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ANALYSIS OF THE VARIATION SPECTRUM OF COSMIC RAY FLUX RECORDED IN EARTH'S ORBIT BASED ON AMS-02 MAGNETIC SPECTROMETER DATA

Abstract; *For the first time, based on the experimental data of AMS-02, a three-parameter spectrum of variations of galactic cosmic rays was obtained in the range of rigidity 1- 30 GV, to which neutron monitors are most sensitive. It was found that during the period of negative polarity of the solar magnetic field, a power-law spectrum of variations is observed with a strong exponential decay in the region of high rigidity. When the polarity changes to positive at the beginning of the new 24th solar cycle, the spectrum of cosmic ray variations becomes purely power-law. The transition to the experimentally obtained spectrum of variations will make it possible to remove a number of uncertainties and increase the accuracy of the analysis of data from the ground network of detectors. This will make it possible to retrospectively obtain fluxes of galactic protons with an average monthly resolution for the period of the space era based on ground-based monitoring on a network of neutron monitors.*

Keywords: *long-term variations, AMS-02, spectrum of variations, ground-based detectors.*

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АНАЛИЗ ВАРИАЦИОННОГО СПЕКТРА ПОТОКА КОСМИЧЕСКИХ ЛУЧЕЙ, ЗАРЕГИСТРИРОВАННЫХ НА ОРБИТЕ ЗЕМЛИ, НА ОСНОВЕ ДАННЫХ МАГНИТНОГО СПЕКТРОМЕТРА AMS-02

Аннотация; *Впервые на основе экспериментальных данных AMS-02 был получен трёхпараметрический спектр вариаций галактических космических лучей в диапазоне жёсткости 1–30 ГВ, к которому нейтронные мониторы наиболее чувствительны. Было установлено, что в период отрицательной полярности солнечного магнитного поля наблюдается степенной спектр вариаций с сильным экспоненциальным спадом в области высоких жёсткостей. При смене полярности на положительную в начале нового 24-го солнечного цикла спектр вариаций космических лучей становится чисто степенным. Переход к экспериментально полученному спектру вариаций позволит устранить ряд неопределённостей и повысить точность анализа данных наземной сети детекторов. Это даст возможность ретроспективно получать потоки галактических протонов со среднемесячным разрешением за период космической эры на основе наземного мониторинга сети нейтронных мониторов.*

Ключевые слова: *долгосрочные вариации, AMS-02, спектр вариаций, наземные детекторы.*

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AMS-02 MAGNET SPEKTROMETRI MA'LUMOTLARI ASOSIDA YER ORBITASIDA YOZILGAN KOSMIK NURLAR OQIMINING VARIATSION SPEKTRINI TAHLILI.

Annotatsiya. *Birinchi marta AMS-02 tajriba ma’lumotlari asosida galaktik kosmik nurlar variatsiyalarining uch parametrli spektri olindi. Ushbu spektr neytron monitorlari eng sezgir bo‘lgan 1–30 GV rigidlik diapazonini qamrab oladi. Aniqlanishicha, Quyosh magnit maydonining manfiy qutblanish davrida yuqori rigidlik sohasida kuchli eksponensial kamayishga ega bo‘lgan darajali (power-law) variatsiya spektri kuzatiladi. Yangi 24-Quyosh siklining boshida qutblanish musbatga o‘zgarganda esa kosmik nurlar variatsiyasi spektri sof darajali ko‘rinishga ega bo‘ladi. Tajribaviy ravishda olingan variatsiya spektriga o‘tish bir qator noaniqliklarni bartaraf etish va yer usti detektorlari tarmog‘i ma’lumotlarini tahlil qilish aniqligini oshirish imkonini beradi. Bu esa neytron monitorlari tarmog‘ida olib borilgan yer usti monitoringi asosida kosmik davr davomida galaktik protonlar oqimini o‘rtacha oylik aniqlikda retrospektiv ravishda tiklash imkonini beradi.*

Kalit so‘zlar: *uzoq muddatli variatsiyalar, AMS-02, variatsiyalar spektri, yer usti detektorlari.*

1. Introduction

Despite the significant progress achieved in recent decades, the physical mechanisms underlying the modulation of galactic cosmic rays in the heliosphere still the subject of discussion. The complex process of particle transfer creates problems for the development of a universal picture of long-term variations in galactic cosmic rays, which covers a long observational period (on the order of 70 years) of continuous monitoring of cosmic radiation.

