Heliospheric modulation of cosmic rays in the 23rd solar cycle and in previous cycles

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Abstract: The base theory of heliospheric modulations of high energy cosmic rays created earlier is generalized here to the region of low energies. The comparison with results of long-term observations in the stratosphere carried out by the group of Lebedev Physical Institute of the Russian Academy of Sciences in Moscow and Murmansk, shows a satisfactory agreement. Both in the observations and in the theory the alternation of even and odd solar activity cycles in which cosmic rays behave themselves in a different way is found out. The reason of effect is the magnetic drift of particles.

The possible reasons of abnormally high intensity of cosmic rays registered in the mentioned observations during the last minimum of solar activity are discussed. It is shown that the whole 23rd solar cycle differs from others by an abnormal behavior. It is characterized by a lower level of magnetic turbulence in the solar wind, more hard spectrum of Forbush-decreases and weak anisotropy of cosmic rays.

Keywords: Heliosphere, modulation, solar activity.

1 Introduction

Long-term regular measurements of cosmic ray intensity in the stratosphere carried out by the group of Lebedev Physical Institute of the Russian Academy of Sciences have led to the detection of record-breaking high intensity in 2010 [1]. Authors [1] believe that the reason of the detected anomaly is unusual long period of a solar minimum. In this work the authors will try to establish what kind of changes in the heliosphere cause the mechanism of the observable phenomenon.

The general picture of interaction of galactic cosmic rays with magnetic fields in the heliosphere is well-known. In [2-4] the main role of diffusion and convection of cosmic rays in the magnetic field of the solar wind was established and the necessity to take into consideration the tensor feature of diffusion coefficient was shown and the substantial influence on the modulation of delay process of particles in the extending solar wind was established.

In [5-8] the important role of magnetic drift of particles was established and the change of character of heliospheric modulations of cosmic rays was found during a sign-change of the general solar magnetic field.

Extensive calculations of modulation taking into account the great number of parameters in the models used were carried out in [9,10] and in a number of other works of the same authors.

In [11] we developed the model of idealized solar cycle relieved of insignificant details up to the maximum. It was supposed that the interplanetary magnetic field consisted of the sum of the regular and turbulent fields whose relation changed with a phase of solar cycle but at each time moment remained the same in the whole volume of the heliosphere. It was postulated that the turbulent field intensity changed linearly depending on the time from a minimum of solar cycle to a maximum and back. During the minimum its value was a fraction from the regular field equal to $1/k_0$ where $k_0 > 1$ was the only free parameter of model. The total field was considered to be invariable during the whole solar cycle.

High energy cosmic ray modulation was described in the linear approach when the solar wind speed involving into the transport equation was considered to be a small parameter. The long-term variations observed by the neutron monitor on Climax mountain, are satisfactorily described by this model both in form and in value. The best agreement was reached at $k_0 = 5$.

2 Idealized model of the solar cycle in cosmic ray variations

Here we will bring little changes in the mentioned model with the purpose so that it could describe the modulation of low energy particles too and then we will compare results.
Figure 1: Long-term variations of the cosmic ray flux $I$ by data of stratospheric measurements from st. Murmansk ($R_c = 0.6\text{GeV}$)(curve 1) and st. Moscow ($R_c = 2.4\text{GeV}$)(curve 2). And also the expected variations at these stations at $k_0 = 5$ (curve 3).

Figure 2: Temporal change of the IMF intensity (a), slope of the IMF turbulence spectra in the frequency range between $2.2 \cdot 10^{-6}$ and $1.39 \cdot 10^{-4}$ Hz (b)

of calculations with the data of stratospheric observations at Moscow and Murmansk resulted in [1].

If we represent the function of cosmic ray distribution in the form $f(p, \vec{r}) = f_0(p)\exp(-\psi(p, \vec{r}))$, where $f_0(p)$ is nondisturbed function depending only on an impulse $p$ and having a power form, and $\psi$ is the disturbance caused by the modulation then substituting the function of cosmic ray distribution into the transport equation we can neglect the square of gradient $\psi$ and its dependence on $p$. The obtained
Figure 3: Temporal change of the numbers of solar spots $R_z$ (a), index of the Forbush-effects spectrum by data of muon telescopes of the Yakutsk spectrograph (b); index of the Forbush-effect spectrum by data of the neutron monitor network (c).

