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Space environment (natural and artificial) — Method of the solar energetic protons fluences and peak fluxes determination

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Environnement spatial (naturel et artificiel) — Méthode des fluences de protons énergétiques solaires et détermination des flux de pic

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Contents

Page

Foreword

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Space environment (natural and artificial) — Method of the solar energetic protons fluences and peak fluxes determination

1 Scope

This Technical Report is intended for calculating the probability for solar energetic particle (SEP) to have an impact on materials, hardware, and biological objects.

This Technical Report establishes the differential energy spectra for the (0,1/10^3) MeV SEP fluences and/or peak fluxes in the near-earth space, beyond the earth magnetosphere during the missions any duration under varying solar activity.

If additional prepositions are used, the method establishes the basic fluences and peak fluxes for their determination throughout the heliosphere. When the effect of the particle penetration into the magnetosphere is taken into account (see ISO/AWI 17520, *Cosmic ray and solar energetic particle penetration inside the magnetosphere: Determination of the vertical cutoff values*, draft standard), the method establishes the basic fluences and peak fluxes for their determination on the near-earth spacecraft and manned station orbits.

Because the occurrence of SEP is a process a probabilistic nature, fluences and peak fluxes calculation relate to the different levels of probability.

The method is intended for specialists engaged in determination of radiation conditions in space.

2 Definitions, notations, and abbreviations

Term	Notation	Abbreviation	Definition
Solar energetic particles (or solar cosmic rays)		SEP	High-energy (≥4 MeV/nucl) charged particle of solar origin.
Mission duration	T		Calendar time period for the SEP peak flux or fluence is model calculated (months).
Wolf (sunspot) number	W		W = $k(10g+f)$, where g is sunspot group number; f is the total sunspot number on the visible solar disc. k is the coefficient adjusting various observation conditions.
Solar activity (SA) level	$\langle W \rangle$		13-month smoothed month sunspot number or predicted by NOAA month sunspot number. <http://www.sec.noaa.gov/Data/>
Solar activity condition	$\Sigma \langle W_i \rangle$		The sum of the smoothed month sunspot numbers during the space mission
Mission parameter	n		The parameter of the model, relative determined as the hypothetic mean number of SEP events with the fluences $F_{30} \geq 10^5$ cm^{-2} protons with energy ≥30 MeV expected during the missions duration.
Particle energy	E		Particle energy (MeV/nucleon).
Particle fluence	F		The total (time-integrated) number of particles in given space mission that traverse a unit area from all directions from solid angle 4π (particle/cm^2).

Term	Notation	Abbreviation	Definition
Differential proton fluence energy spectrum	dF/dE	$F(E)$	Differential particle fluence energy (E) distribution during the space mission [particle/(cm^2·MeV)].
Integral particle fluence energy spectrum	$F(\geq E)$	F_E	Integral particle fluence energy (E) distribution (at E above a given level) during the space mission (particle/cm^2).
Particle peak flux	f		The time when a maximum number of particles traverse a unit area during the space mission, normally to a given observation, direction in unit time through unit solid angle [proton/(cm^2·sr·s)]. NOTE The fluxes of particles with different energy reach maximum values at different times during the SEP event.
Differential particle peak flux energy spectrum	df/dE	$f(E)$	Differential particle peak flux energy (E) distribution during the space mission [particle/(cm^2·sr·s·MeV)].
Integral proton peak flux energy spectrum	$f(\geq E)$	f_E	Integral particle peak flux energy (E) distribution during the space mission (or in a set of SEP events) [particle/(cm^2·sr·s)].
SEP fluences and/or peak fluxes occurrence probability	P	Probability	The probability the given fluences and/or fluxes should be exceeded.
Small fluxes (fluences or peak fluxes)	S	Small	Fluxes, sizes that exceed probability 0,9, or fluxes occurred at the 0,1 confidence level.
Mean fluxes (fluences or peak fluxes)	M	Mean	Fluxes, with probability 0,5 (50/50 case), or at the 0,5 confidence level.
Large fluxes (fluences or peak fluxes)	L	Large	Fluxes, sizes that exceed probability 0,1 or occurred at the 0,9 confidence level.
Extremal fluxes (fluences or peak fluxes)	E	Extremal	Fluxes, sizes that exceed probability 0,01 or occurred above the 0,99 confidence level.
Worst case fluxes (fluences or peak fluxes)	W	Worst case	Fluxes, sizes that exceed probability 0,001 or occurred above the 0,999 confidence level.

3 Main principles of the method

3.1 The method establishes the sizes of the SEP fluences and/or peak fluxes, which are expected with probability P, to get exceeded within a time interval T at a given solar activity conditions.

3.2 Angular distribution of SEP fluxes beyond the earth's magnetosphere is taken to be isotropic.

3.3 The solar activity condition is described as sum of smoothed mean (or predicted) month sunspot (Wolf) numbers $\sum_1^m <W_i>$ where m is the number of months with solar activity, $<W_i>$, each during mission duration T.

3.4 The mission parameter, n, is determined to be equal as:

$$<n> = 1{,}35\times 10^{-2}\sum_i^m <W_i> \qquad (1)$$

The value $<n>/2$ is the mean SEP event (with the fluence, $F(E \geq 30\ \text{MeV}) \geq 10^6$ protons/cm^2) number in the considered period.

3.5 The solar high energy protons ($E \geq 30$ MeV) distribution function by integral fluences is described as:

$$\psi(\geq F) = C \times F^{-\gamma} / \overrightarrow{\exp}(F / F_0) \quad (2)$$

where the parameters are C = 28,7, γ = 0,32, and $\Phi_0 = 8{,}10^9$.

3.6 The differential energy spectra of the particle fluences (*F*) and/or peak fluxes (*f*) (referred to henceforth as energy spectra of *Φ*) for predicted missions are power-law functions of proton energy, *E.*

$$\Phi(E)dE = CE^{-\gamma}dE \quad (3)$$

where *E* is the protons kinetic energy in MeV.

In case of proton fluxes, the following spectral parameters are taken:

a) E_k, the centre of the region in which the energy spectra of the broken off (the effect of the knee).

b) DE_k, the energy region from $E_{min} = E_k/DE_k$ to $E_{max} = E_k \cdot DE_k$, wherein the spectral index is changing from γ_1 to γ_2.

c) *D*, differential fluence (or peak flux) at E_k.

d) At $E < E_k/DE_k$, spectral index is proposed to be γ_1.

e) At $E > E_k \cdot DE_k$, spectral index is proposed to be γ_2.

f) In case of $E_{min} \leq E \leq E_{max}$, γ is proposed to change as:

$$\gamma = (\gamma_1 + \gamma_2)/2 + (\gamma_1 - \gamma_2)/2 \times S \quad (4)$$

where

$$S = \sin[\pi \times (\log(E) - \log(Ek)] / [\log(E_{max}) - \log(E_{min})]$$

Finally, the differential energy spectra [Formula (3)] in range (0,1/10^3) MeV are described by four parameters (1, 3, 4, 5). Therefore, the parameter DE_k is supposed to be constant and equal to 1,37.

4 Calculation technique

4.1 The present model includes the specifications of the differential energy spectra parameters for fluences and peak fluxes for the most frequently used integral probability sequence *P* = 0,9 (small), 0,75, 0,5 (mean), 0,25, 0,1 (large), 0,01 (extreme), and 0,001 (worst case). For the sequence of the mission parameters <*n*> = 1, 2, 4, 8, 16, 32, 64, 128, 256, and 512 are used. The parameters, *n* = 1/2, describe the annual missions at the deep SA minimum; parameters, *n* = 8, 16, and 32, describe the annual missions in case of mean sunspot numbers *W* = 50, 100, and 200 accordingly; parameter, *n* = 128, describe the conditions at the full solar cycle (like 19, 20, 21, 22, and 23 cycles) mission period. In the case of approximation methods used, energy spectra for all possible mission duration at all possible solar active conditions can be described in more detail.