Experimental data on flux variations over the period from the mid-1950s to the present could be obtained with good accuracy only from continuous ground-based measurements on a network of cosmic ray detectors. The need to analyze the results of such long-term ground monitoring led to the creation of special methods. One of the earliest and most successful implementations of the global method was created in Yakutsk [12] and was named the “Global Spectrographic Method” (GSM), since the calculations used data from a network of detectors distributed across the globe. Around the same time, Japanese researchers proposed their methodology [15]. In essence, in all variants this is a method of spherical analysis, where the expansion of the function of cosmic ray variations in spherical harmonics is used. But this takes into account cascade processes in the atmosphere and the movement of particles in the Earth's magnetosphere. With this in mind, we can say that GSM is essentially a sophisticated version of spherical analysis. IZMIRAN has created its own version of GSM [5], which has been used for many years for a detailed and comprehensive study of variations in cosmic rays of the zero harmonic (isotropic component of cosmic ray variations), the first spherical harmonic, and sometimes the second harmonic of cosmic ray variations.

In the simplest case, the problem is reduced to solving a system of equations describing the cosmic ray variations at each point and obtaining the parameters of the isotropic component variation. Directly observed variations in the count rate of the *i*-th cosmic ray detector (where N_B is the base count rate relative to which the variations are calculated) can be represented as

$$v_i = \int_{R_c^i}^{\infty} W^i(R, R_c^i, h_0^i) \cdot \frac{\delta J}{J}(R) \cdot dR + \sigma^i. \qquad (1)$$

Here $W^i(R, R_c^i, h_0^i)$ is a coupling function between primary cosmic ray and variations of the secondary cosmic ray registered by detector i located in the point with geomagnetic cut off rigidity R_c^i on the atmospheric depth h_0. The spectrum of the primary cosmic radiation and the desired spectrum of the isotropic variation are designated, respectively, as $J(R)$ and $\delta J/J\,(R)$. The discrepancy σ^i reflects the inadequacy of the used model of variations and possible hardware variations.

The coupling functions determine the influence of the Earth's atmosphere, and the magnetosphere effect takes into account the rigidity of the geomagnetic cutoff of the considered detector. The coupling functions of the neutron component were calculated by us [4], the coupling functions of the muon component were used from Fujimoto et al. (1976).

An important situation is when the analytical form of the desired solution is known, or the solution can be approximated with a high degree of reliability by a model built on the basis of a priori information. In this case, as a rule, the corresponding system of equations for finding a small number of unknown parameters turns out to be well conditioned. The advantage of this situation is that it is practically impossible to obtain an absurd solution if the analytical model is

chosen in accordance with the process under study.

The objective of this work is to establish the analytical form of the spectrum of variation with a minimum number of parameters for use in analyzing data from the global network of ground-based cosmic ray detectors using the AMS-02 experimental data on the spectrum of protons and nuclei in the range of rigidity from several GV to several tens of GV. This will make it possible to abandon the empirically specified spectra of variation.

2. Data of magnetic spectrometer AMS-02

High-precision data of the orbital detector of cosmic rays AMS-02 for the study of dark matter and antimatter also provide a unique opportunity to measure spectral characteristics at moderate and high rigidity of the particles.

Direct measurements of galactic cosmic rays in the range of rigidities from one to several tens of GV were carried out on the PAMELA [1] and AMS-02 (Ting et al., 2013) spacecraft. The statistical accuracy of the data of the AMS-02 magnetic spectrometer is significantly higher, since the geometric factor of the AMS-02 is about *0.5 m² sr*, and the PAMELA spectrometer is only *21.5 cm² sr*. This work was based on the data of the AMS-02 magnetic spectrometer.

AMS-02 [1,2] is a magnetic spectrometer operating onboard the I*nternational Space Station* from 2011 to the present. The digital data is available in the database [7]. A description of the database can be found in DiFelice et al. (2017). Sampling by rigidity or by time (*t*, *R*) is possible with fixing one of the parameters. For a given moment in time, proton spectra can be obtained in a very wide range of rigidities. In this work, we limited ourselves to the particle rigidity in the range 1 - 30 GV, to which the network of ground-based neutron monitors is most sensitive.

