PROCEEDINGS OF SCIENCE

EMPIRICAL MODEL OF GALACTIC COSMIC RAY PARTICLE FLUXES BASED ON THE EXPERIMENTAL DATA IN SOLAR CYCLES 21–24

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Fundamentals of a new model developed for predicting GCR particle fluxes during space missions are discussed. The model is based on the data set measured onboard spacecraft and stratospheric balloons from 1970s till 2015. The model describes fluxes of GCR particles with charge *z* from 1 to 28 and energy from ~80 MeV/nucleon up to 100 GeV/nucleon in the interplanetary space at heliocentric distance ~1 AU as a function of solar activity (averaged sunspot number).

35th International Cosmic Ray Conference – ICRC2017
10–20 July, 2017
Bexco, Busan, Korea

[1]Speaker

PoS(ICRC2017)001

1. Introduction

Fluxes of galactic cosmic ray (GCR) particles are essential components of cosmic radiation, affecting the spacecraft equipment and spaceship crews. At present time for predicting the GCR particle fluxes during the space missions several models are used, which computer-based versions are included in various software packages (including interactive). There are two widely used models, developed for the interplanetary space for heliocentric distance of ~1 AU. NASA Badhwar & O'Neill (BON) model [1, 2] is based on the solution of the equation of charged GCR particle transport from interstellar media into heliosphere, taking into account the variations of heliospheric environment due to the change of solar activity. Skobeltsyn Institute of Nuclear Physics (SINP) model [3] is purely empirical, summarizing the experimental data from monitors (detectors) and spectrometers from spacecraft and balloon experiments.

The main provisions of the mentioned models were formulated in 1980s and refined several times while receiving the new experimental data. Two versions of BON model (BON2004 and 2010) are included in OLTARIS software package (http://oltaris.larc.nasa.gov/). One of the first versions of SINP model is included into CREME96 software [4] (http://creme.isde.vanderbilt.edu/), and the last version of this model is approved as international standard [5].

In the last years for the engineering applications new empirical models [6, 7] were suggested, which using the common approach generalize the large amount of existing experimental data, including obtained in 23 and 24 cycles of solar activity.

In the current study the SINP-2016 model of GCR particle fluxes with energies from ~80 to 10^5 MeV/nucleon for interplanetary space at heliocentric distance of ~1 AU is discussed and the results of its applications are given.

2. Energy spectra of proton and helium

To obtain the analytic expression for the energy spectrum of particles we analyzed series of spectrometer data (BESS [8, 9], AMS [10, 11], PAMELA [12] etc.). It turned out that a good approximation of the experimental data (with an accuracy of 15% at $E >$ ~80 MeV/nucleon) is observed if

$$F_{(\mathrm{p},\mathrm{He})}(E,t)=A_{(\mathrm{p},\mathrm{He})}\cdot E^{-\gamma}\cdot\left(\frac{E}{E+\varepsilon_{(\mathrm{p},\mathrm{He})}(t)}\right)^{\Delta}, \qquad (1)$$

where γ is power-index, characterizing the unmodulated particle spectrum at high energies ($E >$ 20 GeV/nucleon); $\varepsilon_{(\mathrm{p},\,\mathrm{He})}(t)$ is a parameter (modulation potential) depending on time t and $\Delta = 3.7$.

We applied $\gamma = 2.72$ [13] for proton and helium and obtained a good approximation of the particle fluxes in the given energy interval (with mean deviation ±~12%) if $A_{(\mathrm{p})} = 1.7\cdot10^5$ [(MeV/nucleon)$^{1.72}$/(cm^2·sr·s)] for protons and $A_{(\mathrm{He})} = 1.0\cdot10^4$ [(MeV/nucleon)$^{1.72}$/(cm^2·sr·s)] for helium.

