Long-term variations of cosmic ray intensity: theory and experiment

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Abstract: To study long-term variations of cosmic ray intensity the base model of cosmic ray modulation in the heliosphere is applied. The model has only one free parameter of modulation - the ratio of the regular magnetic field to the turbulent one and can be used for description of cosmic ray intensity variations in a wide range of energies from 100 MeV to 100 GeV. Earlier by means of this model we managed to achieve a satisfactory agreement between the cosmic ray intensity variation registered in various experiments and the theoretically expected one in the 20^{th}-22^{nd} solar cycles. In the given work at essentially greater value of modulation parameter we have attempted to describe behavior peculiarities of cosmic ray intensity in the 23^{rd} solar activity cycle mostly correctly.

Keywords: cosmic rays, modulation, solar cycle, heliosphere.

1 Introduction

The continuous measurements of cosmic ray (CR) intensity are carried out almost 60 years already. At present time it has been established that it undergoes constant variations with a period from several minutes up to decades and more. In this case, the main,the most powerful variation of CR intensity is caused by a manifestation of the 11-year solar activity (SA). According to ground observations the depth of modulation of CR intensity in the 11-year cycle reaches 20-25 % relative to the SA minimum, and in the stratosphere and in space it reaches still more. Temporary changes of CR intensity are characterized by the change of its maxima with sharp and flat vertices. Such shape of behavior of CR intensity in time is caused by effects of the sign-change of the general solar magnetic field (GSMF) and is determined by a direction of CR drift in the interplanetary magnetic field (IMF). Observations show that during the 19-22 of SA cycles the maxima of CR intensity have almost identical values regardless of the shape of its vertices. However, between the 23^{rd} and 24^{th} cycles a considerable excess of CR flow over all previous maxima was observed. Depending on the CR energy this excess constitutes a considerable value up to tens percents [1].

In this paper on the basis of measurements of the CR intensity in the stratosphere and on the ground the attempt to find out the physical reasons of this excess is made.

2 Base model of CR modulation in the heliosphere

To describe the behavior of CR intensity in the 11-year cycle of SA in 2006 at IKFIA of Siberian Branch of the Russian Academy of Science a base model of CR modulation of high energies ($E > 1$ GeV) in the heliosphere [2] has been created. As well as in other similar models (see, for example, [3, 4]), a base of this model is also the transport equation of CRs [5]. Our model is to maximize free from unnecessary detail and a large number of adjustable parameters. In the model it is supposed that the IMF consists of a superposition of the regular and turbulent fields whose a relationship changes with a phase of solar cycle, but at each time moment is equal in the whole volume of heliosphere. In the model it is postulated that the intensity of turbulent field changes linearly with a time from the solar cycle minimum up to the solar cycle maximum and inversely. In the minimum period of SA the value of turbulent field accounts for a fraction from the regular field being equal to $1/k_0$, where the value $k_0 > 1$ termed as a residual level of turbulence by us, is a single free parameter. Such approach allows to avoid bulky numerical calculations and to describe long-term variations of CR intensity depending on a SA cycle [2].

To describe the 11-year variations of CR intensity in the field of lower energies (100 MeV $< E <$ 1 GeV) the model has been modified [6]. In the equation describing the CR behaviour, the logarithm of this value has been used instead of CR intensity. In this case, with the accuracy up to small additions the equation for a logarithm coincides with the equation used earlier for the CR intensity in a high-energy region.

Thus, our model gives a possibility to describe the observable variations of CR intensity in wide range of energies from $\sim$ 100 MeV up to $\sim$ 100 GeV.

The analysis of long-term variations of CR intensity in the $19^{th} - 22^{nd}$ SA cycles, shows that they are well described by the offered model both in form, and in value [2, 6].