3. Ground methods

In Belov et al. [6]a variant of the global spectrographic method is described specially adapted for studying the long-term behavior of isotropic CR variations. The analysis is carried out using the monthly average data of neutron monitors (about 45 detectors), muon telescopes, and stratospheric sounding. In the simplest case of isotropic variations the problem is reduced to solving the system of equations (1). In the model, it was assumed that the spectrum of variations is given in a three-parameter empirical form and is defined as:

$$\delta J/J(R) = a_1/(R_L + R)^{\gamma}. \qquad (2)$$

Area of the parameter changes: $\gamma = 1 \div 2$ and $R_L = (0 \div 4)$ GV. A three-parameter approximation of the galactic CR variation spectrum is suitable for describing the spectrum of long-term variations in the 5-50 GV regions.

Figure 1 shows the parameters of the spectrum of variations in galactic CR:a_{10}, $R_L$andγ, obtained by this method. The bottom panel shows the standard deviations of the experimental data from the model, which makes it possible to assess the adequacy of the applied variation model.

The spectrum of variations in the form (2) was chosen empirically, but other options were also considered. A direct experimental verification of the shape of the spectrum of variations in the range of rigidity from one to several tens of GV has never been carried out, since the maximum rigidity of particles in measurements of fluxes outside the magnetosphere at best reached 2 GV. Direct measurements in a wide range of rigidities using unique magnetic spectrometers will solve this problem.

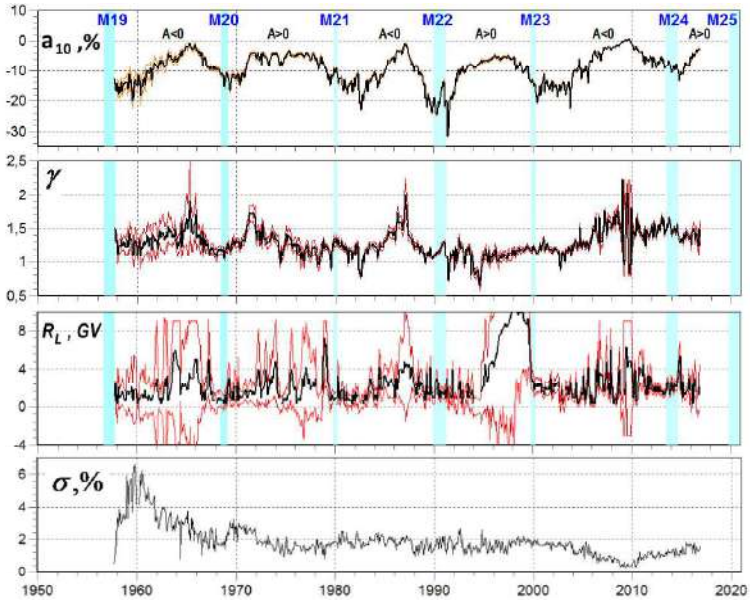


Figure 1. Parameters of the galactic cosmic rays variation spectrum: a_{10}, R_L andγ the model discrepancy is shown at the bottom. The error range is shown in red.

4. Method of experimental determination of the spectrum of variations

To experimentally determine the spectrum of GCR variations, we used data from the AMS-02 magnetic spectrometer

for the entire period of its operation. The time course of AMS-02 flux variations relative to the 2009 base period and their comparison with the GSM results are shown in the top panel of Fig. 2. The period of the polarity reversal of the Sun magnetic field from the second half of 2013 to the first half of 2014 is also highlighted here (Sun, 2015). But above all, the measured flux was freed from the contribution of solar cosmic rays.

For this, the periods of solar events were excluded from the analysis: 13 SPE, including 6 GLEs. The selection criterion for the events was the excess of the proton flux> 100 MeV threshold of 1 pfu (graphical data can be found on the website (SWPC, 2020)).

Analysis shows that the contribution (<10^{-4}%) of solar cosmic rays can be neglected by considering the averaged galactic CR flux per Carrington revolution. In fig. 2 (top left panel), the SPE and GLE moments during the AMS-02 operation period are marked with vertical segments, the length of which is proportional to the effect.

The result of the analysis in Fig. 2 is shown for the period of negative polarity (left) and positive polarity (right) of the Sun magnetic field, and the time point is marked with a vertical line in the upper panel of the figure.

The middle panel shows the spectrum of particles (protons) J for the considered moment of time and the spectrum of particles J_B for the base period. Due to the lack of data for a later period, January-April 2017 was selected as the base period (horizontal segment on the top panel), although the SA minimum and the maximum count rate are observed in April 2020. The results should be considered as preliminary and should be revised after updating the AMS-02 data.

