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COSMIC RAYS IN THE CURRENT DEEP SOLAR ACTIVITY MINIMUM

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Abstract

The experimental data on the galactic cosmic ray fluxes obtained from the measurements in the atmosphere during the period from 1957 till now are presented. They include the unusual long-term period of the solar activity minimum of 2006 – present time. In 2009 we recorded the highest cosmic ray flux (particles with energy more than 0.1 GeV) for the whole history of cosmic particle measurements. The reasons of the extremely low solar modulation of galactic cosmic ray fluxes are discussed, among them the extremely low strength of the interplanetary magnetic field observed in 2008-2009.

Introduction

The robust long-term measurements of cosmic ray fluxes on the ground level and in the atmosphere are carried out from the middle of 50-ies of the last century. The neutron monitors and launchings of standard radiosondes give us the information on cosmic particles and their temporal and spatial variations. In Fig. 1 schematic view of the galactic cosmic ray (GCR) spectrum and solar particle spectrum from powerful solar flare is shown together with the threshold energy of particles detected by neutron monitors and radiosondes in the atmosphere. It is seen that these instrument complement each other.

The main contribution into the counting rate of the instruments discussed gives the primaries with energy $E > 2$ GeV for neutron monitors and $E > 0.2$ GeV for radiosondes. It is worth to note that the flux of particles with $E = 0.1 – 20$ GeV which gives the main contribution to the counting rate of these instrument contains more than 95% of all cosmic ray particles falling on the top of the atmosphere and about 65% of all their energy. The particles with these energies are subjected to modulation processes.

Below we shall consider the long-term changes of GCR fluxes using the data obtained in atmospheric measurements.

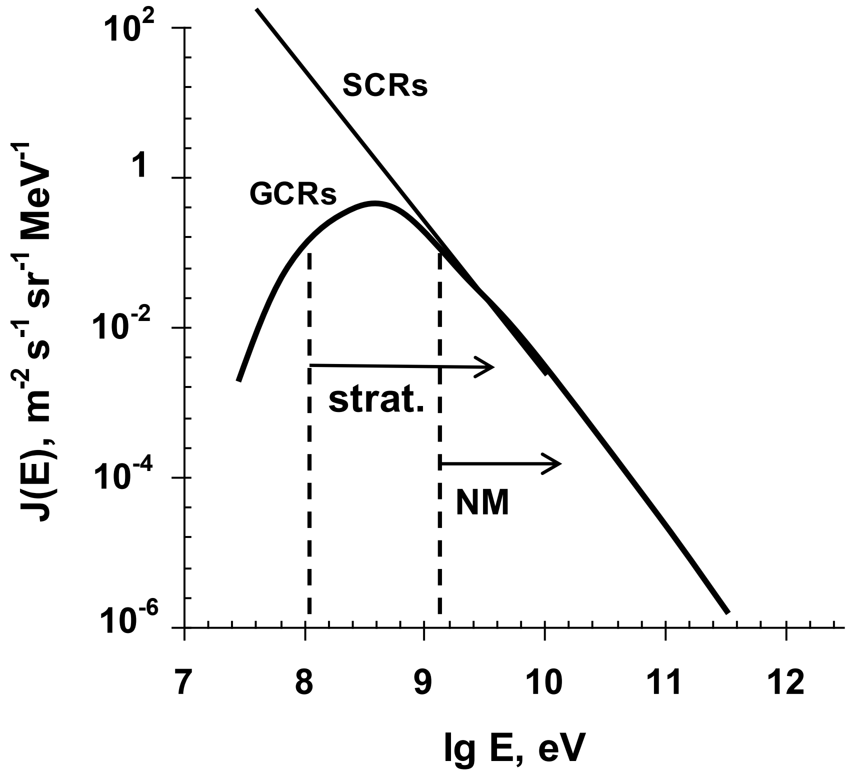

Fig. 1. The schematic view of the galactic cosmic ray spectrum (GCRs, curve with maximum) and solar particle spectrum (SCRs) from powerful solar flare (upper straight line). The vertical dashed lines show the threshold energy of particles detected with neutron monitors (NM) and radiosondes in the stratosphere (strat.).

