The rigidity spectrum of the long-term cosmic ray variations during solar activity cycles 19–24

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Abstract. The monthly rigidity spectrum of cosmic ray (CR) variations in the 19-24 cycles of solar activity was obtained by the global survey method using the data of continuous ground and near-Earth monitoring of CRs, exempted from atmospheric and local effects. The changes of the spectrum, first obtained for such a long period, made it possible to reveal the features of large-scale effects in CR modulation, the presence of 22-year and 11-year CR variations in the spectrum, and confirm an abnormal spectrum change in the 70s. The paper assumes a rigidity spectrum of CRs, given in a three-parameter form. Analysis of the obtained long-term CR variations for particles with rigidity 10 GV shows that the amplitude of the 22-year wave in the CR intensity increases from cycle to cycle and reaches its maximum value at the minimum of 23/24th solar activity cycle. Softening of the spectrum at the cycle minima has been revealed for the negative polarity of the solar magnetic field (qA<0). The reasons for the abnormally high CR density at the minimum of the 24th cycle and the spectrum features in the 70s are discussed. 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.

1. Introduction

60 years of permanent observations of cosmic ray (CR) variations via the worldwide neutron monitor network permits to obtain the information about the influence of the long-term behavior of the solar activity on the CR intensity observed at the Earth and in the interplanetary medium. Different methods are used for the investigation of the cosmic ray modulation like an analysis of 11-year and other kinds of the solar cyclicity, empirical and theoretical modeling of CR modulation etc.

The long duration of the continuous registration of CR intensity by stable working detectors is the necessary and main condition for the investigation of rigidity spectra of long-term CR variations and for the basis of the modulation theory describing CR variations during the solar cycle.

The spectra of CR variations of the ground based and near Earth CR monitoring are generally found using the exempted from atmospheric and local effects CR variations obtained via the global survey method [1] and its modifications [2-5].

It is known that the rigidity dependence of long-term CR variations has a complex shape that is different from the power law one. In the present work we shall use a three-parametric form of the rigidity spectrum. Our task is to obtain the spectral parameters for every month for the long period of 6 solar cycles and to discuss the cyclic changes of the rigidity dependence of CR variations and its features at anomalous periods.

The rigidity 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 [6-10]. 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.

2. Data and method

The spectrum of long-term CR variations was determined for every month in years 1957-2016. For this purpose the data of worldwide neutron monitor network (41 neutron monitor (NM) stations), 3 stations of stratospheric observations [11] and the data of multi-directional meson telescope (Nagoya station, 17 arrival directions) [12] were used.

We determined the spectral characteristics of long-term CR variations based on 1) results of continuous CR observations in 1957-2016 years; 2) the global survey method; 3) three-parameter rigidity dependence of the spectrum $\delta N/N(R) = a/(b+R)^\gamma$; 4) the rigidity cut-off determined for every station in year 2016 [13].

The rigidity dependence is normalized to rigidity 10 GV that is close to the effective rigidity of neutron monitors. The model of variation for primary CRs is the following:

$$\delta = \Delta N / N = a_{10}(10 + R)^\gamma / (b + R)^\gamma$$  \hspace{1cm} (1)

We use the global survey method. The detectors mentioned above are considered as one unified multi-directional detector with high accuracy standard devices.

The spectral parameters $a_{10}$, $b$ and $\gamma$ of long-term CR variations were determined for cycles 19-24 for rigidities $R=1$-25 GV. The calculation of the spectrum for every month during 60 years (1957-2016) was performed for the one basic period 01.2009-12.2009. This helps to avoid errors appearing from the different of base periods. An additional advantage is the high CR intensity in 2009 that is the highest during 60 years. This result in better accuracy of the parameters determined.

3. Parameters of rigidity spectrum of long-term CR variations

The parameters for the spectrum of galactic CR variations $a_{10}$, $\gamma$, $b$ in expression (1) and the standard statistical error $\sigma$ are shown on figure 1.

![Figure 1. The model parameters for long-term changes of CR variation in 1957-2016: the top panel - the amplitude $a_{10}$ and its error (red), the second panel - the spectral index $\gamma$ and its error (red), the third panel - the parameter $b$ and its error (red), the bottom panel - the standard deviation of the data and the model $\sigma$.](image-url)
The value of the parameter \( b \) was found between \( b=0 \) in 1994 and \( b=10.8 \) in 1998. This means that the spectrum of CR variations can be power law at some periods of time while the spectral shape is more complex in other periods of the solar activity. The results found for the parameter \( b \) are not robust because of the low accuracy. The good quality of the model applied is reflected by the small mean square deviation \( \sigma \) of experimental data from the model (see figure 1). Its value is below 2% after 1965 up to the present. The number of stations is about 40 to provide such a value of \( \sigma \). The error is higher at the first years (1957-1965) of the worldwide network operation. The effective area of the ground based detectors was lower at the first years. The same is true for the statistical accuracy. However the high value of \( \sigma \) is probably not because of this. It is mainly explained by maximum time distance from the basic period, by influence of aperture drifts and large CR variations in 19-th cycle.