3 Results and discussion

Figure 1 presents numbers of solar spots (a) and results of CR intensity measurements in the stratosphere over Murmansk (a geomagnetical cutoff threshold $R_c = 0.6$ GV) and Moscow ($R_c = 2.4$ GV) in the $19^{th} - 22^{nd}$ SA cycles (b). From figure 1 it is seen that during four SA cycles (from the 19^{th} to 22^{nd}) the maxima of CR intensity had almost identical values, but in the deep SA minimum, which was observed in 2008-2010, the unusual and considerable ex-

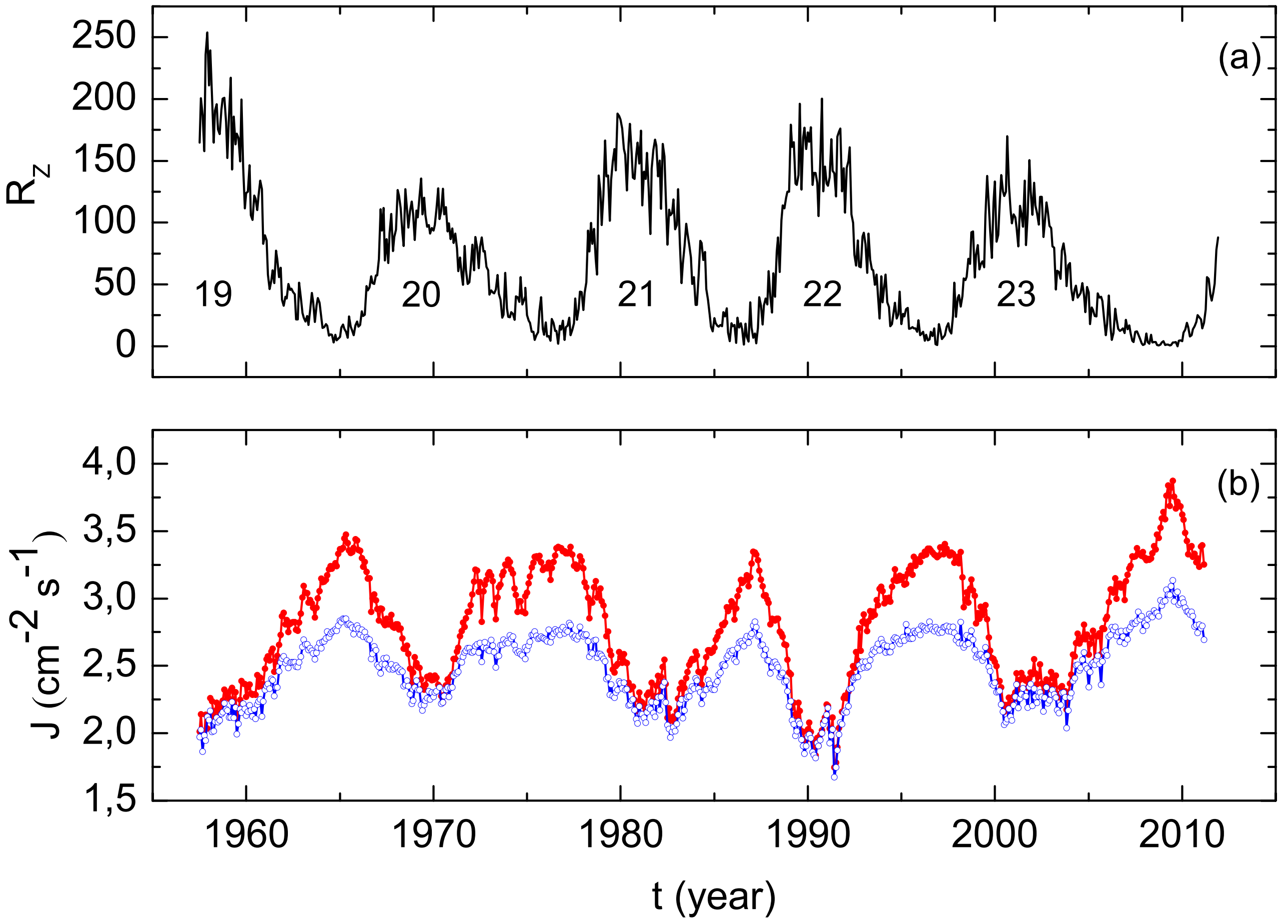

Figure 1: Dependence of monthly average numbers of solar spots (a) and CR flux (b) on time according to measurements in the stratosphere over Murmansk (red line) and Moscow (blue line). Numbers of solar cycles are denoted by numerals.

cess of CR flux over all previous maxima was registered. This excess CR flux is a value of about 15%.

