effective dose rates in the atmosphere. *Radiat. Prot. Dosimetry* 131 (2), 222–228.
- Menzel, H., 2010. The international commission on radiation units and measurements. *J. ICRU* 10(2), 1–35.
- Mertens, C., Meier, M., Brown, S., Norman, R., Xu, X., 2013. Nairas aircraft radiation model development, dose climatology, and initial validation. *Space Weather* 11 (10), 603–635.
- Miroshnichenko, L., Klein, K.-L., Trottet, G., Lantos, P., Vashenyuk, E., Balabin, Y., Gvozdevsky, B., 2005. Relativistic nucleon and electron production in the 2003 October 28 solar event. *J. Geophys. Res.: Space Phys.* 110 (A9), A09S08.
- Mishev, A., Adibpour, F., Usoskin, I., Felsberger, E., 2014a. Computation of dose rate at flight altitudes during ground level enhancements no. 69, 70 and 71. *Adv. Space Res.* 55(1), 354–362.
- Mishev, A., Kocharov, L., Usoskin, I., 2014b. Analysis of the ground level enhancement on 17 May 2012 using data from the global neutron monitor network. *J. Geophys. Res.* 119, 670–679.
- Mishev, A., Usoskin, I., 2015. Numerical model for computation of effective and ambient dose equivalent at flight altitudes: application for dose assessment during GLEs. *J. Space Weather Space Clim.* 5 (3), A10.
- Mishev, A., Usoskin, I., 2016. Analysis of the ground level enhancements on 14 July 2000 and on 13 December 2006 using neutron monitor data. *Sol. Phys.* 291 (4), 1225–1239.
- Mishev, A., Velinov, P., 2011. Normalized ionization yield function for various nuclei obtained with full Monte Carlo simulations. *Adv. Space Res.* 48(1), 19–24.
- Moraal, H., McCracken, K., 2012. The time structure of ground level enhancements in solar cycle 23. *Space Sci. Rev.* 171 (1–4), 85–95.
- O'Brien, K., 1970. Calculated cosmic ray ionization in the lower atmosphere. *J. Geophys. Res.* 75 (22), 4357–4359.
- Petoussi-Henss, N., Bolch, W., Eckerman, K., Endo, A., Hertel, N., Hunt, J., Pelliccioni, M., Schlattl, H., Zankl, M., 2010. Conversion coefficients for radiological protection quantities for external radiation exposures. *Ann. ICRP* 40 (2–5), 1–257.
- Plainaki, C., Mavromichalaki, H., Laurens, M., Gerontidou, M., Kanellakopoulos, A., Storini, M., 2014. The ground-level enhancement of 2012 May 17: derivation of solar proton event properties through the application of the NMBANGLE PPOLA model. *Astrophys. J.* 785 (2), 160.
- Ploc, O., Ambrozova, I., Kubancak, J., Kovar, I., Dachev, T., 2013. Publicly available database of measurements with the silicon spectrometer Liulin onboard aircraft. *Radiat. Meas.* 58, 107–112.
- Reames, D., 2013. The two sources of solar energetic particles. *Space Sci. Rev.* 175 (1–4), 53–92.
- Sato, T., Yasuda, H., Niita, K., Endo, A., Sihver, L., 2008. Development of parma: PHITS-based analytical radiation model in the atmosphere. *Radiat. Res.* 170, 244–259.
- Shea, M., Smart, D., 1982. Possible evidence for a rigidity-dependent release of relativistic protons from the solar corona. *Space Sci. Rev.* 32, 251–271.
- Shea, M., Smart, D., 1990. A summary of major solar proton events. *Sol. Phys.* 127, 297–320.
- Shea, M., Smart, D., 2000. Cosmic ray implications for human health. *Space Sci. Rev.* 93 (1–2), 187–205.
- Smart, D., Shea, M., 1994. The relativistic solar proton groundlevel enhancements associated with the solar neutron events of 11 June, 15 June 1991. In: AIP Conference Proceedings, vol. 294, pp. 222–229.
- Smart, D., Shea, M., Gentile, L., 1993. The relativistic solar proton event of 15 June 1991. In: Proc. of 23th ICRC 19–30 July 1993, Calgary, Canada, vol. 3, pp. 59–62.
- Spurny, F., Dachev, T., 2001. Measurements in an aircraft during an intense solar flare, ground level event 60, on April 15, 2001. *Radiat. Prot. Dosimetry* 95 (3), 273–275.
- Spurny, F., Votockova, I., Bottollier-Depois, J., 1996. Geographical influence on the radiation exposure of an aircrew on board a subsonic aircraft. *Radioprotection* 31 (2), 275–280.
- Spurny, F., Dachev, T., Kudela, K., 2002. Increase of onboard aircraft exposure level during a solar flare. *Nucl. Energy Saf.* 10 (48), 396–400.
- Stoker, P., 1995. Relativistic solar proton events. *Space Sci. Rev.* 73 (3–4), 327–385.
- Usoskin, I., Bazilevskaya, G., Kovaltsov, G., 2011. Solar modulation parameter for cosmic rays since 1936 reconstructed from ground-based neutron monitors and ionization chambers. *J. Geophys. Res.* 116, A02104.
- Usoskin, I., Ibragimov, A., Shea, M., Smart, D., 2015. Database of ground level enhancements (GLE) of high energy solar proton events. In: Proceedings of Science, Proc. of 34th ICRC Hague, Netherlands, 30 July–6 August 2015 30-July-2015, 054.
- Usoskin I.G., Alanko-Huotari K., Kovaltsov G.A., Mursula K., 2005. Heliospheric modulation of cosmic rays: monthly reconstruction for 1951–2004. *J. Geophys. Res.* 110, A12108.
- Usoskin, I., Kovaltsov, G., 2006. Cosmic ray induced ionization in the atmosphere: full modeling and practical applications. *J. Geophys. Res.* 111, D21206.
- Vainio, R., Desorgher, L., Heynderickx, D., Storini, M., Flückiger, E., Horne, R., Kovaltsov, G., Kudela, K., Laurens, M., McKenna-Lawlor, S., Rothkaehl, H., Usoskin, I., 2009. Dynamics of the earth's particle radiation environment. *Space Sci. Rev.* 147 (3–4), 187–231.
- Vashenyuk, E., Balabin, Y., Gvozdevskii, B., Karpov, S., 2006a. Relativistic solar protons in the event of January 20, 2005: model studies. *Geomag. Aeron.* 46 (4), 424–429.
- Vashenyuk, E., Balabin, Y., Gvozdevsky, B., 2011. Features of relativistic solar proton spectra derived from ground level enhancement events (GLE) modeling. *Astrophys. Space Sci. Trans.* 7 (4), 459–463.

- Vashenyuk, E., Balabin, Y., Miroshnichenko, L., 2008. Relativistic solar protons in the ground level event of 23 February 1956: New study. *Adv. Space Res.* 41(6), 926–935.
- Vashenyuk, E., Balabin, Y., Perez-Peraza, J., Gallegos-Cruz, A., Miroshnichenko, L., 2006b. Some features of the sources of relativistic particles at the sun in the solar cycles 21–23. *Adv. Space Res.* 38 (3), 411–417.
- Xapsos, M., Stauffer, C., Jordan, T., Barth, J., Mewaldt, R., 2007. Model for cumulative solar heavy ion energy and linear energy transfer spectra. *IEEE Trans. Nucl. Sci.* 54 (6), 1985–1989.