Significant deviations for the rigidity dependence of variations manifest themselves in the behavior of the parameter \( \gamma \) (see figure 1). The parameter \( \gamma \) is shown together with the mean statistical error. The value of the parameter \( \gamma \) was found in the interval \( 0.6(09.1994) - 2.2(02.2009) \). The statistical error for the parameter \( \gamma \) is small. Therefore we can make justified conclusions about \( \gamma \) behavior in the solar cycles with opposite directions of the polar magnetic field \( qA>0 \) \& \( qA<0 \) that is the standard notation used for the modulation of charged particles for negative and positive directions of the heliospheric magnetic field.

4. Cyclic changes of CR variation spectra in 1957-2016 calculation

Results of long continuous observations of CRs, solar and heliospheric magnetic fields were not available during early investigations of CR variations. Therefore it was difficult to reveal the long-term effects in CR modulation. The situation is different now. In particular it is possible to investigate how solar magnetic cycles influence on the rigidity dependence of the long-term CR variations.

The periodicity found for the parameter \( \gamma \) for the used spectral model (1) in 6 cycles of solar activity (19-24) is related with the dependence of CR variations on the cycle phase and on the sign of the global solar magnetic field \( qA>0 \) \& \( qA<0 \). It is shown in this work that there exist 22-year wave of CR intensity at the negative minima of
the solar activity \(qA<0\). The amplitude of this wave increases with time and is maximal in the last minimum of the solar activity between 23th and 24th cycle.

The periodicity found for the parameter \(\gamma\) for the used spectral model (1) in 6 cycles of solar activity (19-24) is related with the dependence of CR variations on the cycle phase and on the sign of the global solar magnetic field \(qA>0\) and \(qA<0\). It is shown in this work that there exist 22-year wave of CR intensity at the negative minima of the solar activity \(qA<0\). The amplitude of this wave increases with time and is maximal in the last minimum of the solar activity between 23th and 24th cycle.

The change of the parameter \(\gamma\) points to the softening of the CR variation spectrum in three minima of 22-year cycles of the solar activity when the solar magnetic field was negative \(qA<0\): 19/20 \((\gamma\approx1.9)\), 21/22 \((\gamma\approx2.0)\) and 23/24 \((\gamma\approx2.2)\) (see figure 2a). This is not the case for the positive minima of cycles of the solar activity \(qA>0\): 20/21 \((\gamma\approx1.4)\) and 22/23 \((\gamma\approx1.2)\) (see figure 2b).

We cannot obtain accurate values of \(\gamma\) in the minimum of 23/24 cycle because 2009 year is the basic period and CR variations are close to 0 in 2009. Nevertheless the parameter \(\gamma\) is high also before the CR maximum in 2009 and after 2009. At this time the spectrum of CR variations was soft with the parameter \(\gamma\) close to 1.5-1.7.

CR variations at high and low energies have a different behavior at this period. Low energy particles show a faster increase of intensity in comparison with high energy ones. We investigated the rigidity dependence in 24th cycle and compared it with CR intensity in minima of other cycles [16]. Time dependence of CR variations reflects the complex behavior of modulation for particles with different energies in 2009. In particular we found that low energy particles reach the maximum intensity faster contrary to the standard point of view. CRs of 10 GV rigidity reach the maximum two months later (09.2009) than 5 GV particles (07.2009).

The different behavior for the modulation of low energy and high energy particles during subsequent minima of solar activity was already mentioned in the paper [17]. It was explained by the difference of the drift motion of charged particles in the heliospheric magnetic field during the change of solar magnetic polarity. It seems that our results show a clear difference of the rigidity dependence of CR variations at opposite magnetic polarities. However this is not so clear at 70th years between 21 and 22 cycles. This special period is discussed below.

### 5. Anomalous behavior in 70th

It is clear from figure 2 that the spectral index of CR variations \(\gamma\) increases in 70th years and its behavior is strongly different in comparison with the next similar period of the magnetic polarity with \(qA>0\) in 90th years. This is not the only one special feature of this period.