4.2 The standard method tabulates the parameters of differential spectra for fluences and peak fluxes.

E_k, *D*, γ_1, and γ_2 for model parameters *P* (probability) and <*n*> (mission parameter eq. mean number of SEP events).

4.3 The particle fluence and/or peak flux calculations involve:

4.3.1 Calculation of the mission parameter, <*n*>, by Formula (1).

In case of future missions, use the predicted sunspot number data from:

<http://www.swpc.noaa.gov/ftpdir/weekly/Predict.txt>

or in accordance with the data of high activity SA cycle 19 (years 1954-1964) from:

<ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SUNSPOT_NUMBERS/INTERNATIONAL/yearly/YEARLY>

4.3.2 Establish the probability (confidence) level needed.

4.3.3 Use the tabulated parameters data or calculation of four parameters using interpolation of the tabulated data (if needed). In case of parameter *D* for the interpolation, the logarithm values of *D* should be used.

4.4 Calculate the differential energy spectrum for needed values, <*n*>, and *P*, using Formula (3) and Formula (4).

4.5 In case the integral proton energy spectra are to be calculated, use Formula (5):

$$\Phi(\geq E) = \int_{E}^{\infty} \Phi(E)\, dE \tag{5}$$

NOTE As the present model, the tabulated parameters, but not figures, are established. The figures, presented in Annexes, serve only as illustrations.

5 Base tables

Table 1 — The coefficients of the proton fluence spectrum log, *D*(<*n*>/P)

<*n*>/P	**0,9**	**0,75**	**0,5**	**0.,5**	**0,1**	**0,01**	**0,001**
1	-	-	6,041	7,241	7,991	8,732	9,442
2	-	6,076	7,041	7,775	8,253	8,983	9,600
4	6,378	6,972	7,870	8,173	8,571	9,236	9,732
8	7,324	7,874	8,220	8,520	8,820	9,442	9,860
16	8,140	8,380	8,630	8,859	9,010	9,647	9,982
32	8,640	8,820	8,986	9,137	9,367	9,810	10,190
64	9,037	9,176	9,322	9,465	9,671	9,978	10,210
128	9,441	9,556	9,658	9,799	9,942	1,127	10,320
256	9,829	9,899	9,989	10,104	10,199	10,360	10,440
512	10,143	10,233	10,303	10,405	10,479	10,577	10,613

Table 2 — The knee energy (MeV) of the proton fluence spectrum, *Ek*(<*n*>/P)

<*n*>/P	0,9	0,75	0,5	0,25	0,1	0,01	0,001
1	-	-	9,715	8,279	9,636	18,240	16,067
2	-	9,809	8,700	9,900	12,732	17,540	15,756
4	9,900	9,500	8,500	11,689	14,380	16,720	15,182
8	9,545	8,946	9,500	13,250	16,500	16,092	14,518
16	7,983	8,500	12,100	14,454	16,800	15,449	14,455
32	9,429	12,087	13,321	15,200	15,970	14,782	14,373
64	12,123	12,898	13,700	14,992	14,645	14,562	14,580
128	13,185	13,424	14,179	14,397	14,276	14,468	14,800
256	13,499	13,745	14,083	14,087	14,024	13,984	14,918
512	14,384	13,992	14,152	13,698	13,596	13,672	14,757

Table 3 — The index $\gamma 1$ of the proton fluence spectrum, $\gamma 1$(<*n*>/P)

<*n*>/P	0,9	0,75	0,5	0,25	0,1	0,01	0,001
1	-	-	1,681	1,619	1,464	1,375	1,398
2	-	1,677	1,671	1,538	1,420	1,375	1,418
4	1,710	1,640	1,530	1,461	1,400	1,380	1,440
8	1,674	1,583	1,490	1,430	1,392	1,390	1,460
16	1,549	1,472	1,449	1,400	1,390	1,400	1,480
32	1,480	1,450	1,430	1,400	1,389	1,420	1,507
64	1,440	1,433	1,409	1,402	1,392	1,440	1,530
128	1,434	1,418	1,409	1,398	1,400	1,450	1,542
256	1,420	1,412	1,406	1,400	1,411	1,450	1,537
516	1,421	1,411	1,408	1,407	1,412	1,451	1,477

Table 4 — The index $\gamma 2$ of the proton fluence spectrum, $\gamma 2$(<*n*>/P)

<*n*>/P	0,9	0,75	0,5	0,25	0,1	0,01	0,001
1	-	-	3,218	3,089	2,986	2,772	2,560
2	-	3,217	3,120	3,027	2,910	2,689	2,507
4	3,192	3,150	3,050	2,970	2,840	2,610	2,470
8	3,136	3,065	2,980	2,900	2,870	2,556	2,425
16	3,060	2,990	2,920	2,837	2,700	2,520	2,390
32	3,000	2,940	2,870	2,779	2,650	2,500	2,360
64	2,950	2,870	2,803	2,730	2,620	2,474	2,350
128	2,906	2,822	2,757	2,675	2,602	2,460	2,360
256	2,859	2,777	2,718	2,655	2,593	2,460	2,400
612	2,809	2,743	2,699	2,641	2,580	2,469	2,440

Table 5 — The coefficients of the proton peak flux spectrum log, *D*(<*n*>/P)

<*n*>/P	0,9	0,75	0,5	0,25	0,1	0,01	0,001
1	-	-	0,190	1,340	2.037	2,882	3,617
2	-	0,238	1,097	1,800	2,320	3,124	3,799
4	0,668	1,111	1,744	2,160	2,560	3,340	3,945
8	1,356	1,720	2,080	2,420	2,800	3,540	4,134
16	1,820	2,070	2,360	2,682	3,037	3,723	4,270
32	2,150	2,330	2,600	2,921	3,279	3,893	4,430
64	2,387	2,585	2,868	3,182	3,500	4,064	4,570
128	2,678	2,845	3,072	3,401	3,684	4,253	4,700
256	2,930	3,083	3,348	3,600	3,852	4,390	4,780
512	3,111	3,316	3,549	3,790	3,989	4,520	4,870

Table 6 — The knee energy (MeV) of the proton peak flux spectrum, *Ek*(<*n*>/P)

<*n*>/P	0,9	0,75	0,5	0,25	0,1	0,01	0,001
1	-	-	9,872	8,642	10,86	19,52	16,76
2	-	9,356	9,059	8,333	14,20	18,80	15,83
4	7,979	8,854	9,700	12,73	17,70	17,81	15,00
8	8,334	8,957	12,12	15,60	18,50	16,85	13,90
16	8,915	11,91	13,90	18,30	19,13	16,10	13,10
32	12,600	15,20	18,28	19,20	18,21	15,25	12,71
64	17,016	18,40	19,33	18,78	16,85	14,15	10,80
128	19,096	19,78	19,78	17,60	16,06	12,97	9,70
256	19,765	19,71	18,50	16,70	15,50	12,00	8,80
512	20,513	18,58	16,80	15,63	14,84	11,11	7,80

Table 7 — The index $\gamma 1$ of the proton peak flux spectrum, $\gamma 1$(<*n*>/P)

<*n*>/P	0,9	0,75	0,5	0,25	0,1	0,01	0,001
1	-	-	1,650	1,601	1,459	1,349	1,394
2	-	1,650	1,590	1,490	1,393	1,351	1,424
4	1,644	1,590	1,522	1,426	1,374	1,365	1,454
8	1,600	1,510	1,450	1,400	1,353	1,385	1,480
16	1,510	1,430	1,400	1,370	1,354	1,410	1,514
32	1,434	1,382	1,370	1,360	1,356	1,445	1,570
64	1,379	1,360	1,360	1,346	1,366	1,480	1,650
128	1,333	1,338	1,352	1,360	1,390	1,526	1,720
256	1,332	1,347	1,357	1,378	1,415	1,570	1,786
512	1,350	1,359	1,376	1,413	1,456	1,630	1,823

