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Space environment (natural and artificial) — Galactic cosmic ray model

Environnement spatial (naturel et artificiel) — Modèle de rayonnement cosmique galactique

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Foreword

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Space environment (natural and artificial) — Galactic cosmic ray model

1 Scope

This International Standard specifies a model for estimating the radiation impact of galactic cosmic rays (GCR) on hardware and on biological and other objects when in space. This International Standard can also be used in scientific research to generalize the available experimental evidence for GCR fluxes. This International Standard establishes the model parameters and characteristics of variations in the 10^1 MeV to 10^5 MeV GCR particles (electrons, protons, and $Z = 2$ to 92 nuclei in the near-Earth space beyond the Earth's magnetosphere).

2 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

2.1
galactic cosmic rays
GCR
high-energy charged particle fluxes penetrating the heliosphere from local interstellar space

2.2
Wolf number
W

$$W = 10g+f$$

where

g is sunspot group number;

f is the total sunspot number on the sun's visible disk

2.3
rigidity spectrum
$\Phi_i(R)$
rigidity distribution of cosmic ray particle fluxes

2.4
energy spectrum
$F_i(E)$
energy distribution of cosmic ray particle fluxes

3 Principles of the model

3.1 The model describes the variations of GCR fluxes due to variations in solar activity and in the large-scale heliospheric magnetic field (the sun's polar magnetic field) throughout 22-year cycles.

3.2 The angular distribution of galactic cosmic ray fluxes in the Earth's orbit beyond the Earth's magnetosphere is to be isotropic.

3.3 Solar activity is characterized by 12-month averages of Wolf numbers (sunspot numbers) $\overline{W}$.

3.4 The variations of the large-scale heliospheric magnetic field are assumed to be proportional to the variations of the Sun's polar magnetic field whose intensity and polarity are taken to be dependent on solar activity and on whether a given solar cycle is even or odd:

$$M\left[\overline{W}(t),n\right] = (-1)^{n-1} \times S \times \left\{1 - \left[\frac{\overline{W}(t) - \overline{W_n^{\text{min}}}}{\overline{W_n^{\text{max}}} - \overline{W_n^{\text{min}}}}\right]^{2,7}\right\} \quad (1)$$

where

$S = 1$ at $t - t_n^{\pm} \geqslant 0$ (otherwise, $S = -1$);

$t_n^{\pm}$ is the sign reversal moment of the polar magnetic field in the nth solar cycle identified with solar maximum (values suggested for particle flux prediction: $t_{19}^{\pm} = 1\,958{,}21$; $t_{20}^{\pm} = 1\,968{,}87$; $t_{21}^{\pm} = 1\,979{,}96$; $t_{22}^{\pm} = 1\,989{,}46$; $t_{23}^{\pm} = 2\,000{,}71$ and $t_{24}^{\pm} = 2\,011{,}3$);

W_n^{max} is the highest level of solar activity in the nth solar cycle;

W_n^{min} is the least solar activity level that borders the nth solar cycle.

3.5 The dynamics of the large-scale GCR modulation is characterized by the effective modulation potential of the heliosphere, $R_0\,(t,R)$, (for particles of rigidity R at a given moment t) calculated as

$$R_0 \left\{\overline{W}\left[t - \Delta t(n,R,t)\right]\right\} = 0{,}37 + 3 \times 10^{-4} \times \overline{W}^{1{,}45}\left[t - \Delta t(n,R,t)\right] \quad (2)$$

3.6 The lag, $\Delta t\,(n,R,t)$, of GCR flux variations relative to solar activity variations is taken to depend on magnetic rigidity, R, of particles, on whether a solar cycle is odd or even (n), and on solar cycle phase:

$$\Delta t(n,R,t) = 0{,}5 \times \left[T_+ + T_-(R)\right] + 0{,}5 \times \left[T_+ - T_-(R)\right] \times \tau\left(\overline{W}\right) \quad (3)$$

where the lag amplitude is independent of particle rigidity in even cycles (T_+):

$$T_+ = 15 \text{ months} \quad (4)$$

and in odd cycles (T_-) is

$$T_-(R) = 7{,}5 \times R^{-0{,}45} \text{ months} \quad (5)$$

The time function of the lag variations from Equation (3) to be

$$\tau\left(\overline{W}\right) = (-1)^n \times \left[\frac{\overline{W}(t - \delta_w t) - \overline{W_n^{\text{min}}}}{\overline{W_n^{\text{max}}}}\right]^{0{,}2} \quad (6)$$

where $\delta_w t = 16$ months.