Experimental data on GCR fluxes in the atmosphere

The long-term set of the homogeneous data on cosmic ray fluxes in the atmosphere of the polar and middle latitudes was obtained at the Lebedev Physical institute of the Russian Academy of Sciences. This set covers period from the middle of 50-ies of the last century to date. The standard radiosondes tied to meteorological balloons have measured CR fluxes in the atmosphere from the ground level up to 30-35 km. The detailed description of this experiment and experimental data is given in [1- 3].

In Fig. 2 the time variations of CR fluxes (monthly averages) at Pfotzer maximum in the atmosphere of the polar and middle latitudes are presented. They cover more than 4 solar activity cycles. The interleaving of sharp and flat periods of CR maxima is seen during the period under discussion. This interleaving is caused by the inversion of solar polar magnetic fields and changes of drifts of particles in the heliomagnetosphere. Such changes occur each 11 year in (or near) solar activity maximum.

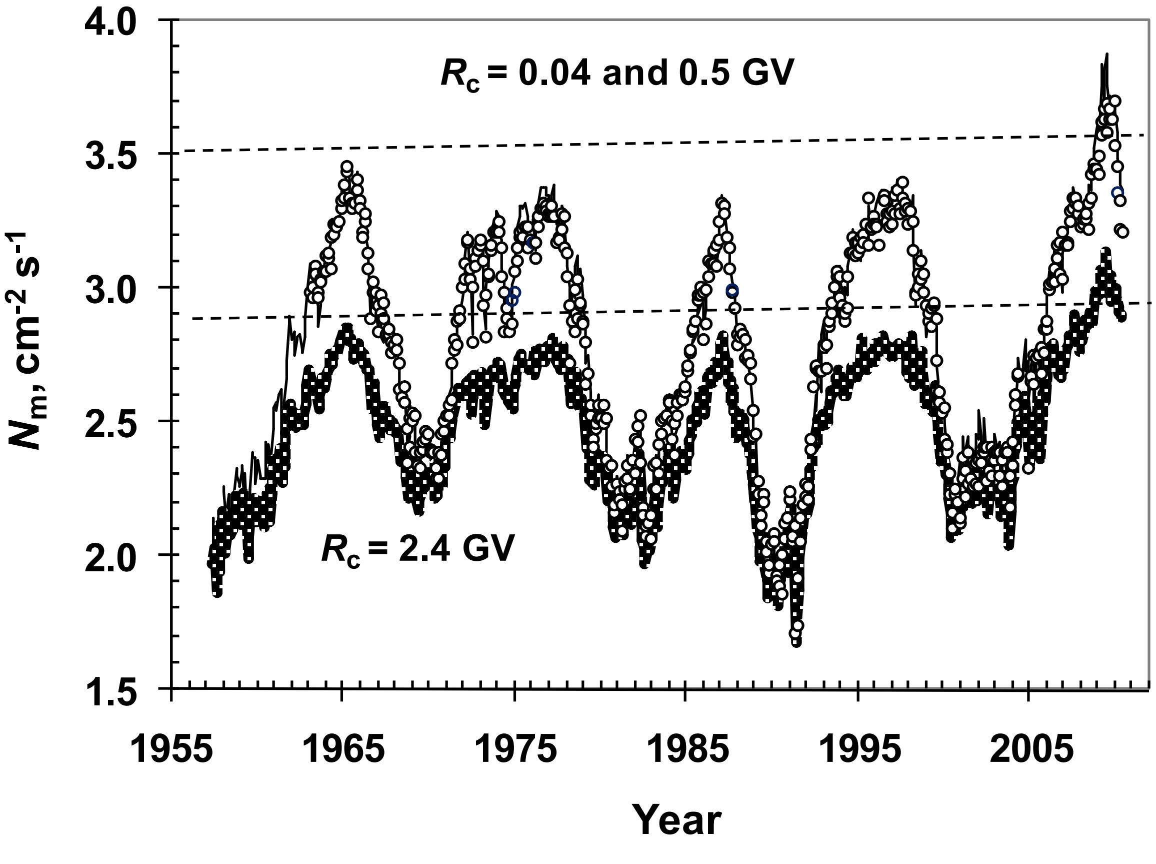

Fig. 2. Time variations of CR fluxes measured at Pfotzer maximum in the atmosphere N_m at the northern polar latitude (thin curve), southern polar latitude (open points) and at the middle northern latitude (dashed curve). Monthly averages of N_m are presented. The geomagnetic cutoff rigidities R_c are shown near the each

curve. The horizontal dashed lines show the highest cosmic ray fluxes observed in 1965 [2, 3].

From these data it is seen that the amplitudes of 11-year variations are about 30% at the polar latitudes and about 15% at the middle latitudes (the amplitude A was evaluated as $A = [(N_m)_{max} - (N_m)_{min}] / [(N_m)_{max} + (N_m)_{min}]$.

Drift effect of particles

The data presented in Fig. 2 allow to evaluate the influence of drift effects on CR modulation in the heliomagnetosphere. We have used the yearly averages of N_m, the 11-year smoothing of these data, and approximation of the smoothed data by straight line (see Fig. 3).