The influence of the magnetic drift on the CR intensity during 1970-1971 years was discussed in paper [18]. The observed peculiarity of the long-term CR modulation was explained by the same sign of the magnetic field at both solar poles. Such a magnetic configuration produced an additional penetration of galactic CR particles in near-equatorial regions at \(\pm40^\circ\) latitudes [18]. This extra penetration of particles resulted in the fast increase of CR intensity at the end of 1971.

The special behavior of CR variations was explained in (Belov et al., 1993) by consequences for observed CR variations of a so called “mini-cycle” in (1972-1974) [19 and references therein]. It was characterized by the rigidity dependence of CR modulation close to the one found in negative \(qA<0\) minima of the solar activity like in 1965 and 1987. This feature was mentioned in the paper [20] where it was related with the magnetic drift of particles in the framework of the heliospheric model of CR modulation in different solar cycles.

So the anomalous behavior of the index \(\gamma\) is related with the anomalous conditions in the heliosphere in 70th years. This does not contradict to our conclusion about 22-year periodicity for the spectrum of CR variations. The spectrum is softer for \(qA<0\) than for \(qA>0\). It is not excluded that this difference increases with time.
6. Drift effects and energy dependence of CR 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 \( \Delta E \) [6]:

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

(2)

here \( \gamma \) 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 [6]

\[
\Delta E = |q\Phi| + \int_{r_i}^{r_e} \frac{\Phi}{\lambda} u \, dr.
\]

(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. 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 \( \Phi_0 \):

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

(4)

that is 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.

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

\[
\Phi = \Phi_0, \quad qA>0; \quad \Phi=0, \quad qA<0
\]

(5)

This expression is written for protons. The dependence on the magnetic polarity is opposite for electrons.

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 Eq. (3). For the opposite sign of 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.

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 \( \lambda \sim p^2 \) [21] for this case.

The free path length have a weak energy dependence at lower energies.

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 [21]. 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.

7. 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.

This work was partially supported by RFBR grant 17-02-00508, by the program of the Presidium of RAS №3, support the project UNU "Russian national network of ground stations of cosmic rays". We are grateful to all the staff of the World Network of cosmic ray stations http://cr0.izmiran.ru/ThankYou.

References

[1] Krymsky G F 1969 Cosmic Rays Modulation in the Interplanetary Space (Moscow: Nauka) P152
[2] Dorman L I 1975 Variations of Galaxy Cosmic Rays (Moscow: MGU) P214
[3] Dorman L I 1976 Geomagnetism and Aeronomy 16 6 980
[4] Belov A V, Gushchina R T, Sirotina I V 1993 Proc. 23rd ICRC (Calgary) 3 605
[5] Belov A V, Eroshenko E A, Yanke V G et al. 2018 Solar Phys 293 4 23
[6] Kota J 1979 Proc. 16th ICRC (Kyoto) 3 13
[7] Jokipi J R, Thomas BT 1981 Astrophys. J. 243 1115
[8] Kota J, Jokipi J R 1983 Astrophys. J. 265 573 doi: 10.1086/160701
[9] Potgieter M S, Burger R A Ferreira S.E.S. 2001 Space Science Reviews 97 Issue 1–4 295
[10] Siulszyk M., Iskra K., Alania M V 2014 Solar Phys 289 4297 doi:10.1007/s11207-014-0573-z.
[11] Stozhkov Yu I, Svirzhevsky N S, Bazilevskaya G A et al. 2007 Cosmic ray fluxes in the maximum of absorption curve maximum in the atmosphere and on the atmospheric boundary FIAN N. 14 Moscow
[12] http://www.stelab.nagoya-u.ac.jp/ste-wwv1/div3/muon/muon3.html
[13] Gvozdevskii B B, Abunin A A, Kobelev P G et al. 2016 Geomagnetism and Aeronomy 56 4 381
[14] Belov A V, Gushchina R T, and Sirotina I V 1995. Proc. 24-th ICRC (Roma) 4 542
[15] Belov A V, Gushchina R T, Yanke V G 1998 Geomagnetism and Aeronomy 38 N4 131
[16] Gushchina R.T., Belov A.V., and Yanke V.G. 2013 Bull. Russ. Acad. Sci.: Phys. 77 N 5 513
[17] Reinecke J. P. L., Potgieter M S 1994 JGRA 991 (A8) doi: 10.1029/94JA00792
[18] Alekseev V A, Ustinova G K 2013 Doklady Akademii Nauk 450 N 2 158 ISSN 0869-5652
[19] Alanko-Huotari K, Mursula K, Usoskin I G et al. 2006 Solar Phys. 238 391
[20] Krymsky G F, Krivoshapkin P A, Mamrukova V P et al. 2007 J. Exp. Theor. Phys. 104 N 2 189
[21] Dolginov A Z 1966 JETP 51 177