The application of our model to the data of stratospheric observations leads to a conclusion that up to the end of the 22^{nd} SA cycle the long-term variations of CR flux are satisfactorily described at values of the parameter $k_0 = 5$, characterising a level of residual turbulence of the solar wind (SW). However, with the beginning the 23^{rd} cycle this agreement is sharply broken. Calculations show that the agreement between a theory and experiment is reached at significantly greater value of the free parameter $k_0 = 15$. As an example, the results of measurements and modelling calculations for two time periods for SA minimuma registered in the $19^{th} - 20^{th}$ and $23^{rd} - 24^{th}$ cycles are given in figure 2.

The application of modulation base model to the data of CR intensity registration for higher energies ($E > 1$ GeV) is shown in figure 3. Here there are data of A.I. Kuzmin CR spectrograph, namely, of the neutron monitor (effective energy $E_{eff} = 13$ Gev) and the muon telescope ($E_{eff} = 32.5$ Gev), arranged on the earth surface at Yakutsk and registering the particles coming from a vertical direction (panels (a) and (b), respectively). From figure 3 it is seen that at values of the free parameters of our model $k_0 = 5$ and $k_0 = 15$ between the experiment and theory a satisfactory agreement is also observed.

The obtained results mean that in the 23^{rd} cycle the IMF should be much more regular than in the previous cycles. Then it becomes clear that at the small number of scatterings of the particles entering in the heliosphere from outside, on the Earth's orbit the increased CR flux should be observed as it was registered in numerous experiments.

The conclusion about more regular IMF in the 23^{rd} SA cycle is confirmed by the circumstance that at this time in the frequency range of $2.2 \cdot 10^{-6} - 1.4 \cdot 10^{-4}$ Hz of the energy part of SW turbulence spectrum the decreased level of IMF fluctuations is observed [7]. The results on study of Forbush-effects obtained in the same work show that in the 23^{rd} solar cycle more hard spectra of the CR decreases than in the previous ones were observed. It testifies to the decrease of a degree of resonance scattering of CRs on the IMF inhomogeneities. Thus, there are strong grounds to state that, really, the 23^{rd} solar cycle considerably differs from other cycles by more regular IMF. And it is the reason of observation of unusually high CR fluxes in a wide energy range.

4 Conclusions

Thus, the base model of CR modulation in the heliosphere [2, 6] satisfactorily describes the results of CR intensity measurements both in the stratosphere and on the ground. The application of the supposed model allows to state that just the level of turbulence in describing of long-term CR intensity variations is a decisive factor and its decrease in the 23^{rd} cycle in relation to previous ones is the reason