4 GCR rigidity and energy spectra

4.1 General

In terms of the GCR model, the particle flux rigidity and energy spectra are calculated consecutively.

4.2 GCR particle rigidity spectra

4.2.1 GCR particle rigidity spectra $\Phi_i(R, t)$ (s·m^2·sr·GeV)$^{-1}$ for particles of rigidity R at moment t are calculated using the following equation:

$$\Phi_i(R,t) = \frac{C_i \times \beta^{\alpha_i}}{R^{\gamma_i}} \times \left[\frac{R}{R + R_0(R,t)}\right]^{\Delta_i(R,t)} \tag{7}$$

where

$\Delta_i(R, t)$ is a dimensionless parameter calculated using the following equation:

$$\Delta_i(R,t) = 5{,}5 + 1{,}13\,\frac{Z_i}{|Z_i|}\,M\left[\overline{W}(t),n\right] \times \frac{\beta \times R}{R_0(R,t)}\exp\left[-\frac{\beta \times R}{R_0(R,t)}\right] \tag{8}$$

where β is the particle velocity-to-luminal velocity ratio:

$$\beta = \frac{R}{\sqrt{R^2 + \left(\frac{A_i m_i}{|Z_i|}\right)^2}} \tag{9}$$

where A_i and Z_i are particle mass number and particle charge respectively (see Tables 1 and 2);

m_i is particle rest mass, namely,

$m_e = 5{,}1 \times 10^{-4}$ GeV for electrons,

$m_p = 0{,}938$ GeV for protons,

$m_{Z \geqslant 2} = 0{,}939$ GeV/nucleon for nuclei.

C_i, α_i, γ_i are parameters of non-modulated rigidity spectrum of i-specie particles. For particles with $Z \leqslant 28$ see Table 1. For particles with $Z \geqslant 29$, $\alpha_i = \alpha_{26}$ and $\gamma_i = \gamma_{26}$, C_i, is calculated from equation

$$C_i = C_{26}\,\frac{C_i}{C_{26}}$$

where $\frac{C_i}{C_{26}}$ data is found in Table 2.

4.2.2 The standard deviation values, [$\sigma_{\Phi_i(R,\,t)}$], are calculated using the following equation:

$$\sigma_{\Phi_i(R,t)} = \Phi_i(R,t) \times \sqrt{\left(\frac{\sigma_{C_i}}{C_i}\right) + \frac{0{,}08}{\left[1 + \frac{R}{R_0(R,t)}\right]^2}} \tag{10}$$

4.3 GCR energy spectra

4.3.1 The energy spectra $F_i(E,t)$ (s·m^2·sr·GeV)$^{-1}$ of GCR particles of energy E at moment t are calculated using the following equation:

$$F_i(E,t) = \Phi_i(R,t)\,\frac{A_i}{|Z_i|}\,\frac{10^{-3}}{\beta} \tag{11}$$

For particles with $A_i = 1$, the units are (s·m^2·sr·MeV)$^{-1}$.

For particles with $A_i \geqslant 2$, the units are (s·m^2·sr·MeV/nucleon)$^{-1}$.