3. Energy spectrum of heavy charged particles

Analyzing the CRIS/ACE data [14] in solar cycle 23 and 24 and the spectrometer data we concluded that the heavy charged particle (HCP) energy spectra multiplied by a constant coefficient (specific for different types of HCPs) coincided with a helium energy spectrum measured in the same time period. Figure 1 demonstrates the validity of this conclusion.

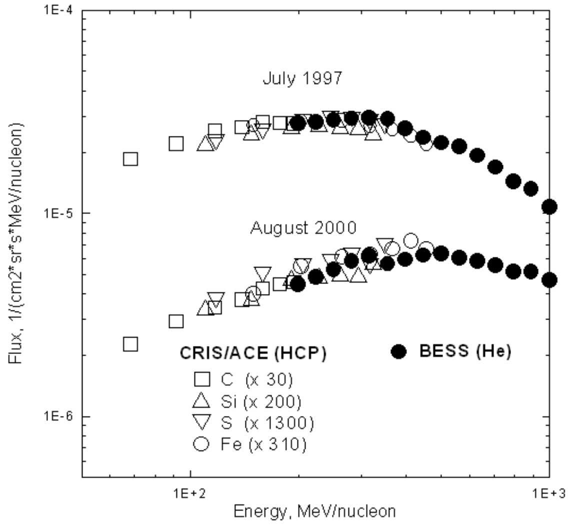

Figure 1. The experimental (CRIS/ACE) fluxes of some heavy nuclei (open badges) normalized to the experimental (BESS) fluxes of the helium (dark badges) at 1997 and 2000. The error of the data is limited by the size of the badges.

Therefore the HCP energy spectra are determined by the formula

$$F_{(\mathrm{HCP})}(E,t) = \zeta_{(\mathrm{HCP})} F_{(\mathrm{He})}(E,t) \ , \tag{2}$$

where $\zeta_{(\mathrm{HCP})}$ is the normalization coefficient which we obtained (see [6]) from the experimental data (http://www.srl.caltech.edu/ACE/).

Thus, expressions (1) and (2) establish the GCR particle energy spectra $F(E, t)$ versus time t if known the modulation potential $\varepsilon(t)$ versus time t.

4. Modulation potential $\varepsilon(t)$

To find the time dependence of modulation potential $\varepsilon(t)$ we substituted in formula (1) the experimental particle fluxes $F(E, t)$ measured by GME/IMP8 (protons and helium) [15, 16], EPHIN/SOHO (proton) [17] and CRIS/ACE (HCPs, http://www.srl.caltech.edu/ACE/) monitors. Figure 2 shows the temporal dependence of $\varepsilon_{\mathrm{exp}}(t)$ for protons and helium in comparison with the temporal dependence of the smoothed monthly mean sunspot numbers $W(t)$.

To improve the correlation between the $\varepsilon_{\mathrm{exp}}(t)$ and $W(t)$ a known effect [18, 19] of the time delays $W(t) \rightarrow W(t - \Delta t\ )$ in odd (Δt_{odd}) and even (Δt_{even}) solar cycles was taken into account. It turned out that the maximum value of the correlation coefficient between $\varepsilon(t)$ and $W(t - \Delta t)$ is at $\Delta t_{\mathrm{odd}} = 15.5$ and $\Delta t_{\mathrm{even}} = 5.5$ months.

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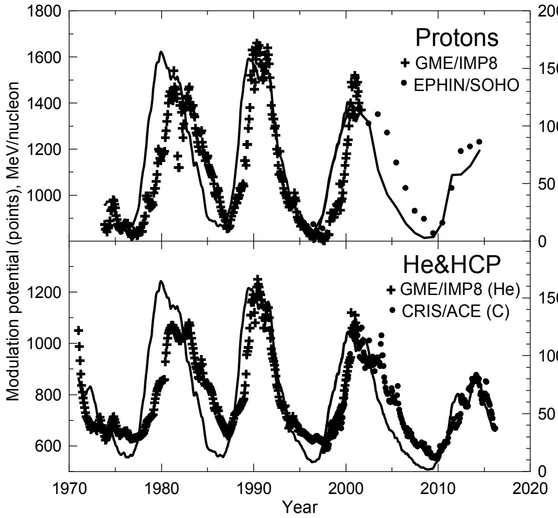

Figure 2. The experimental temporal dependencies of modulation potential $\varepsilon_{exp}(t)$ (points) and International smoothed monthly mean sunspot numbers v.1 $W(t)$ (solid curves).