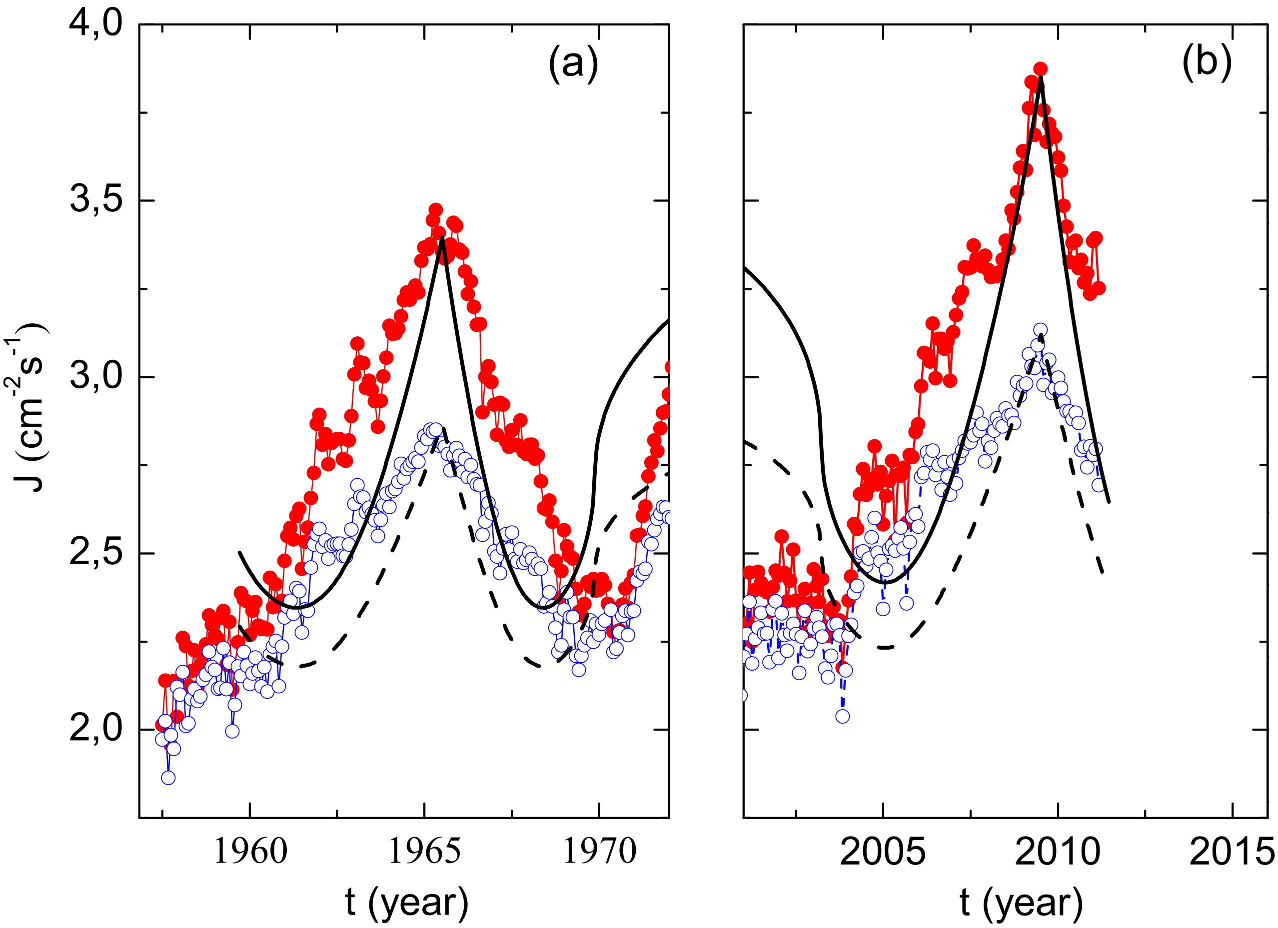

Figure 2: CR fluxes by measurements in the stratosphere over Murmansk (red line) and Moscow (blue line) as a function of time for periods of the minimum between the $19^{th} - 20^{th}$ (a) and $23^{rd} - 24^{th}$ (b) of SA cycles. By solid and dashed lines the results of modelling calculations for $k_0 = 5$ (a) and $k_0 = 15$ (b) are shown.

of the observable increase of the CR flux in the past deep minimum of solar activity.