Table 8 — The index $\gamma 2$ of the proton peak flux spectrum, $\gamma 2(<n>/P)$

<*n*>/P	0,9	0,75	0,5	0,25	0,1	0,01	0,001
1	-	-	3,224	3,110	2,988	2,784	2,488
2	-	3,198	3,140	3,040	2,920	2,692	2,451
4	3,180	3,120	3,070	2,963	2,840	2,584	2,400
8	3,130	3,050	2,989	2,882	2,760	2,490	2,380
16	3,080	2,970	2,907	2,850	2,680	2,430	2,357
32	3,000	2,890	2,830	2,730	2,610	2,480	2,340
64	2,930	2,820	2,750	2,640	2,520	2,350	2,328
128	2,860	2,750	2,670	2,560	2,457	2,340	2,320
256	2,794	2,660	2,592	2,486	2,420	2,340	2,310
512	2,724	2,607	2,520	2,439	2,388	2,340	2,300

In Annex A, the main methodical principles used at development of the present model are described and some main references are presented also. The presented model calculation results are compared with another model description and the revealed differences are discussed.

In Annex B, these model examples of the proton fluences and peak fluxes calculation results for different mission duration at different solar activity conditions together with available experimental data are presented.

Annex A
(informative)

Main methodical principles

A.1 Introduction

In this method, the SEP event fluences and peak flux determination is the result from a large investigation of the regularities inherent to the SEP particle events. The successive use of these regularities allows the composition of the complete mathematical description of the full set of solar energy proton fluences and peak flux occurrence for any solar activity conditions and any mission duration.

Sufficient description of these regularities and calculation technique in frames of this Technical Report is hardly possible.

Therefore, the most important positions and reference were stated here.

These regularities are:

1. The mean solar energy particle occurrence frequency is proportional to the solar activity, expressed as the smoothed monthly mean sunspot number, given by NOAA (Boulder).[1-3]

2. The SEP event distribution by $E \geq 30$ MeV proton fluences is independent from solar activity level (is invariant).[3-5] The form of the distribution function for SEP events by integral fluences of the ≥30 MeV protons is established by spacecraft measured[3-6] and Greenland ice nitrate isotope[7] data, reproduced in Reference [6]. Sizes of the SEP event fluences $F_{30} \geq 10^5$ protons/cm^2 were calculated as random values from distribution function, presented on Figure A.1.

3. As it follows from two regularities above, the long missions at the low solar activity conditions have analogues to the short missions at the high solar activity. Therefore, for any mission at any solar activity, the same model parameter <*n*> can be used, which is the function of the sum of monthly mean Wolf numbers only.

4. The form of the SEP event energy spectra description is based on the publications[8-10] and the additional detailed analysis of all SEP event energy spectra, determined in 23 SA cycle. The parameters of the SEP events fluences and peak fluxes (not for spectra of event fluxes at certain moment) differential energy spectra in range from 0,16 MeV to 500 MeV were determined by spacecraft ACE instrument ULEIS and spacecrafts GOES — (8, 10, and 11) instruments Telescope and Dome during 1998 — 2006 years.

5. Sizes of the SEP event peak fluxes were determined as random values of determined above fluences to peak flux ratio from lognormal distribution with mean $<\log(F_{30}/f_{30})> = 5{,}95$ and standard deviation 0,125.

The parameters, presented in Table 1 to Table 8 are the results of accounting the regularities inherent to the energy spectra parameters for model calculation of the very large of number (~10^6) of random-calculated mission periods, showing *n* proton fluences and/or peak fluxes spectra. Here, *n* is a random number for SEP events, which corresponds to the mean number <*n*> according to Poisson (in case of <*n*> ≤ 8), or normal (in case of <*n*> > 8) distributions.

A.1.1 General

The object of this Technical Report is the content of the tables only. If you find any discrepancies or errors, you should contact the author of the Technical Report to address the deficiencies identified.

It is considered that the details of the calculation is a “black box”, followed by the fact that the calculation results by this method for any mission duration and any solar activity period (the quiet sun period included) are in complete agreement with the experimental data available.

The possible errors, inherent to this method, because of the probabilistic character of SEP phenomenon and different reliability of the experimental data are not presented here. This problem can be cleared only in conditions of much more statistical experimental data in future.

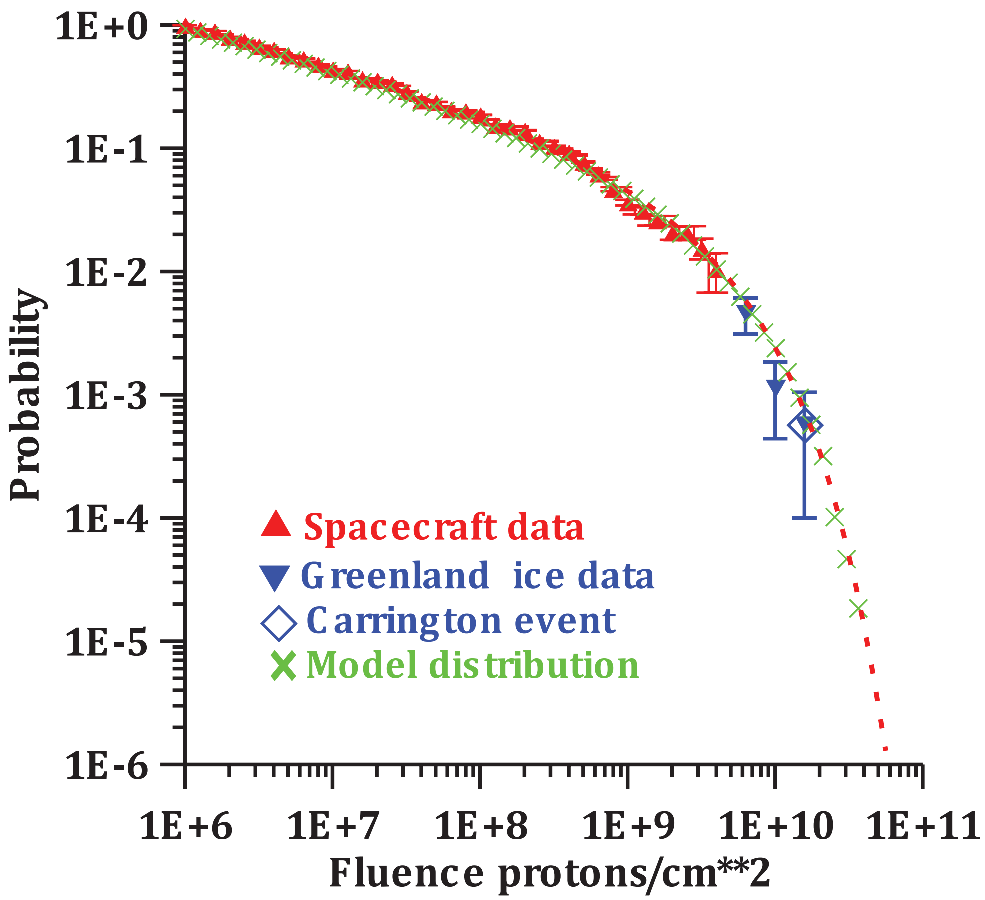

Figure A.1 — Distribution function used in the model — published in Reference [6]

Red dashed line is the solution (Figure A.1). Green crosses are the one of model-generated distributions data.

