On the rigidity spectrum of the long-term cosmic ray variations

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Over a long 60-year period, a spectrum of cosmic ray variations and its variations was obtained, which made it possible to reveal the features of large-scale effects in cosmic-ray modulation, the presence of 22-year and 11-year cycles in the spectrum of cosmic-ray variations, and confirmed the anomalous modulation in the 1970s.

The spectrum of long-term cosmic-ray variations in the 19-24 cycles of solar activity, determined from the experimental data, allows us to verify certain conclusions of the theory of heliospheric modulation of cosmic rays with respect to the role of magnetic drift of particles in cycles with different polarities of the solar magnetic field. In particular, the rigidity dependence of the $R^{-2}$ spectrum of variations of cosmic rays in minima of negative cycles of solar activity associated with scattering of particles near the neutral current sheet is experimentally confirmed.
Method and Data

The method is based on the global spectrographic method GSM [Belov et al., 2018] in the zero-harmonic approximation. The equation for the spectrum of the primary variations $\delta J / J$ is given by the integral Fredholm equation of the first kind:

$$\delta^i = \int_{R^i_c}^{\infty} W^i (R_c^i, h_0^i, R) \cdot \delta J / J(R) dR$$

where the coupling function $W^i (R_c^i, h_0^i, R)$ of the observed secondary $\delta^i$ and primary variations acts as the nucleus of the equation. The search for the unknown function of the spectrum of the primary variations is carried out in the form

$$\frac{\delta J}{J} = \frac{a_1}{(b + R)\gamma}$$

where three parameters $a_1, b, \gamma$ determine the spectrum of the primary variations.

To solve the system of spectrographic equations, the following data were used:
1) world network of neutron monitors (40 detectors) [http://www.nmdb.eu/nest],
2) Stratospheric sounding data (3 points) [Stozhkov et al., 2007],
3) data of the Nagoya multidirectional muon telescope (17 directions of arrival of particles) [http://www.stelab.nagoya-u.ac.jp].
Behavior of the parameters of the stiffness spectrum of long-term variations of cosmic rays.

Proceeding from the obtained parameters of the spectrum of cosmic ray variations $a_{10}$, $\gamma$, $b$, we can draw the following conclusions:

- The amplitude of the spectrum is determined with very good accuracy, even in the early period.
- Significant changes in the stiffness dependence of the variations are displayed in the behavior of the parameter $\gamma$ (the exponent is given with a standard statistical error). The error in determining $\gamma$ is relatively small, and this allows us to make well-founded conclusions about the behavior of $\gamma$ in the analyzed cycles of solar activity with the direction of the polar magnetic field $q_A$.

- The interval of changes in the parameter $b$ is in the range 0 ÷ 4. This indicates that in some periods the spectrum of variations may be just power-law, but the growth of the SA leads to its complication. Analysis of the behavior of the parameter of the spectrum $b$ requires caution, since this parameter is determined least accurately.

- The adequacy of the applied variation model can be judged from the value of the standard deviation of the experimental data and the $\sigma$ model, which is $\leq 2\%$, not taking into account the early period. The number of stations providing such $\sigma$ is about 40.
Cyclic changes of cosmic ray variation spectra in 1957-2017 годы.

Question: how do the solar magnetic cycles affect the stiffness dependence of long-term variations of cosmic rays?

Changes in the index $\gamma$ indicate a softening of the spectrum of cosmic ray variations in the three minima of the 22-year CA cycles with the direction of the global magnetic field of the sun $qA < 0$: $\gamma = 1.2 \div 1.4$ (Fig. A).

For a different field direction $qA > 0$: $\gamma = 1.8 \div 2.0$ (Fig. B).
Anomalous behavior in 70th. “Mini-cycle”.

The role of drift in the change of the CR intensity in the period 1972-1974 was considered in [Alekseev et al., 2013]. This feature was explained by the authors as the long-term modulation of CR due to the fact that for two years both poles were negative, so that the heliosphere turned out to be open not only near the poles, but also partially in the equatorial zone ± 40 ° (experimental data are available only from the late 70's) . Apparently, this additional possibility of the arrival of charged particles in the heliosphere through a kind of "hole" in the heliomagnetosphere led to a rapid increase in the intensity of galactic CRs during this period [Alanko-Huotari at al., 2006; Krymsky at al., 2007].

Thus, the revealed anomaly in the behavior of the indicator fits well to the anomalous picture of the 70s. It does not prevent us from asserting that in the changes of the spectrum shape in the long-period CR variations there exists a 22-year cycle: for \( qA < 0 \), the spectrum of the variations is softer than for \( qA > 0 \).
Drift effects and energy dependence of cosmic rays modulation.

The spectrum of CR variations derived from the experimental data obtained during the long time period (19-24 cycles of solar activity) can be used to check some predictions of the theory of CR heliospheric modulation concerning the role of magnetic drifts in solar cycles with the opposite magnetic polarity.