Figure 4: Temporal change of cosmic ray flux $I$ by data of stratospheric measurements in stations at Murmansk ($0.6$ GeV)(curve 1) and at Moscow ($2.4$ GeV)(curve 2) in the 21st (a) and 23rd (b) solar activity cycles. The solid curves (curve 3) are the expected variations for st.Murmansk at $k_0 = 5$ (the 21st cycle) and $k_0 = 15$ (the 23rd cycle). The dashed curves (curve 4) are the expected variations for st. Moscow at $k_0 = 5$ (the 21st cycle) and $k_0 = 15$ (the 23rd cycle).

equation for $\psi$ doesn’t differ at all from the linear equation investigated in [11] and gives the necessary decision for us. To average the value of effect in cosmic ray spectrum it is necessary to know the multiplicity of $m(p)$ representing the contribution of cosmic rays with an impulse $p$ on the observable intensity calculated for one primary particle, the following expression for multiplicity has been accepted:

$$m(p) = \text{const}(1 - \frac{E^2_{\text{max}}}{p^2})p$$

where $p_m = 1.2$ GeV/s is an ionization multiplicity cutoff for measurements in the atmosphere at the depth of $100$ g/cm$^2$.

The value of modulation averaged in spectrum is shown in Fig.1 jointly with the observation data [1]. In this case the same value $k_0 = 5$, as well as in the field of high energies has been accepted. On the whole, the satisfactory agreement is observed. The theory also describes the absolute value of intensity and its variations. It is seen that in the model the effect of drift has been overestimated which manifests itself in the observations but in some smaller degree.

3 Anomaly of the 23rd cycle

The agreement of theory and observations is sharply broken in the 23rd solar activity cycle. Fig. 2 presents the observable level of magnetic turbulence in the solar wind for the long period. It is seen that the whole period of the 23rd cycle is characterized by decreased magnetic turbulence. Fig. 3 shows values of a power spectrum index of Forbush-decreases. This value has shown the decrease in the 23rd cycle that is also indicative of the decrease of turbulence level. Thus, the turbulence level in the 23 cycle is decreased not only by local measurement data but also in the significantly big regions of interplanetary magnetic space.

The cosmic ray anisotropy observed at Yakutsk according to the data of neutron monitor and ground muon telescope during the 21 and 23 solar activity cycles is resulted in Table 1.

The Table gives the parameters of anisotropy spectrum representing a constant value $A_0$ at energies lower than the cut-off energies $E_{\text{max}}$. The value $A_0$ doesn’t change, whereas the cutoff energy in the 23rd cycle has decreased by a factor of 2.

The mentioned facts testify that in the 23rd cycle the heliosphere is more laminar than usually. Therefore, calculations of intensity curves corresponding to values of $k_0$ parameter have been carried out, whose results are shown in Fig. 4 and in the Table 2.

As is seen from Figures, during an epoch of negative polarity the minimum of solar activity is accompanied by a short-term increase of cosmic ray whose value increases as $k_0$ increases.

In the Table the value of intensity to which the calculated values have been normalized is underlined.
The general agreement of measured and calculated intensities is only for the Earth’s orbit. The character of distribution of cosmic rays is that which the increase at high heliolatitudes during this period shouldn’t be observed.

4 Conclusions

Observations of cosmic rays are in agreement with the elementary theory of heliospheric modulations. The abnormal increase of cosmic rays is caused by the decreased turbulence of the interplanetary magnetic field.

5 Acknowledgement

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References


Table 1: Cosmic ray anisotropy at Yakutsk (in %)

<table>
<thead>
<tr>
<th>Solar cycle</th>
<th>Detector</th>
<th>$A_{18}$, %</th>
<th>$A_{12}$, %</th>
<th>$A_0$, %</th>
<th>$E_{\text{max}}$, GeV</th>
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<tr>
<td>21</td>
<td>NM</td>
<td>0.365</td>
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<td>MT0</td>
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<td>0.067</td>
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<td></td>
</tr>
<tr>
<td>23</td>
<td>NM</td>
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<td>0.015</td>
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<td>70</td>
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<tr>
<td></td>
<td>MT0</td>
<td>0.188</td>
<td>-0.013</td>
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Table 2: Intensity of cosmic rays at Murmansk and Moscow during the period of solar activity minimum.

<table>
<thead>
<tr>
<th>Stations</th>
<th>Observations, $\text{sm}^{-2}\text{s}^{-1}$</th>
<th>Theory, $k_0 = 5$</th>
<th>Observations, $\text{sm}^{-2}\text{s}^{-1}$</th>
<th>Theory, $k_0 = 15$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Murmansk</td>
<td>3.37</td>
<td>3.37</td>
<td>3.95</td>
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<td>Moscow</td>
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<td>2.82</td>
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