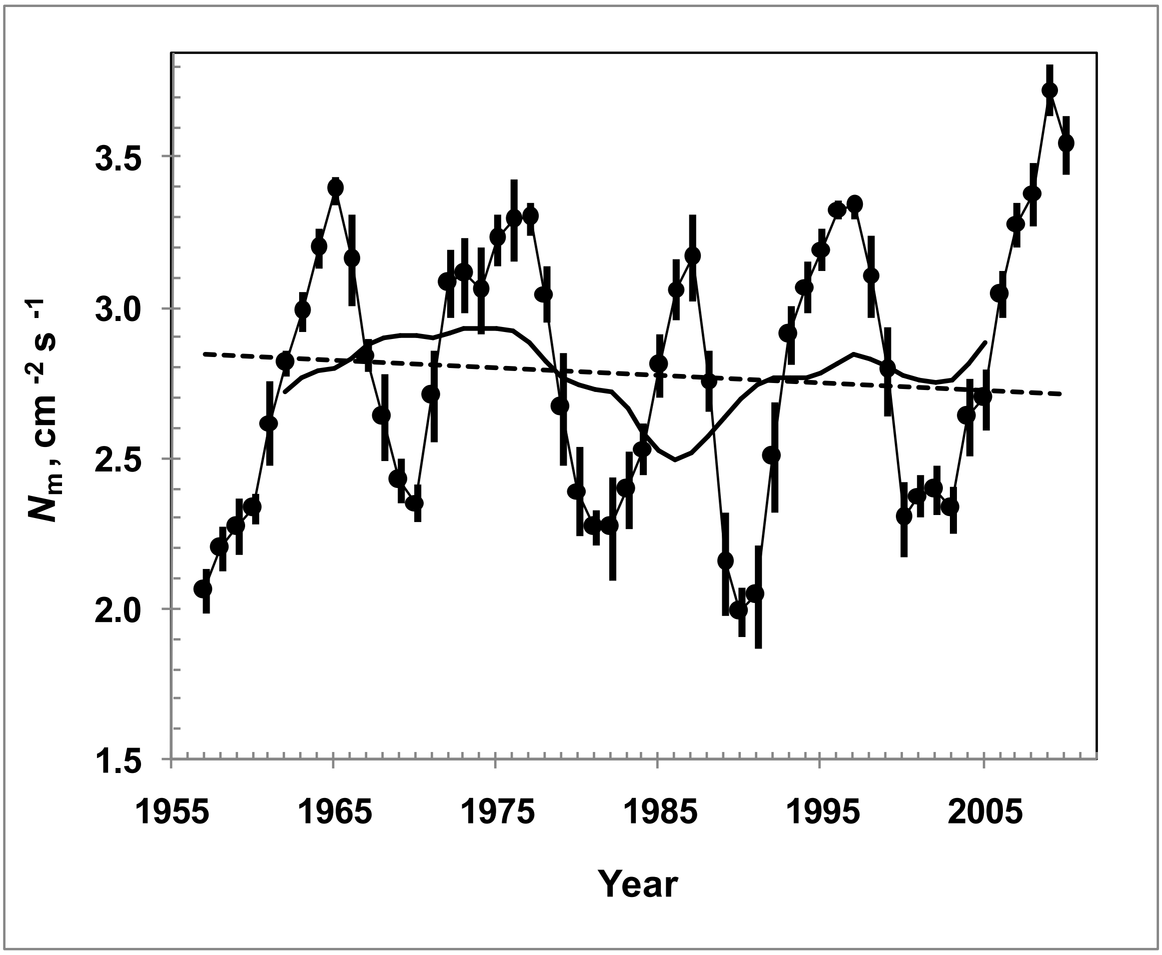

Fig. 3. Time variations of yearly averages of cosmic ray fluxes measured at Pfotzer maximum in the atmosphere N_m at the northern polar latitude (R_c = 0.5 GV, black points with standard deviations and black thin curve). The thick curve shows the

11-year smoothed data and dotted straight line is the linear approximation of the smoothed data.

After that we found the differences between linear approximation and smoothed data. These differences shown in Fig. 4 give us the amplitude of 22-year wave which is caused by drift effects of particles in the heliomagnetosphere.