Changes in the particle spectrum relative to the particle spectrum in the base period determine the spectrum of variations. By definition, the spectrum of variations for each point in time is defined as:

$$v = J/J_B - 1 \qquad (3)$$

In the last expression, the variables are functions of time and rigidity, i.e. $v(t,R)$, $J(t,R)$ and $J_B(R)$.

The experimental spectrum of variations, in this way determined, is shown in the lower panel of Fig. 2 (points and errors in their determination) for two polarities of the total magnetic field of the Sun.

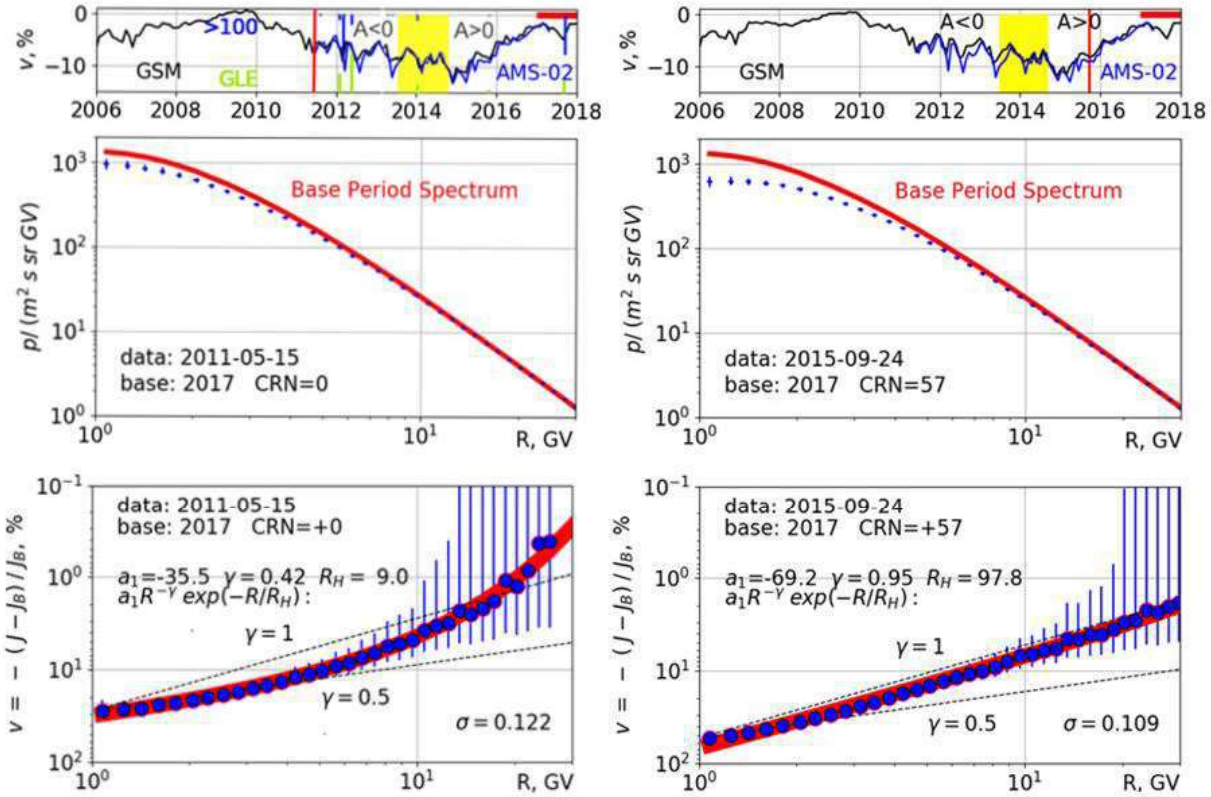


Figure 2. An example of spectra for two points in time: for a period of negative (left) and positive polarity (right) of the total magnetic field of the Sun. The middle panels show the particle spectra (obtained from AMS-02) and the spectra of variations found on their basis, shown in the lower panels.

The choice of the approximating function for the spectrum of variation depends on the rigidity range and the problem being solved. Several analytical models of the spectra of cosmic ray variations were considered, including the spectrum of variations of the form (2).

However, the most successful for approximating the experimental spectrum of cosmic ray variations in a wide range of rigidities was the power-law spectrum modulated by an exponential in the region of upper rigidities, i.e.

$$v = a_1 R^{-\gamma}\, exp(-R/R_H), \qquad (4)$$