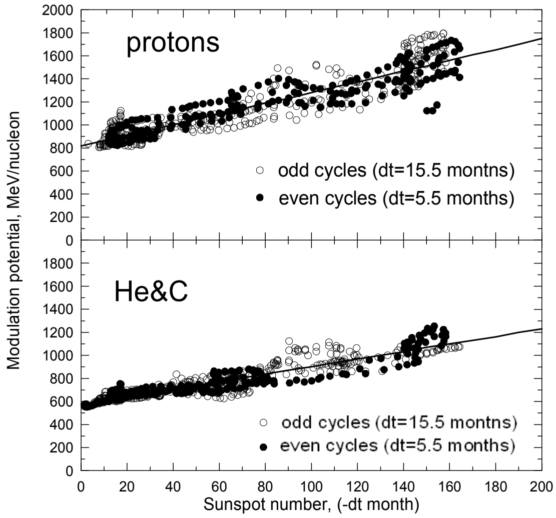

Figure 3. Scatter plot for protons (top panel) and helium & carbon (bottom panel). Straight lines are linear dependency (3) with the average parameters ε_0 and κ (see the text).

Using the adopted values Δt_{odd} and Δt_{even} the scatter plot $\varepsilon_{exp}(t)$ & $W(t-\Delta t)$ was constructed (Figure 3). As we see in Fig. 3 a linear relationship between $\varepsilon_{exp}(t)$ & $W(t-\Delta t)$ exists

$$\varepsilon(t)=\varepsilon_0+\kappa\cdot W(t-\Delta t) \quad (3)$$

To determine the mean values and standard deviations from the mean values for the ε_0 and κ parameters in expression (3) the least squares method was used. The straight lines in Figure 3 are the dependencies (3) with the parameters: $\varepsilon_{0(p)}$ = 817±8.5 MeV/nucleon and $\kappa_{(p)}$ = 4.64±0.08 for protons and $\varepsilon_{0(He)}$ = 576±4 MeV/nucleon and $\kappa_{(He)}$ = 3.26±0.05 for helium.

5. Comparison of model and experimental data

In Figures 4 we can see the examples of comparison of typical temporal dependencies of GCR particle fluxes that was measured by the different monitors and calculated by the SINP-2016 model.

In top panels of Figures 4 we can see the irregular fluctuations of deviation between the experimental and calculated data $(F_{exp}-F_{cal})/F_{cal}$ that sometimes can reach ± ~50% in the phase of solar activity increase and near the solar maximum. We can associate these fluctuations with fluctuations that occur in the solar wind and the interplanetary magnetic field that the model cannot take into account. The mean deviation between calculated and experimental data for long-term intervals (about and more than solar cycle) is within the range of experimental errors about ±10–15% which is within the usual range of experimental errors.

