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A ready-to-use galactic cosmic ray model

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Abstract

Galactic cosmic ray nuclei close to Earth are of great importance in different fields of research. By studying their intensity in near-Earth interplanetary space and modeling their modulation in the heliosphere it is possible to gain knowledge both about the structure of the heliosphere and the transport processes within. Additionally, secondary phenomena like cloud formation, ionization processes in the atmosphere, cosmogenic nuclide production and radiation exposure in space and at aviation altitudes are related to the intensity of the galactic cosmic rays and their modulation in the heliosphere. In order to improve the knowledge about these processes and underlying mechanisms it is often beneficial to perform numerical simulations. A necessary prerequisite for such simulations is a model describing the galactic cosmic ray intensities for all particle types and energies of importance. Several of these models exist in the literature. However, many of these do not provide essential characteristics like the description of heavier nuclei or it is difficult to associate them to recent or actual solar modulation conditions. In this work a model is presented which describes the galactic cosmic ray spectra of nuclei based on a single parameter. The values of this parameter for different solar modulation conditions are derived from measurements of the Advanced Composition Explorer (ACE) spacecraft and Oulu neutron monitor count rates. Comparing the galactic cosmic ray spectra predicted by the model to a comprehensive set of experimental data from literature shows very good agreement.

Keywords: Galactic Cosmic Rays; Solar modulation; Neutron monitors; Solar activity; Sun spot number

1. Introduction

Galactic Cosmic Rays (GCRs) are of importance in many geophysical phenomena and are a major source of the radiation exposure in interplanetary space, low Earth orbit and at aviation altitudes. The nuclear component of the Galactic Cosmic Rays accounting for about 98% of the particles consists mainly of hydrogen (≈87%), helium (≈12%) and to a lesser extent of heavier nuclei (≈1%) (Simpson, 1983). Regardless of their low numbers, nuclei heavier than helium play an important role in some phenomena due to their large number of nucleons, the corresponding masses and their high energies. The enhanced biological effectiveness of the heavier nuclei are of particular relevance concerning the radiation exposure in space (Cucinotta et al., 2003, 2008; McKenna-Lawlor et al., 2011).

Galactic Cosmic Rays are not only the major source of radiation exposure in space, but they are also the cause for a number of atmospheric phenomena such as elevated exposure at aviation altitudes (Reitz, 1993; EURADOS, 2004; Beck et al., 2009), the formation of cosmogenic nuclei (Matthiä et al., 2011; Beer et al., 1988, 1990; Steinhilber et al., 2008), and they are possibly linked to low-level cloud formation and climate change (Svensmark and Friis-Christensen, 1997; Kirkby, 2007).

In order to study such processes in detail and to relate their magnitude to the galactic cosmic ray intensity, an accurate and applicable model of the Galactic Cosmic Rays, their temporal modulation and respective energy distribution is essential. Many of the existing models lack a description of nuclei heavier than hydrogen or helium, e.g. Garcia-Munoz et al. (1975) and Usoskin et al.

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(2005), or are difficult to handle due to an extensive formalism (e.g. the GALPROP model, http://galprop.stanford.edu Strong and Moskalenko (1998), Strong et al. (2007), Shibata et al. (2004, 2006), Nymmik et al. (1992, 1996). Some of these models focus on energies above hundreds of GeV per nucleon which are of great interest in astrophysical questions but do not contribute significantly to most atmospheric processes or radiation exposure due to the low intensities at these energies.

The CHIME model (Chenette et al., 1994) provides spectra of GCR ions in near Earth interplanetary space and inside the geomagnetic field based on estimates of the solar modulation of GCR from IMP-8 helium measurements in the energy range between 70 and 95 MeV/n and Climax neutron monitor count rates for the epoch from 1973 to 1993.

Other models (CREME96/CREME2009, https://creme.isde.vanderbilt.edu/, and O'Neill (2010) are not capable to describe accurately the changes in GCR intensities due to solar modulation. It was found that especially during the recent very deep and extended solar minimum in the years 2008–2010 widely used models could not to describe the prolonged increase in GCR intensity (Mrigakshi et al., 2012).