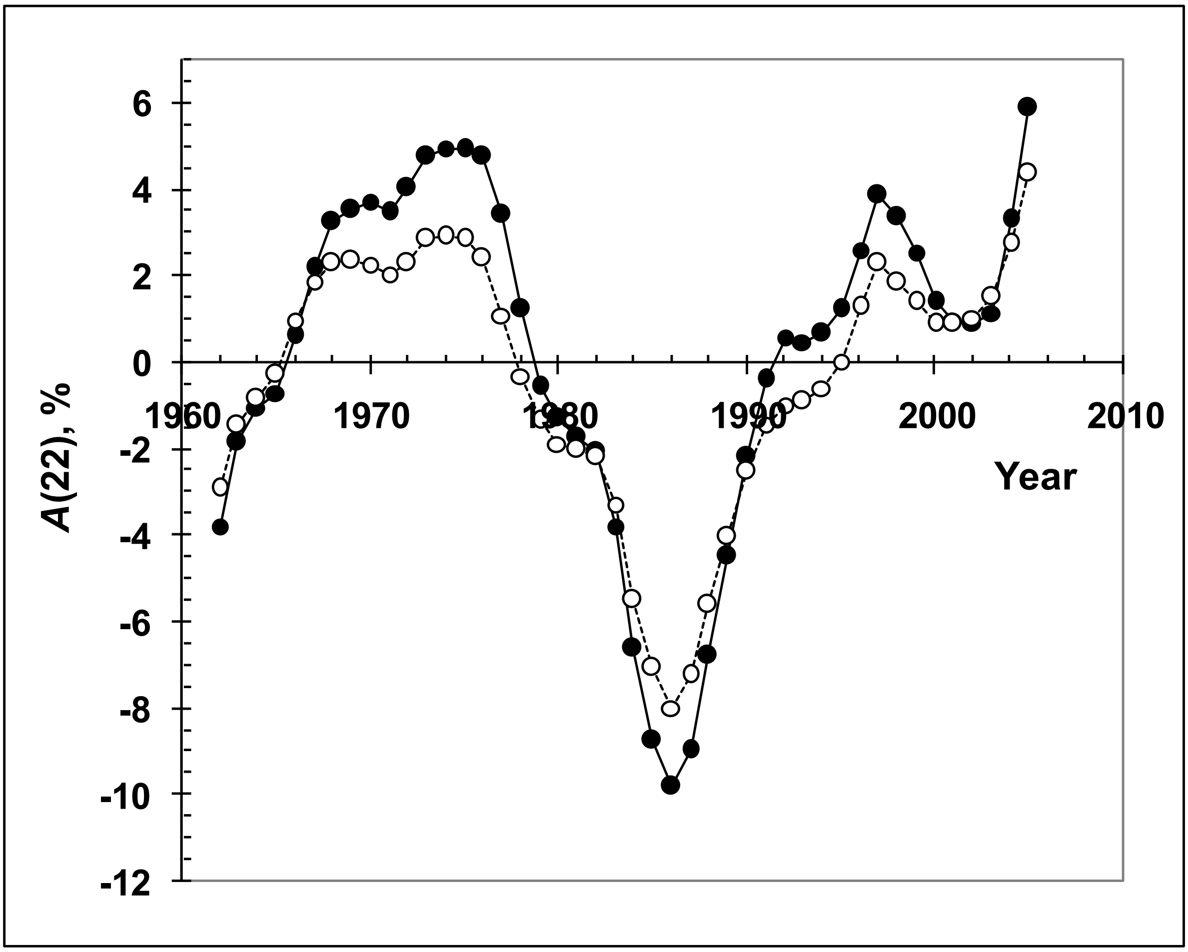

Fig. 4. Amplitude of 22-year wave *A* vs. time. The black points show the values of *A* for particles with *E* > 0.2 GeV (measurements at the northern polar latitude). The open points show the values of *A* for particles with *E* > 1.5 GV (measurements at the middle latitude).

As one can see from Fig. 4 the amplitudes of 22-year wave in cosmic ray fluxes do not exceed 10%. The same values of *A* are obtained if we have used the smoothed data with the 22-years instead of linear approximation of 11-year smoothed data.

Let us compare the amplitudes of 11-year changes of CRs (A_{11}) with the amplitudes of 22-year wave (A_{22}) caused by drift of particles in the heliomagnetosphere. For the integral flux of particles with $E > 0.2$ GeV the value $A_{11} \approx 30\%$ and $A_{22} \approx 8\%$. It means that for particle with $E > 0.2$ GeV the drift effects give about 25% of the total CR modulation. For the integral flux of particles with $E > 1.5$ GeV the value $A_{11} \approx 15\%$ and $A_{22} \approx 5\%$. In this case for particle with $E > 1.5$ GeV the drift effects give about 30% of the total CR modulation.

Unusual increase of cosmic ray flux in 2009

From Fig. 2 and 3 the highest flux of CRs is seen to be observed in 2009 for the whole history of the regular cosmic ray measurements. From the data on CR fluxes obtained in our experiments one can get the flux of primary CRs falling on the top of the atmosphere. The monthly data of primaries presented in Fig. 5 shows that the increase of primary CR flux for particles with $E > 0.2$ GeV was about 20% in comparison with the highest flux observed in the solar activity minimum of 1965. Also in Fig.5 the monthly averages of primary CR fluxes detected with the spectrometer PAMELA from the middle of 2006 to date are shown. Without any normalization the good agreement between two sets of data obtained different instruments and methods is take place. The PAMELA data confirm the increase of CR flux observed in the polar atmosphere in 2009.