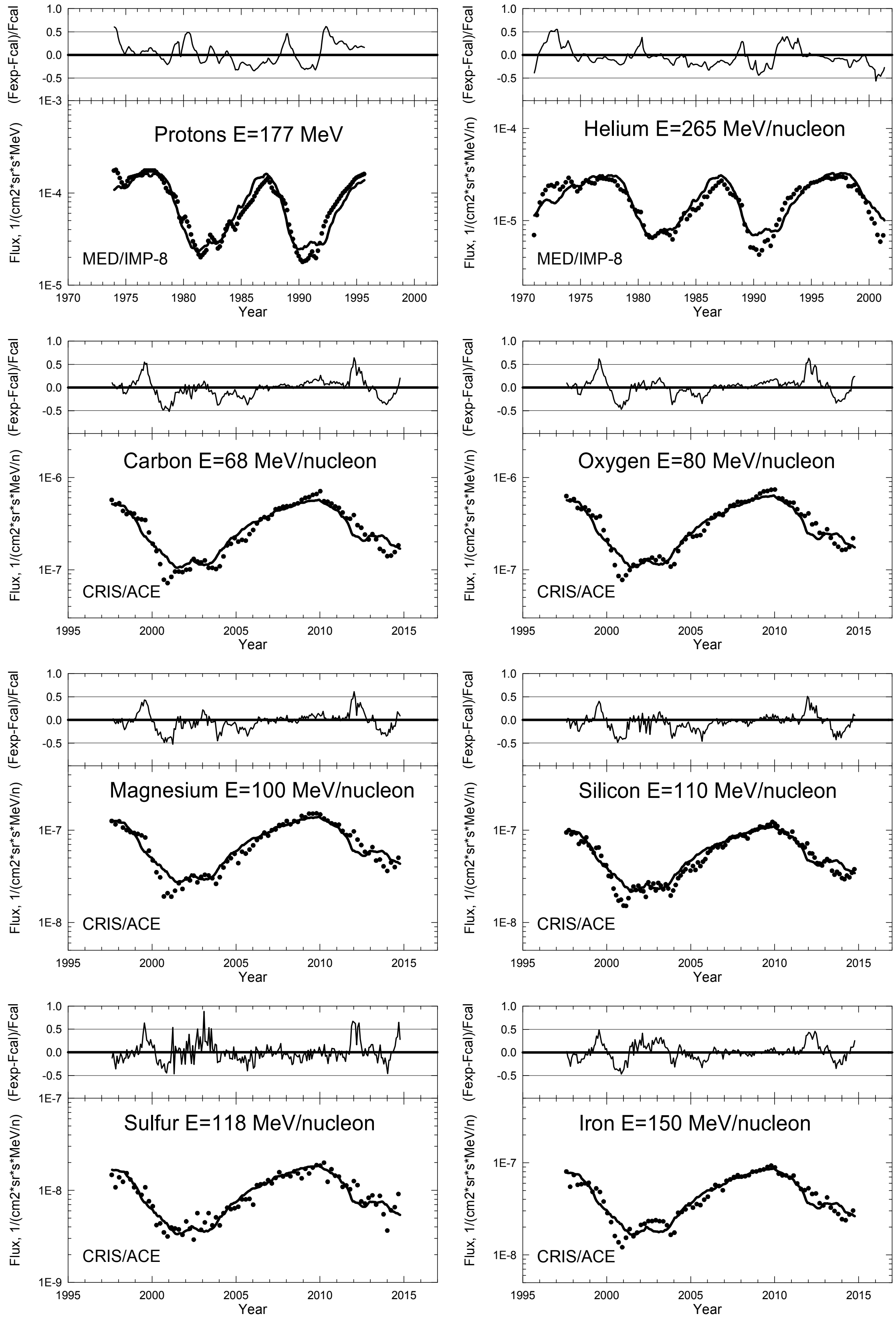

Figure 4. Temporal dependence of the experimental (points) and model (curves) GCR particle fluxes (the bottom panels) and deviations between experimental and calculated data (the top panels).

6. Conclusion

In the current study the main provisions of SINP-2016 empirical model of GCR particle fluxes, developed for the engineering applications, are discussed. The analytical expressions and the parameters of the model generalize the data, obtained by monitors and spectrometers in 21–24 solar activity cycles. The model establishes the relation between the sunspot number and the fluxes of GCR particles with $z = 1–28$) in the interplanetary space in the ecliptic plane at heliocentric distance of ~1 AU. The accuracy of the model is estimated at the level of ±50% during the phase of solar activity increase and near the solar maximum and not worse than ±20% during the phase of solar activity decrease.

Acknowledgments

This work was funded by Russian Science Foundation by Grant 17-29-01022.

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