4.3.2 With prescribed rigidity R of GCR particles, the kinetic energy E, in GeV (GeV/nucleon for nuclei), is calculated using the following equation:

$$E = -m_i + \sqrt{m_i^2 + \left(\frac{Z_i}{A_i}R\right)^2} \tag{12}$$

4.3.3 With prescribed kinetic energy of particles, the rigidity R and the relative velocity β of the particles are calculated using the following equation:

$$R = \frac{A_i}{|Z_i|}\sqrt{E(E + 2m_i)} \tag{13}$$

$$\beta = \frac{\sqrt{E(E + 2m_i)}}{E + m_i} \tag{14}$$

4.3.4 Standard deviation values [$\sigma_{F_i(E,\,t)}$] are calculated using the following equation:

$$\sigma_{F_i(E,t)} = \frac{\sigma_{\Phi_i(R,t)}}{\Phi_i(R,t)} \times F_i(E,t) \tag{15}$$

Table 1 — Parameters of GCR rigidity spectra for particles $Z \leqslant 28$

Z	**Particle**	A_i	$C_i \pm \sigma_{C_i}$	γ_i	α_i
−1	e	1,0	170	γ_e [a]	—
1	H	1,0	(1,85 ± 0,13) 10^4	2,74 0,02	2,85 0,02
2	He	4,0	(3,69 ± 0,22) 10^3	2,77 ± 0,02	3,12 ± 0,02
3	Li	6,9	19,5 ± 1,5	2,82 ± 0,02	3,41 ± 0,11
4	Be	9,0	17,7 ± 1,3	3,05 ± 0,02	4,30 ± 0,12
5	B	10,8	49,2 ± 1,6	2,96 ± 0,01	3,93 ± 0,05
6	C	12,0	103,0 ± 3,0	2,76 ± 0,01	3,18 ± 0,04
7	N	14,0	36,7 ± 1,2	2,89 ± 0,01	3,77 ± 0,05
8	O	16,0	87,4 ± 2,1	2,70 ± 0,01	3,11 ± 0,04
9	F	19,0	3,19 ± 0,28	2,82 ± 0,03	4,05 ± 0,06
10	Ne	20,2	16,4 ± 0,70	2,76 ± 0,01	3,11 ± 0,07
11	Na	23,0	4,43 ± 0,28	2,84 ± 0,02	3,14 ± 0,09
12	Mg	24,3	19,3 ± 0,70	2,70 ± 0,01	3,65 ± 0,27
13	Al	27,0	4,17 ± 0,22	2,77 ± 0.02	3,46 ± 0,21
14	Si	28,1	13,4 ± 0,50	2,66 ± 0,01	3,00 ± 0,10
15	P	31,0	1,15 ± 0,04	2,89 ± 0,01	4,04 ± 0,41
16	S	32,1	3,06 ± 0,12	2,71 ± 0,02	3,30 ± 0,22
17	Cl	35,4	1,30 ± 0,08	3,00 ± 0,04	4,40 ± 0,30
18	Ar	39,9	2,33 ± 0,07	2,93 ± 0,01	4,33 ± 0,21
19	K	39,1	1,87 ± 0,05	3,05 ± 0,01	4,49 ± 0,20
20	Ca	40,1	2,17 ± 0,06	2,77 ± 0,01	2,93 ± 0,16
21	Sc	44,9	0,74 ± 0,02	2,97 ± 0,01	3,78 ± 0,19
22	Ti	47,9	2,63 ± 0,08	2,99 ± 0,01	3,79 ± 0,17
23	V	50,9	1,23 ± 0,04	2,94 ± 0,01	3,50 ± 0,14
24	Cr	52,0	2,12 ± 0,06	2,89 ± 0,01	3,28 ± 0,17
25	Mn	54,9	1,14 ± 0,05	2,74 ± 0,02	3,29 ± 0,27
26	Fe	55,8	9,32 ± 0,24	2,63 ± 0,01	3,01 ± 0,07
27	Co	58,9	0,10 ± 0,08	2,63	4,25 ± 0,79
28	Ni	58.7	0,49 ± 0,02	2,63 ± 0,01	3,52 ± 0,28

NOTE 1 In the case of $Z > 2$ nuclei, the C_i, γ_i, α_i values are for a mixture of the respective isotopes.

NOTE 2 Atomic masses corresponding to the natural elemental abundances are taken to be mass numbers A_i for $Z > 2$ nuclei in conformity with the periodic system chart. This is within the model accuracy.

[a] In the case of electrons, the parameter $\gamma_e = 3{,}0 - 1{,}4 \exp\left(\frac{R}{R_e}\right)$, where $R_e = 1$ GeV.