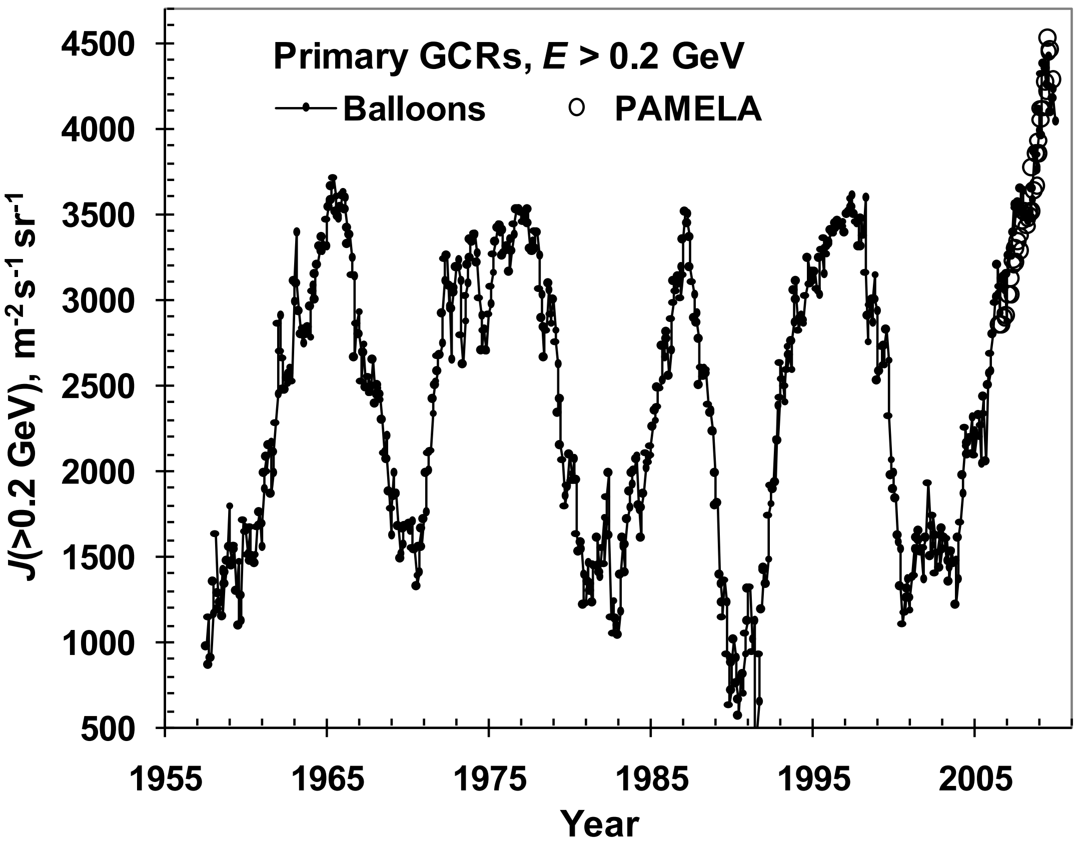

Fig. 5. The monthly averages of CR fluxes falling on the top of the atmosphere obtained from the regular measurements of CRs in the northern polar atmosphere (particles with $E > 0.2$ GeV, black points and black curve) and fluxes of primaries measured with the PAMELA spectrometer (particles with $E > 0.2$ GeV, open points). The data are given without any normalization.

The unusual increase of nuclei fluxes (Ne - Ni and Fe) in 2009 was recorded by ACE spacecraft. During the same year neutron monitors also recorded CR high fluxes. But in comparison with 1965 the excess of CRs was rather small about 2%.

We measure cosmic ray fluxes at the different altitude in the atmosphere and suggesting that additional flux of particles in 2009 consisted from protons it is possible to get integral spectrum of these particles (see Fig. 6).