A.1.2 The main fluences (or peak fluxes) for different mission conditions, reflected in the model

Tabulated data are not sufficiently descriptive to reflect the regularities inherent to the SEP fluxes, which are reflected in this Technical Report. For proper use of these data, some additional tables and graphs that facilitate the application of this Technical Report were presented here.

A.1.2.1 Model parameter and space missions

In Table A.1, the main conditions corresponding to the model parameter <*n*> is given.

Table A.1 — Model Parameter

Model parameter <*n*>	Annual solar activity (SA) level <W_{year}>	Missions duration
1	~5 — deepest minimum of SA (like in 2008)	Annual
2	12.5 — ordinary minimum of SA	Annual
4	25 — weak SA level	Annual
8	2 × 25 — weak SA level	2-year mission
8	50 — (very small SA maximum** or intermediate phases (recession, growth) of ordinary SA	Annual
16	100 (ordinary SA maximum*)	Annual
32	200 (very high SA maximum***)	Annual
32	2 × 100 (ordinary SA maximum**)	2-year mission
64	4 × 100 (ordinary SA maximum**)	4-year mission
128	11-year ordinary SA cycle**	SA cycle (10/12 years)
216	2 ordinary SA cycles**	20/25 years
512	Overlong mission	Up to 50 years
* ordinary, like in 20 to 23 SA cycles ** like in 24th SA cycle *** like in 19th SA cycle		

A.1.3 The probability to occur quite different SEP fluxes in case of the same space mission duration at the same solar activity

Occurrence of an event of SCR is probabilistic in nature. At a certain average number of events can occur, some close to the expected number. But the main reason for the difference between particle fluxes is the distribution function, according to what each new emerging event can have (but with different probabilities), a value differing in hundreds of thousands of times. By calculating the magnitude of fluxes for all possible (many) options, the appropriate assessments for fluxes that have appeared in the middle (50/50) or exceed a given value with any probability can be determined. That kind of fluxes can be called as middle (M).

Probability of 0,1 at the same time means that in one case of the 10 possible missions, particle fluxes exceed a certain value. Probability of 0,1 in a different terminology means the 90 % confidence level. Such fluxes can be arbitrarily named as large (L).

Probability of 0,01 at the same time means that in one case of the 100 possible missions, particle fluxes exceed a certain value. Probability of 0,01 in a different terminology means the 99 % confidence level. Such fluxes can be arbitrarily named as extremal (E).

Probability of 0,001 at the same time means that in one case of the 1000 possible missions, particle fluxes exceed a certain value. Probability of 0,001 in a different terminology means the 99,9 % confidence level. Such fluxes can be arbitrarily named as worst case (W).

Historically, the term “worst case” applies to the largest particle fluxes that were observed in the experiment. However, experience has shown that the magnitude of these fluxes are measured and interpreted with large errors and do not have a clear probability criterion. Therefore, the scope of the term is offered to change on a clear quantitative counterpart, describing a practical point of view, the most incredible case.

Below, for illustrative purposes, are given the differential energy spectra for the three specific missions, with the parameters <*n*> = 4, 16, and 128 (see Table A.1) — Figures A.2, A.3, and A.4.

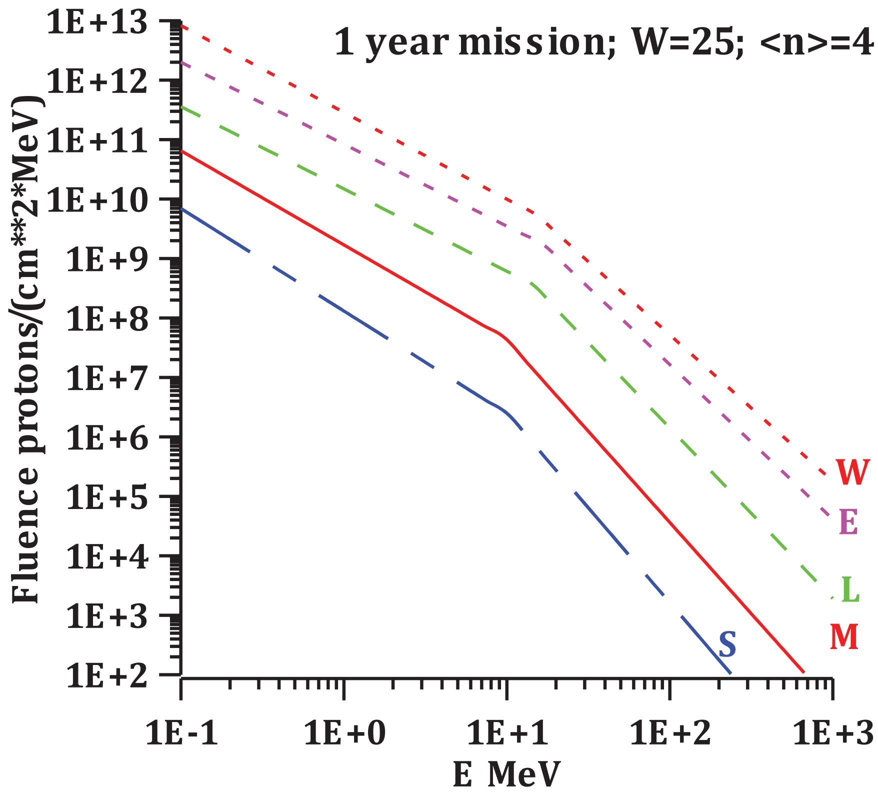

Figure A.2 — Differential energy spectra proton fluences for annual mission at the "quiet sun" conditions

NOTE 1 Fluences, which occur in this period can differ by three orders.

NOTE 2 This period (W = 25), was declared by authors of JPL-91[11] and ESP[12] models as a "quiet sun" period (W < 40), when it's possible to neglect the SEP fluxes. It is an erroneous statement. Comparing the Figure A.2 and Figure A.3 shows that the large fluences (L) that occur in the quiet sun period are equal to the middle (M) fluences that occur during the ordinary maximum of solar activity.

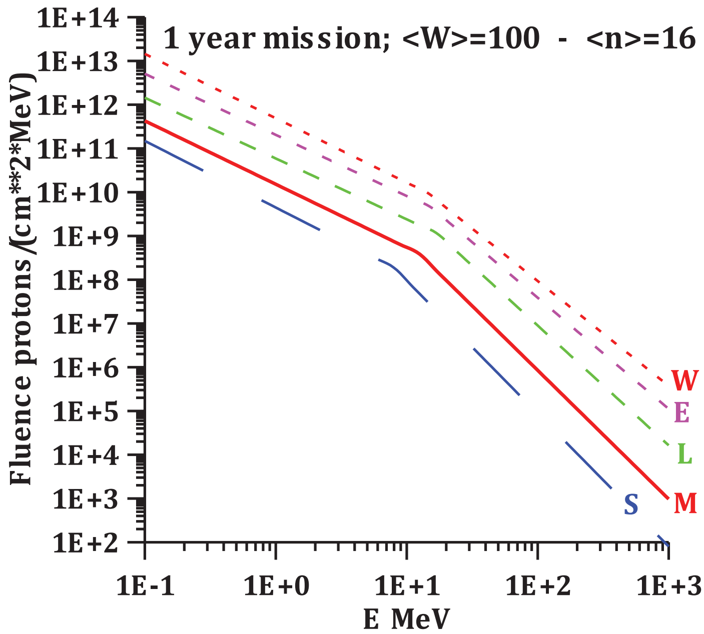

Figure A.3 — Differential energy spectra proton fluences for annual mission at ordinary SA maximum conditions

NOTE Possible fluences which can occur in this period differ in this case by two orders.