In the case of the weak modulation the decrease of CR intensity in the heliosphere \( \delta N \) is determined by the energy losses \( \Delta E \) (Kota, 1979):

\[
\frac{\delta N}{N} = (2 + \gamma) \frac{\Delta E}{E}
\]

(2)

here \( \gamma_0 \) is the slope of CR differential energetic spectrum. The energy losses in the idealized heliosphere with the flat neutral current sheet are given by the following expression (Kota, 1979)

\[
\Delta E = |q\Phi| + p \int_r^R \frac{u}{\lambda} \, dr
\]

(3)

Here \( u \) is the solar wind speed, \( \lambda, q \) and \( p \) are the free path length, the charge and the momentum of the particle respectively, \( \Phi \) is some electric potential difference.
Drift effects. $A<0$.

For negative magnetic polarity $A<0$ the protons enter the heliosphere along neutral current sheet, drift on latitude from the equator to poles and leave the heliosphere in polar regions. Therefore the potential difference $\Phi$ in expression (3) for the equator region is

$$\Phi = 0, \quad A<0$$

In this way, for $A<0$ the proton modulation is determined by energy losses during the propagation in the equatorial region. They are described by the second term in Eq. (3). The dependence on the free path length $\lambda$ does not mean that the particles reach the Earth along magnetic field lines. In the outer heliosphere the particles move across magnetic lines with the speed comparable with the speed of light moving along the neutral current sheet. Random scattering of particles destroy this motion along the current sheet and diminish the mean speed of particles in the radial direction. The higher the scattering frequency the lower the mean speed and the longer time for the particle to reach the Earth. The same is true for the energy losses described by the second term in (3).
Drift effects. $A>0$.

For the magnetic polarity $A>0$ there are an additional energy loses related with the magnetic drift from the pole to equator. It is described by the first term in Eq. (3). This heliospherical potential about 180 MV corresponds to 8 percent of modulation for 10 GeV protons.

\[ \Delta E = |q\Phi| + p \int_{r}^{R} \frac{u}{\lambda} \, dr \]  

During the period of positive magnetic polarity $A>0$ the galactic CR protons penetrate into heliosphere in polar regions, after that they drift in the nonuniform magnetic field from the poles to the equator and leave the heliosphere along the neutral current sheet. The magnetic drift from the pole to the equator is accompanied by energy losses corresponding to the potential difference $\Phi$ that is equal to the heliospheric potential $\Phi_0$ and determined by the solar magnetic field $B_0$, by the solar radius $r_0$ and by the angular rotation velocity of the Sun $\Omega$. It can be also rewritten in terms of solar wind speed and azimuthal component of the interplanetary magnetic field $B_e$ at the Earth orbit:

\[ \Phi_0 = B_0 r_0^2 \Omega / c = 180MV \frac{u}{400km / c} \frac{B_e}{3 \cdot 10^{-5} Gauss} \]  

\[ \Phi = \Phi_0, \ A>0 \]  

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Dependence of modulation on energy.

\[ \frac{\delta N}{N} = (2 + \gamma) \frac{\Delta E}{E} \]  

(2)

\[ \Delta E = |q\Phi| + p \int_{r}^{R} \frac{u}{\lambda} \, dr \]  

(3)

It is important that two terms in Eq. (3) have a different energy dependence. The particles with energies above several GeV are scattered by magnetic inhomogeneities with size that is smaller than the gyroradius of the particles. The theory predicts the quadratic dependence of the free path length on momentum of cosmic rays particles \( \lambda \sim p^2 \) (Dolginov and Toptygin, 1967) for this case.

Therefore during the minima of negative solar cycles when the tilt of the current sheet is small we expect to observe \( p^2 \) dependence for CR modulation and for long-term CR intensity variations of 10 GeV protons. In real situation the tilt makes the path of CR particles to the Earth longer and results in stronger modulation (Dolginov and Toptygin, 1967). However Eq. (3) is not valid for large tilts. It is expected that in this case the mean speed is determined by the magnetic drifts which corresponds to \( p^{-1} \) dependence of modulation and CR variations.

During the minima of positive cycles \( A>0 \) the modulation is mainly determined by the first term in Eq. (3) and we expect to observe \( p^{-1} \) dependence of the modulation and CR variations. At this period the influence of the tilt on the modulation is minimal. During the maxima when the tilt is large the drift of particles in the vicinity of the neutral current sheet is directed to the outer heliosphere and can partially compensate fast inward drift motion of particles in polar regions. This will result in stronger modulation with the same \( p^{-1} \) energy dependence.
Conclusion.

- Rigidity spectrum of CR variations is obtained for every month during the last 60 years using the data of worldwide network detectors and applying the improved global survey method that provides the accuracy of the spectral parameters derived.
- The shape of the rigidity spectrum of CR variations depends on the level of the solar activity and on the magnetic polarity. It is impossible to describe this shape with one set of parameters.
- We observe the softening of long term CR variation spectrum in minima of the solar activity and change from $R^{-1}$ to $R^{-2}$ dependence after even cycles.
- The spectrum of long-term CR variations in the 19-24 solar activity cycles, determined from the experimental data, makes it possible to verify some conclusions of the theory of heliospheric CR modulation concerning the role of the magnetic drift of particles in cycles with the different polarity of the solar magnetic field. In particular, we propose the explanation for the observed $R^{-2}$ spectrum of the variations in the minima of the negative solar activity cycles, related with the scattering of particles in the vicinity of the neutral current sheet.