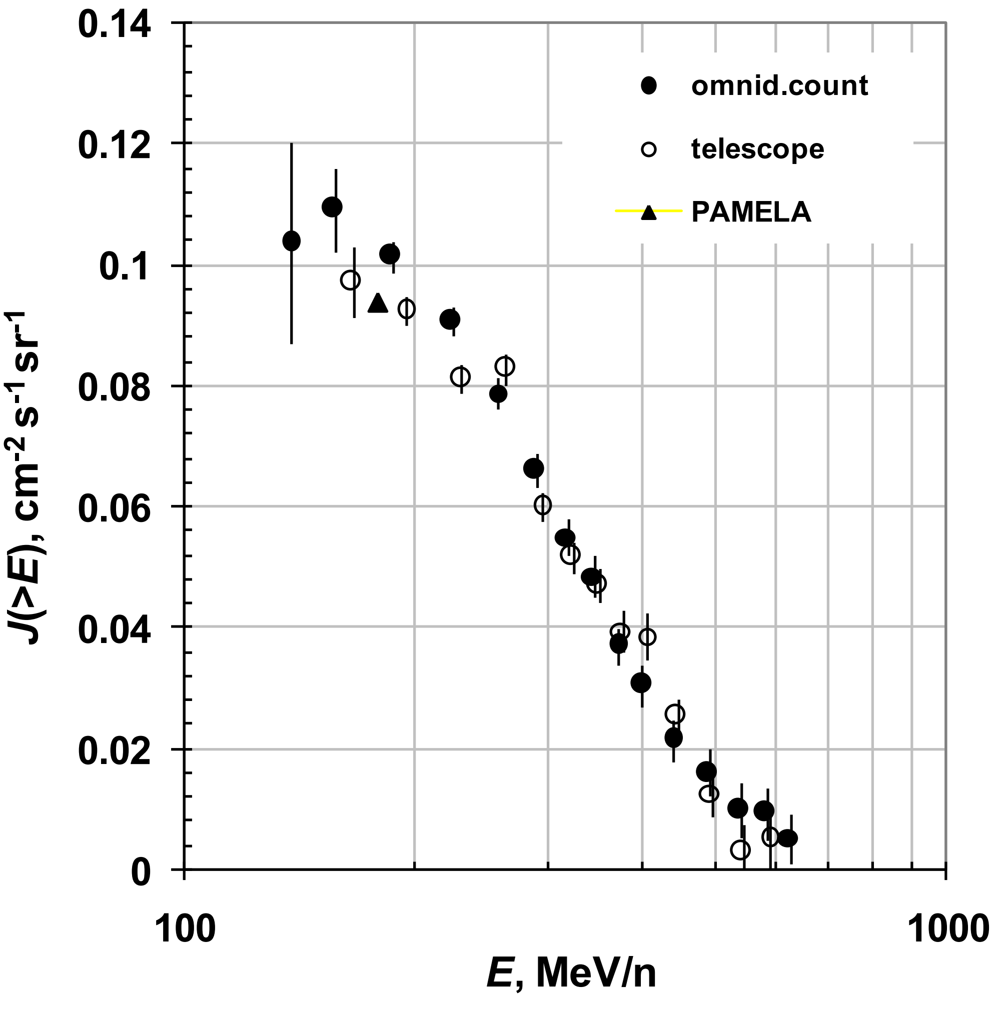

Fig. 6. The spectrum of additional flux of protons. This spectrum was found from the differences of particle fluxes observed at the different atmospheric pressures in July - August 2009 and February – April 2008 (in this period CR flux was the

same as in maximum of 1965). The spectra were obtained from the data of a single Geiger counter detected omnidirectional flux of particles (black points) and a telescope detected vertical flux of particles (open points). Also, the flux of protons measured with PAMELA spectrometer is shown by black triangle without any normalization.

What is the physical cause of the increase of CR flux in 2009?

The unusual increase of CR flux in 2009 was due to very weak interplanetary magnetic field (IMF) strength. The monthly averaged values of IMF strength at r =1 a.u. are depicted in Fig. 7 [4, 5]. In the previous solar activity minima IMF strength at the Earth's orbit was about 5 nT but in 2009 it was about 3.5 nT. Till now this value changes between 3.5 - 5.3 nT. Also, the very low solar wind velocity was observed in 2009.