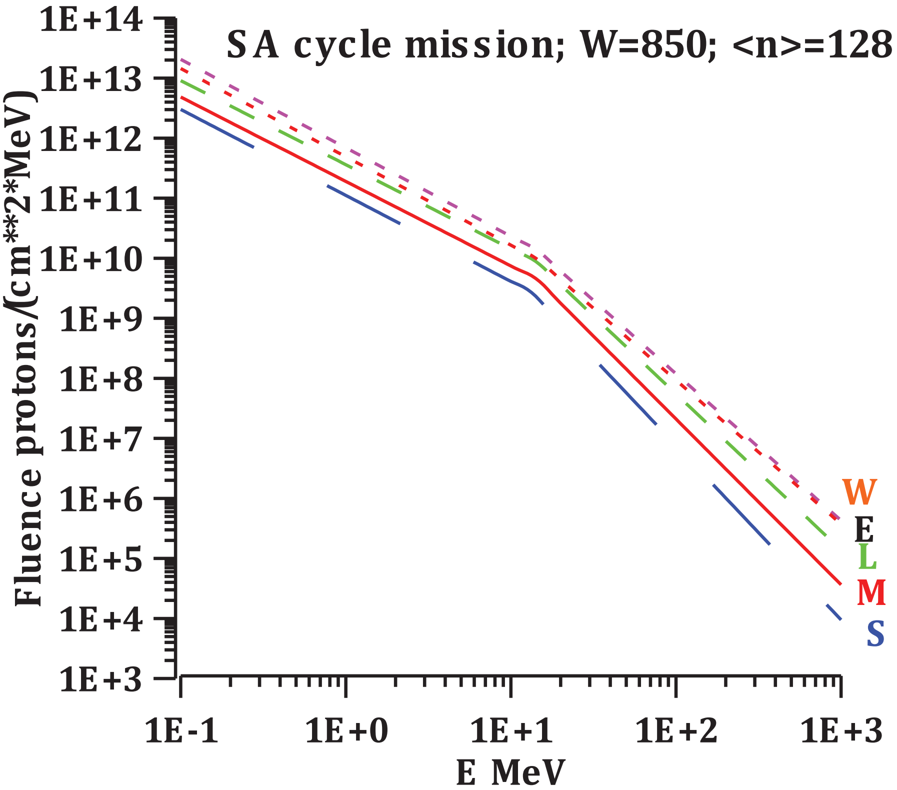

Figure A.4 — Differential energy spectra proton fluences for ordinary solar activity cycle (11 years) conditions

NOTE The possible differences of fluences, which can occur in that period differ only about three times.

It needs to mention that in the case of solar active cycle duration missions, the differential fluences is not large. In Figure A.5, the differential energy spectra in case of <*n*> = 128 and 19 and 23 SA cycle missions was demonstrated.

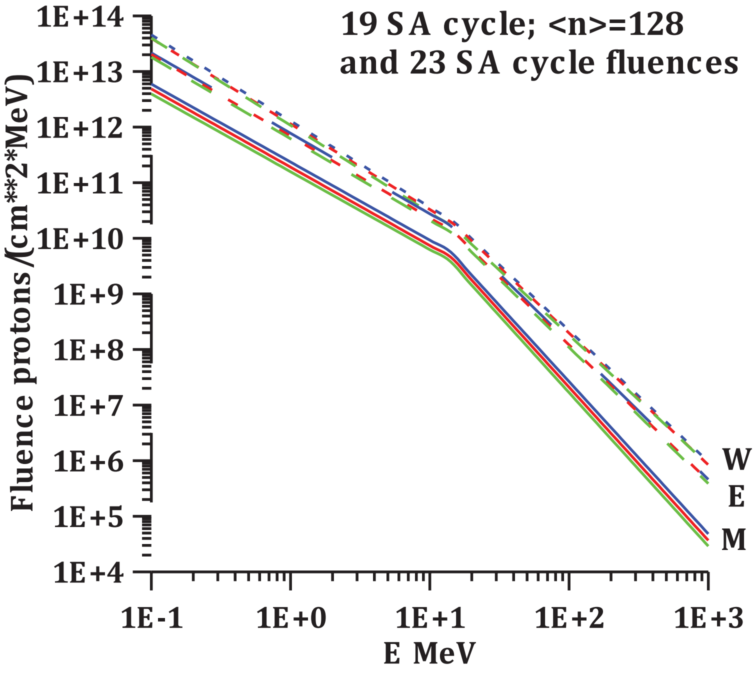

Figure A.5 — Differential energy spectra proton fluences for conditions of 19 and 23 solar activity cycle (11 years) and model parameter <*n*> = 128 conditions for M, E, and W probability cases

NOTE In case of 11-year missions, the difference between the highest cycle (19) and the lowest cycle (23) of the model parameter <*n*> = 128 for all probabilities, is small (~10/20 %). In the case of new cycles, exact SA activity level of what is unknown, is allowed to use the parameter, <*n*> = 128 data.

A.1.4 Comparing the present model with others

The present model outputs with model ESP[11] outputs were compared, and there were no changes in the data reproduced from the website, http://www.spenvis.oma.be. [Figure A.6 a), Figure A.6 b), and Figure A.6 c)] and ESP's author M.Xapsos private message from 24.10.2011 [Figure A.6 d)]. Another well-known model JPL-91[12] and Rosenqvist[13] by their character are close to model ESP and conclusions based on the ESP model also partly refer to these models.

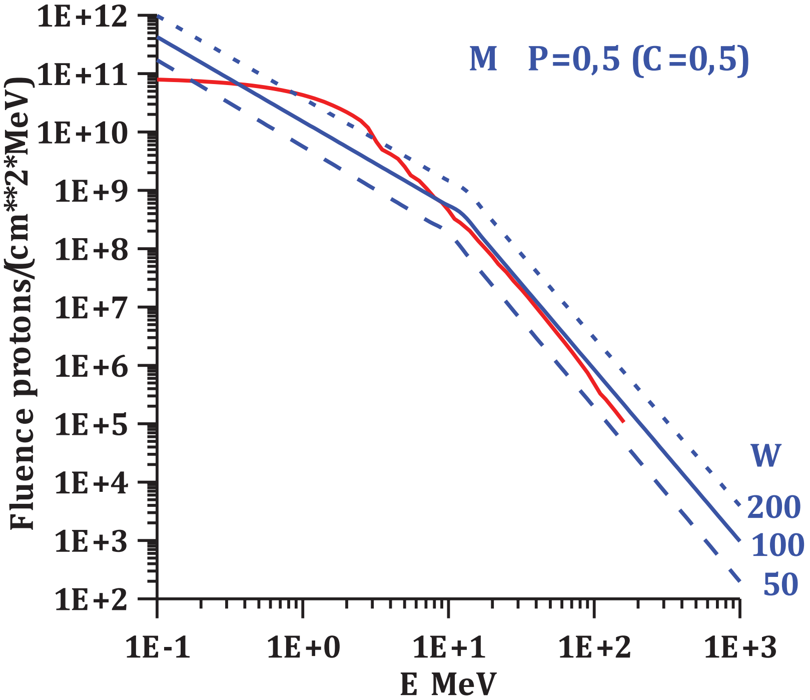

Figure A.6a — Differential energy spectra of annual missions in case of spectra M, *P* = 0,5, (or confidence level 0,5 for model ESP) and present model for solar activity, W = 50, 100, and 200 (model parameters <*n*> = 8, 16, and 32)