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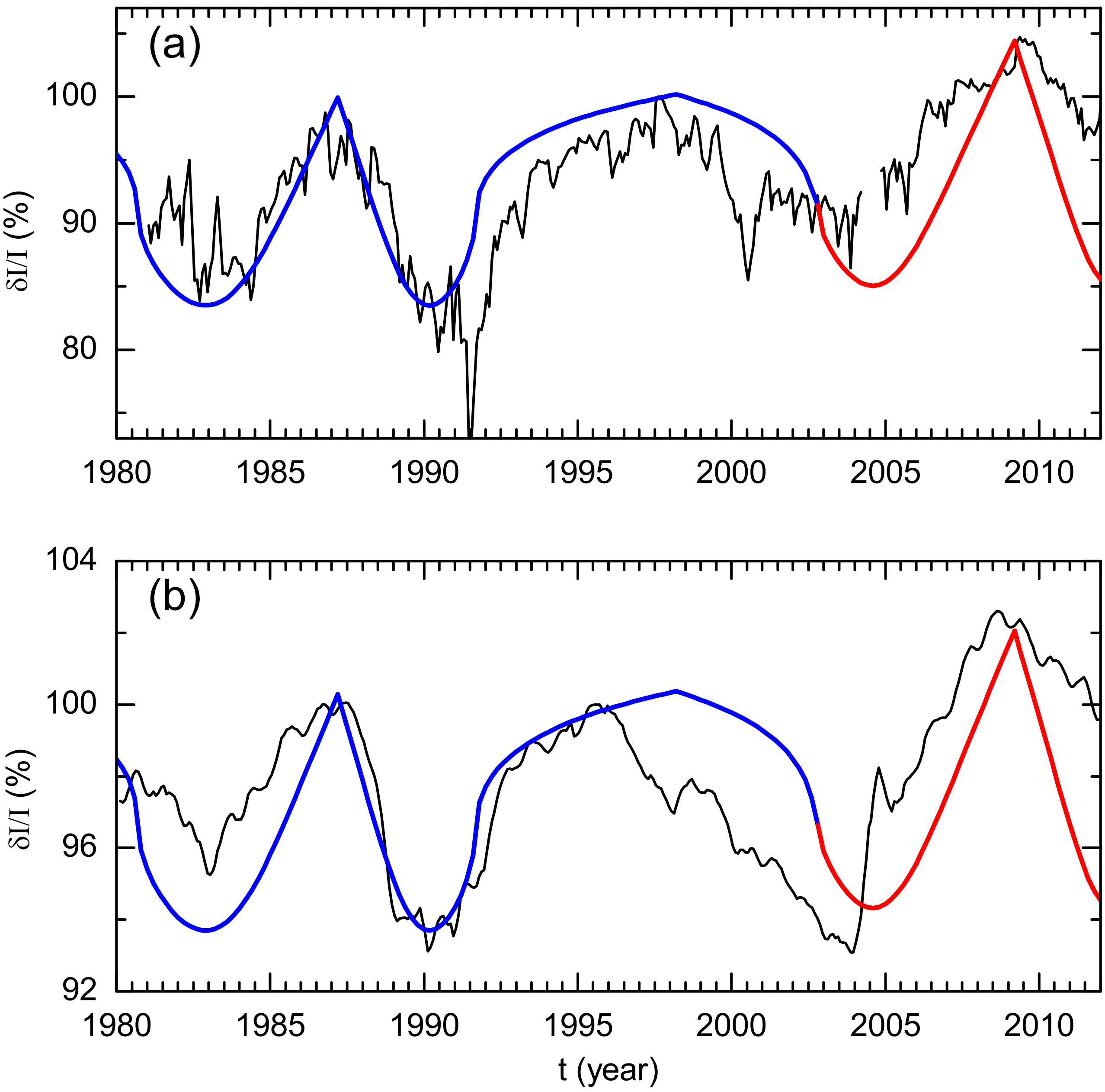

Figure 3: Dependence of CR intensity registered at Yakutsk by the neutron monitor (a) and muon telescope (b) from time. The modelling calculations for $k_0 = 5$ (blue line) and $k_0 = 15$ (red line) are shown.