This work presents a simplified version of the GCR ISO-model (ISO, 2004) modified in order to reduce the number of free parameters to one. This single free parameter is then derived from measurements of galactic cosmic ray carbon fluxes by the Cosmic **R**ay **I**sotope **S**pectrometer (CRIS) on-board the **A**dvanced **C**omposition **E**xplorer (ACE) spacecraft (Stone et al., 1998) for the time period between August 1997 and April 2012. By establishing a linear relationship between the model parameter derived from ACE data and the count rate of the Oulu neutron monitor, http://cosmicrays.oulu.fi/, the backward estimate of the parameter can be extended until the year 1964. Based on these data, an extensive comparison of the model predictions of other galactic cosmic ray nuclei with experimental data is presented and very good agreement is found.

2. The Galactic Cosmic Ray model

The galactic cosmic ray model presented in this work was derived from the GCR-ISO model (ISO, 2004). The ISO model itself is based on publications by Nymmik et al. (1992, 1996), Nymmik and Suslov (1995) and relates the particle intensities to 12 month averages of the sun spot number. In practice, the maximum and minimum average sun spot number during the solar cycle of interest are used together with the average sun spot number at the time of interest taking into account a certain time lag between sun spot numbers and GCR intensities. Additionally, the time of the polar magnetic field reversal of the sun in the solar cycle has to be put in the model. Due to the fact that these quantities are not easily derived and sometimes not even well defined, for instance in the time period close to the end of a solar cycle and the beginning of the subsequent or in the ongoing cycle prior to the magnetic field reversal, the goal of this work was to eliminate the manifold dependence on the sun spot number and on the time of the field reversal and replace it by a single dependence on a well observed parameter.

The starting point of the GCR-ISO model is a description of the rigidity spectrum of the different nuclei:

$$\Phi_i(R,t) \equiv \frac{dN}{dAdt'd\Omega dR}(R,t) = \frac{C_i\beta^{\alpha_i}}{R^{\gamma_i}}\left[\frac{R}{R+R_0(R,t)}\right]^{\Delta_i(R,t)} \qquad (1)$$

- Φ_i is the differential fluence rate or flux density of GCR particle type i with respect to particle rigidity R in GV at time t, i.e., number of particles N per area A, time t', solid angle Ω, and rigidity R.
- β is the ratio of particle speed to the speed of light.
- C_i, α_i, γ_i are parameters given by the ISO model and listed in Table 1. C_i is in the unit $(\text{s sr m}^2\ \text{GV})^{-1}$.
- $\Delta_i(R,t)$ and $R_0(R,t)$ describe the modulation of the GCR in the heliosphere.

At very large rigidities the right part of Eq. (1) and β approach unity and the spectrum is described by a pure power law: $\Phi_i = C_i R^{-\gamma_i}$. The right part of the equation describes the modulation of the spectrum at lower rigidities.

R_0 is a function of the mean sun spot or Wolf number W:

Table 1
Parameters of the galactic cosmic ray ISO-Model.

Nucleus	Z_i	A_i	C_i [(s sr m^2 GV)$^{-1}$]	γ_i	α_i
H	1	1.0	1.85×10^4	2.74	2.85
He	2	4.0	3.69×10^3	2.77	3.12
Li	3	6.9	19.50	2.82	3.41
Be	4	9.0	17.70	3.05	4.30
B	5	10.8	49.20	2.96	3.93
C	6	12.0	103.00	2.76	3.18
N	7	14.0	36.70	2.89	3.77
O	8	16.0	87.40	2.70	3.11
F	9	19.0	3.19	2.82	4.05
Ne	10	20.2	16.40	2.76	3.11
Na	11	23.0	4.43	2.84	3.14
Mg	12	24.3	19.30	2.70	3.65
Al	13	27.0	4.17	2.77	3.46
Si	14	28.1	13.40	2.66	3.00
P	15	31.0	1.15	2.89	4.04
S	16	32.1	3.06	2.71	3.30
Cl	17	35.4	1.30	3.00	4.40
Ar	18	39.9	2.33	2.93	4.33
K	19	39.1	1.87	3.05	4.49
Ca	20	40.1	2.17	2.77	2.93
Sc	21	44.9	0.74	2.97	3.78
Ti	22	47.9	2.63	2.99	3.79
V	23	50.9	1.23	2.94	3.50
Cr	24	52.0	2.12	2.89	3.28
Mn	25	54.9	1.14	2.74	3.29
Fe	26	55.8	9.32	2.63	3.01
Co	27	58.9	0.10	2.63	4.25
Ni	28	58.7	0.48	2.63	3.52