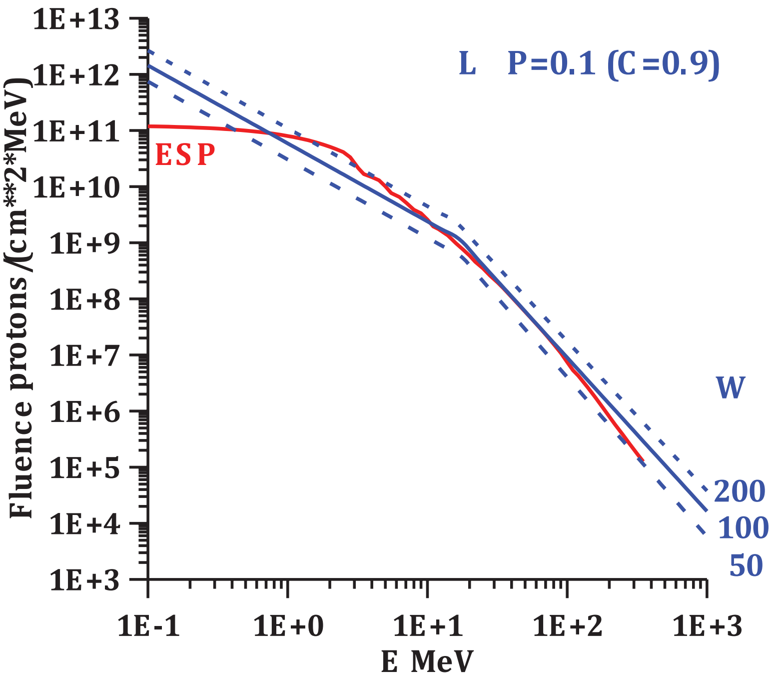

Figure A.6b — Differential energy spectra of annual missions in case of spectra, L, *P* = 0,1 (or confidence level 0,90) for model ESP and present model for solar activity, W = 50, 100, and 200 (model parameters <*n*> = 8, 16, and 32)

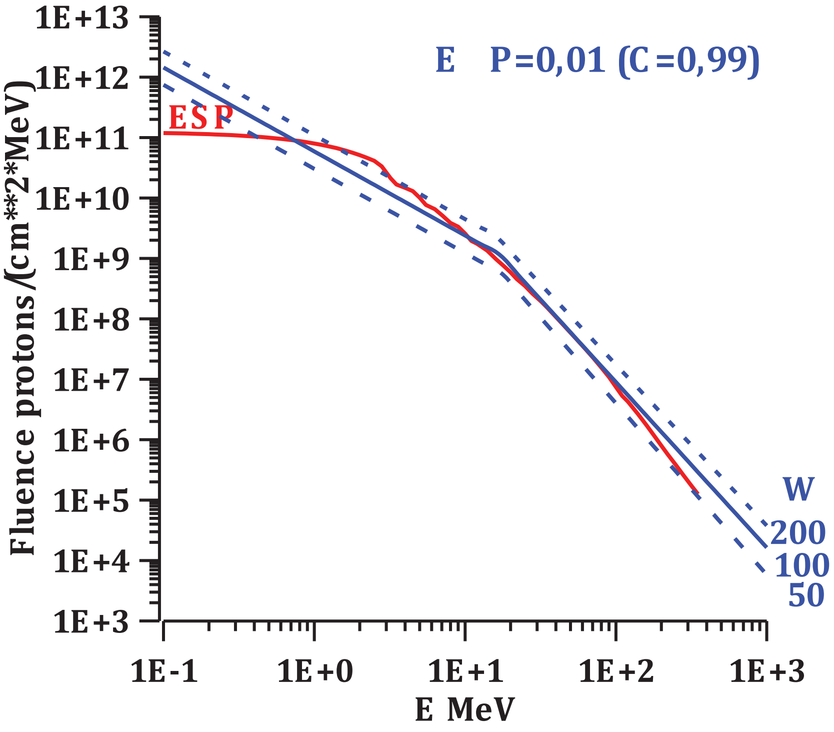

Figure A.6c — Differential energy spectra of annual missions in case of spectra, E (*P* = 0,01, or confidence level 0,99 for model ESP) and present model for solar activity, W = 50, 100, and 200 (model parameters <*n*> = 8, 16, and 32)

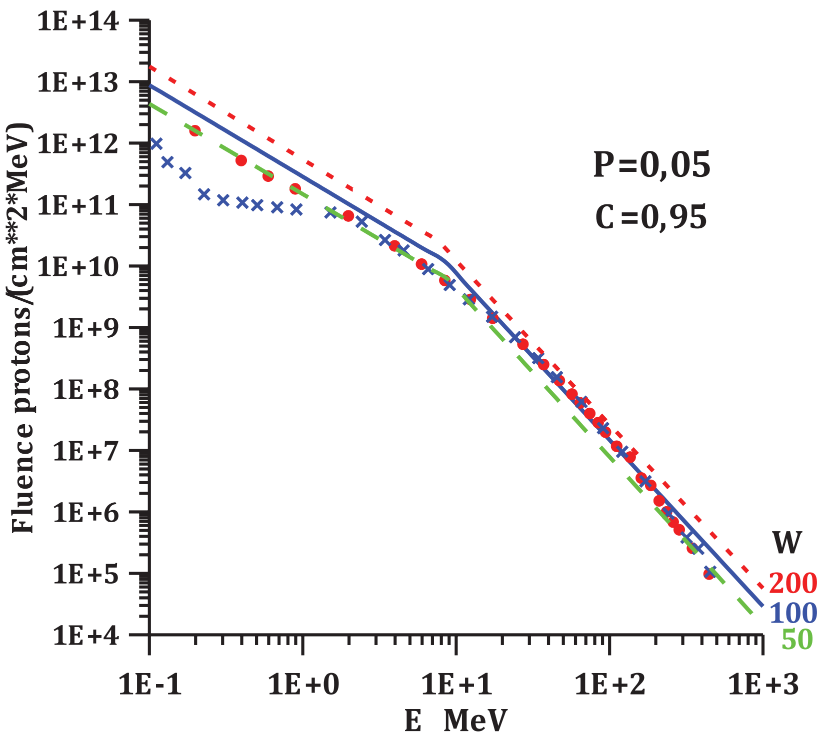

Figure A.6d — Differential energy spectra of annual missions in case of probability, *P* = 0,05 or confidence level 0,95

Lines are the present model data for solar activity W = 50, 100, and 200 (model parameters <*n*> = 8, 16, and 32). Crosses are the ESP model by SPENVIS version and reds dots are the M.Xapsos version (both are in accordance with the M.Xapsos private message from 24.10.2011 data, but the details of this version are not yet known).

From the data plots, the following conclusions can be made:

— All spectra of ESP model are irregular and hardly can be expressed in analytical form.

— All of the ESP spectra (by public SPENVIS version), at energies approximately 3 MeV, coincide with present model for W = 200, at energies approximately 30 MeV for W = 100, and at energies approximately 300 for W = 50. At energies <1 MeV models, data diverge sharply.

— The data corrected by M.Xapsos ESP model better coincides with the present model, but they also don't differ in dependent of solar activity, as all data of models JPL-91[12] and Rosenqvist[13], which in addition are limited by energy ranges.

The problem of the validity of each model can be established by comparison with experimental data, which is dedicated to Annex B.

Annex B
(informative)

Comparing model and experimental data

B.1 General

This Annex gives examples of applying the calculation technique to various time intervals and various solar activity (SA) conditions. Here, the results of calculations are compared with the experimental data available. In the majority of cases, the experimental data are presented in the form of differential fluxes, in such a manner, as they were measured by Stellite instruments.

B.2 "Quiet sun" period

Authors of the models[11-13] divide the solar cycle into two parts, a 7-year period of "active sun " and a 4-year period, the "quiet sun". This division clearly leads to a quantitative criterion during the quiet sun, W < 40. It is assumed that the fluxes of SEP during "quiet sun" can be neglected and particle fluxes in the rest of the 7-year period are the same.