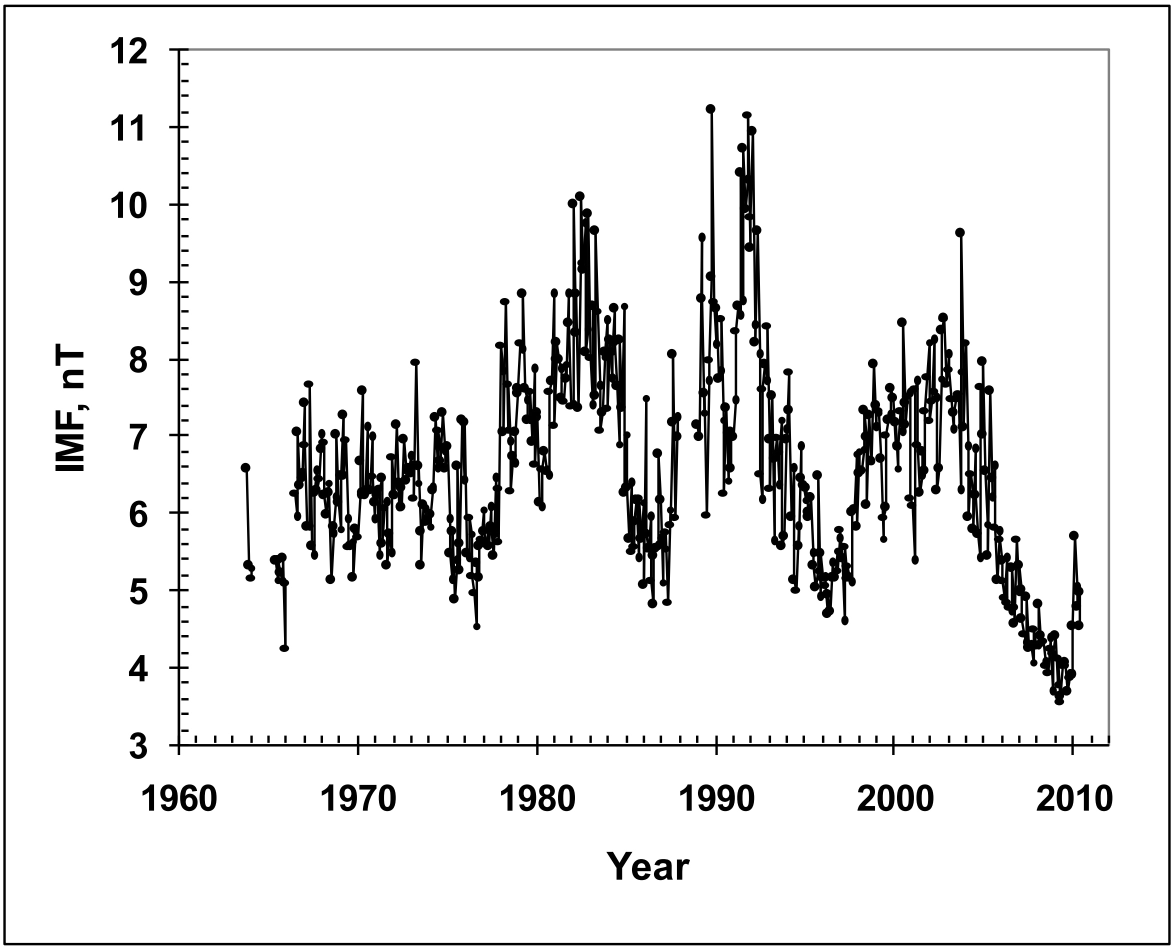

Fig. 7. The monthly averages of IMF strength at r = 1a.u. One can see very low IMF values about 3.5 nT in 2009 [4, 5].

The increase of diffusive galactic CR flux due to the low IMF strength and the decrease of convective flux of CRs due to low solar wind velocity caused the growth of CR flux in 2009.

Conclusion

The data on galactic cosmic ray fluxes measured in the atmosphere from the middle of 1957 today are presented. For this period of time the total number of small balloon launchings was about 80000.

From the cosmic ray data obtained the evaluation of 22-year wave amplitude was made and it was shown that drift effects give ~ (25 - 30)% from the total 11-year CR modulation.

In 2009 the highest flux of galactic CRs during the whole history of regular monitoring of CRs in the atmosphere was measured. The amplitude of increase of CR flux was about 20% in comparison with maximum flux observed in 1965.

The physical cause of unusual galactic CR increase in 2009 was very low solar activity, namely, the IMF strength at 1 a.u. was ~ 3.5 nT (in the 3 previous solar activity minima this value was ~ 5 nT), also the solar wind velocity was lowest for the last 40 years.

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