Reference [4] demonstrated that this assumption is erroneous and argued that the quiet sun can appear large during fluxes of SEP. This happened in 2005 to 2006, when the quiet sun appeared in large SEP events. Meanwhile, Reference [14] was an attempt to model quiet time SEP fluxes development. Neglect of probabilistic nature of the event led to the SEP model, even extreme particle fluxes according to this model were more than one order less fluences, which appeared in 2005 (<W> = 28) and 2006 (<W> = 15). [6] See Figure B.1 a).

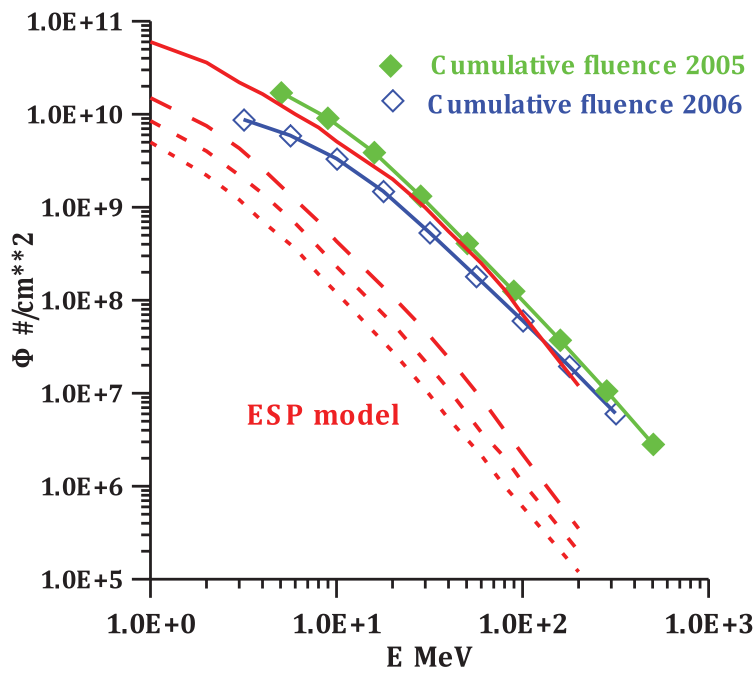

Figure B.1a — ESP model[14] energy spectra predictions for cases of averaged (dotted curve) and worst solar minimum years (short dashed curve)

NOTE Worst solar minimum period (long dashed curve) and average solar maximum year (solid curve). Annual fluence energy spectra, measured by GOES-11 in 2005 (<W> = 28) and 2006 (<W> = 15) are also displayed.

The present model prediction for the "quiet sun" period [Figure B.2 a)] was demonstrated. The data of 1985, 1995, and 2006 for which the average number of sunspots is <W> = 16 were selected.

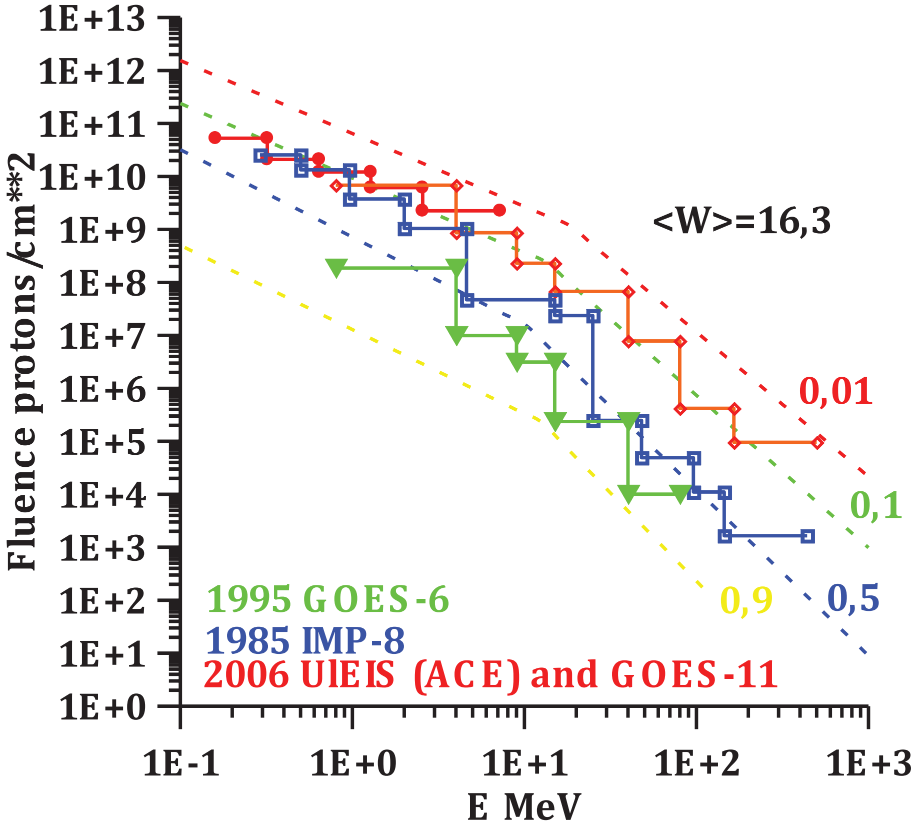

Figure B.1b — Results of calculation of energy spectra of SEP proton fluences whose excess is expected for the annual interval at the average annual number of solar spots <W_y> = 16,3 with probabilities *P* = 0,9, 0,5, 0,1, and 0,01

In contrast to the data in Figure B.1 a), all experimental data are within the present model perfectly explained.

B.3 Annual proton fluences at another SA levels

Figure B.2 a) demonstrates the model calculated spectra for SA level <W> = 100 and experimental data from three different SA cycles (1982, 1992, and 2000). All experimental data are in agreement with the model representation.

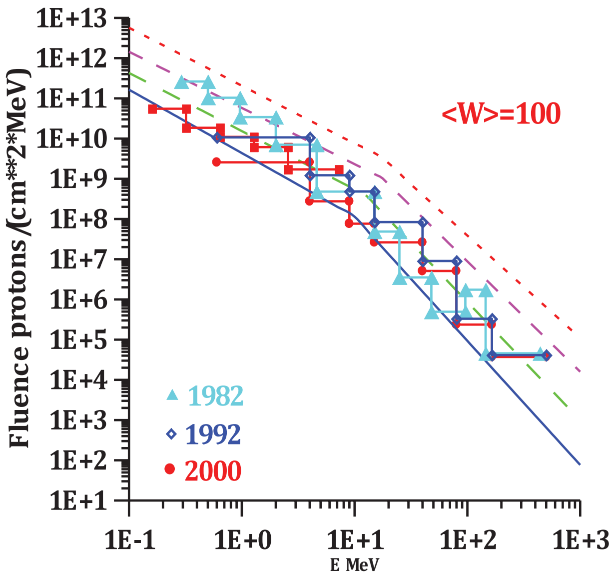

Figure B.2a — Present model calculation for annual activity period <W> = 100 and experimental data from 1982, 1992, and 2000

NOTE Probabilities of energy spectra demonstrated are 0,5, 0,1, 0,01, and 0,001.

The annual ESP fluence spectra for "active sun" period and annual differential fluences and spectra, measured in 2000 by GOES spacecrafts and ULEIS instrument (ACE spacecraft) was analysed in Figure B.2 b).

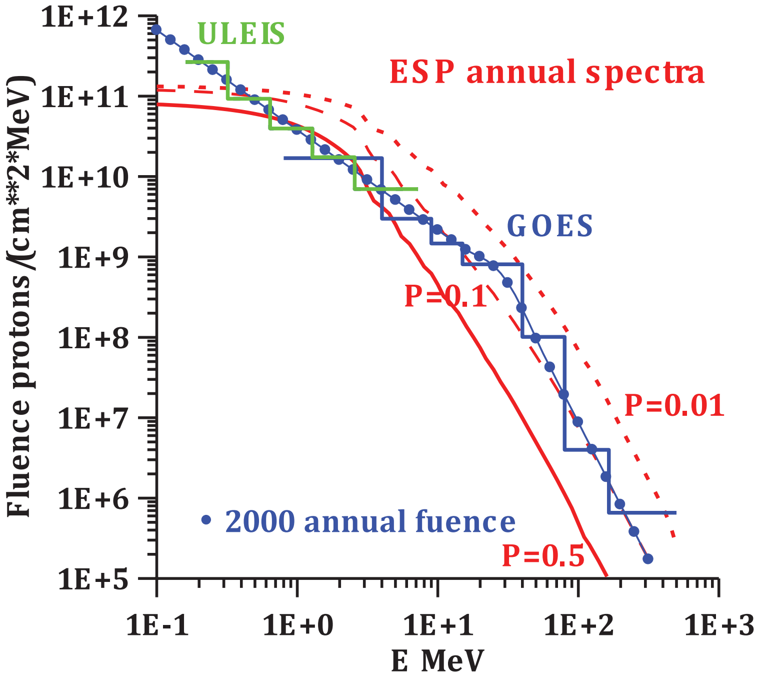

Figure B.2b — ESP model calculation for annual activity period and experimental data about cumulative fluence from 2000

NOTE Probabilities of energy spectra demonstrated are 0,5, 0,1, and 0,01.

Without falling into a detailed analysis, the simulated spectra conflict with the nature of the measured spectrum can be concluded. Of particular note is the systematic neglect by ESP model of low-energy particles.

B.4 SEP proton fluences for SA cycle periods

Figure B.3 demonstrates the 23 cycle measured cumulative fluences, together with present model calculation, result for the corresponding solar activity.

From the data displayed follows that the measured fluences are close to middle ($P = 0{,}5$) model spectrum, which is a normal situation.

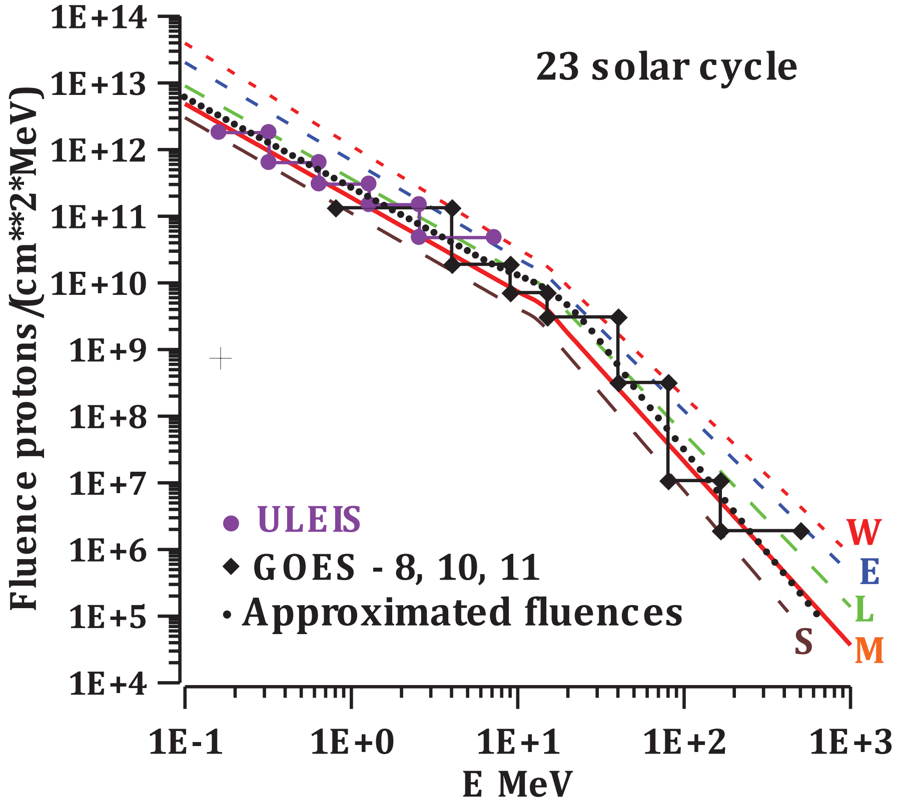

Figure B.3 — 23 cycle measured cumulative fluences together with present model calculation results (S, M, L, E, and W probability cases) for the corresponding solar activity

The model ESP data for solar cycles and their difference from the experimental data will not be analysed. The comments are the same, as in case of annual fluxes.

B.5 Model calculated result for peak fluxes

Figure B.4 demonstrates the results of the peak flux measurement together with model-calculated differential energy spectra.

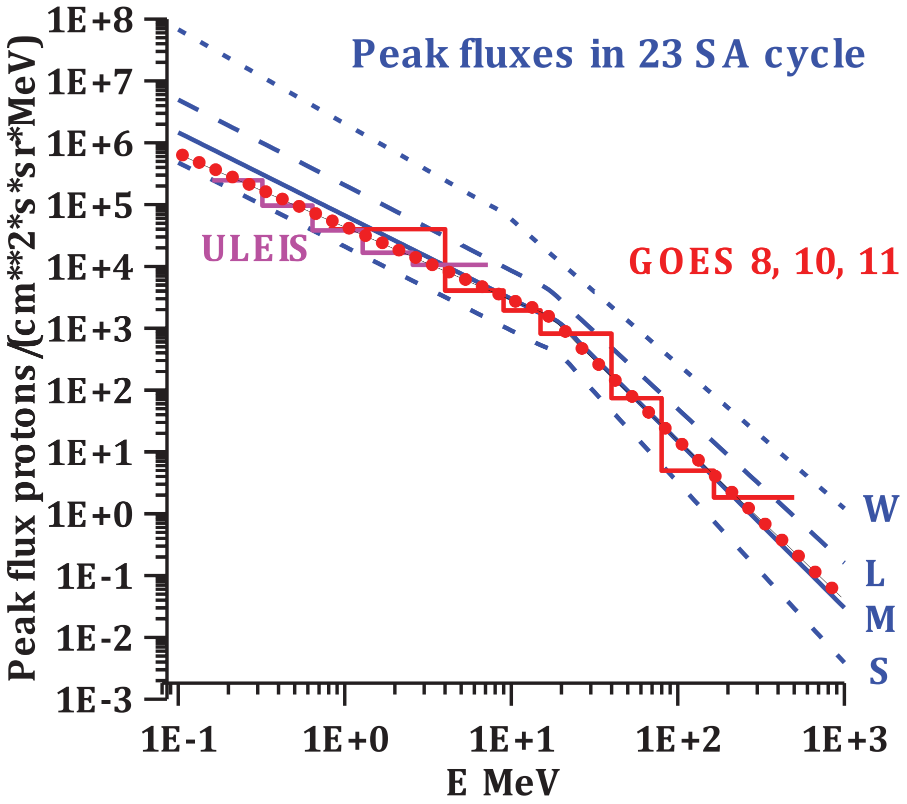

Figure B.4 — 23 cycle measured (instrument ULEIS on ACE spacecraft and proton detektors on spacecrafts GOEA-10 and 11) peak fluxes together with present model calculation results (S, M, L, E, and W probability cases) for the corresponding solar activity

Peak fluxes, measured by GOES instruments ideally coincide with the calculated spectrum for the probability of 0,5. The results of measurements of peak fluxes in the energy range at E < 1 MeV are smaller than this spectrum. A simple analysis shows that in the case of high energies, the fluxes in largest SEP event of 14. July 2000 were measured correctly by GOES instrument, but the low-energy particle fluxes size in this event were distorted in ULEIS instrument six times.

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