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Cosmic rays in the stratosphere in 2008–2010

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Abstract. The experimental data on the galactic cosmic ray fluxes obtained from the measurements in the atmosphere during the period 2008–2010 are presented. They include the unusual long-term period of the low solar activity. In 2009, we recorded the highest cosmic ray fluxes (particles with energy more than 0.2 GeV) in the history of the cosmic particle measurements. The reasons for the extremely low solar modulation of galactic cosmic ray (GCR) fluxes are briefly discussed.

1 Introduction

The long-term measurements of cosmic ray (CR) fluxes on ground level and in the atmosphere are carried out from the middle of the 1950s of the last century. Standard radiosondes launched on balloons and neutron monitors give us the information on cosmic particles and their temporal and spatial variations. At the polar latitudes in the stratosphere the main contribution to the counting rate of the instruments is given by the primaries with energy $E > 0.2$ GeV for radiosondes and $E > 2$ GeV for neutron monitors on ground level. It is worth noting that the flux of particles with $E = 0.1 - 20$ GeV contains more than 95% of all cosmic ray particles falling on top of the atmosphere and about 65% of their energy (Charakhchyan, 1964; Stozhkov et al., 2009). The particles with these energies are subject to modulation processes.

2 Experimental data on cosmic ray fluxes in the atmosphere

The long-term set of homogeneous data on cosmic ray fluxes in the atmosphere at the polar and middle latitudes has been obtained by the Lebedev Physical Institute of the Russian Academy of Sciences. This set covers the period from the middle of 1957 to the present. The standard radiosondes launched with meteorological balloons have measured CR fluxes in the atmosphere from ground level up to 30–35 km. The total number of small balloon launchings was about 80 000 during 1957–2010. The detailed description of this experiment and the results of the measurements are given in Charakhchyan (1964); Stozhkov et al. (2007, 2009).

The time variations of yearly averaged CR fluxes at Pfotzer maximum, N_m, in the atmosphere on the polar and middle latitudes are presented in Fig. 1 for more than 4 solar activity cycles. The interleaving of sharp and flat forms of CR maxima is seen during the period under discussion. This interleaving is caused by the alternate sign of the solar polar magnetic fields and changes in the directions of drifts of particles in the heliosphere. Such changes occur each 11 yrs at (or near) the solar activity maximum.

From these data one can see that the amplitudes of 11-year variations in CRs, A_{11}, are about 30% at the polar latitudes and about 15% at the middle latitudes. The amplitude A_{11} was evaluated as $A_{11} = [(N_m)_{\max} - (N_m)_{\min}]/[(N_m)_{\max} + (N_m)_{\min}]$, where $(N_m)_{\max}$ and $(N_m)_{\min}$ are the maximal and minimal CR fluxes in any selected 11-year solar cycle.

3 Drift effect of particles

The data presented in Fig. 1 allows us to evaluate the influence of drift effects on the CR modulation in the heliosphere (Jokipii and Kopriva, 1979; Le Roux and Potgieter, 1995). To do it, we used the following treatment of the data: (1) yearly averages of N_m were smoothed with the 11-year period; (2) the smoothed data were approximated by a straight line; (3) the differences were found between the linear approximation and the smoothed data. The differences shown in Fig. 2 give a 22-year wave which is caused by drift

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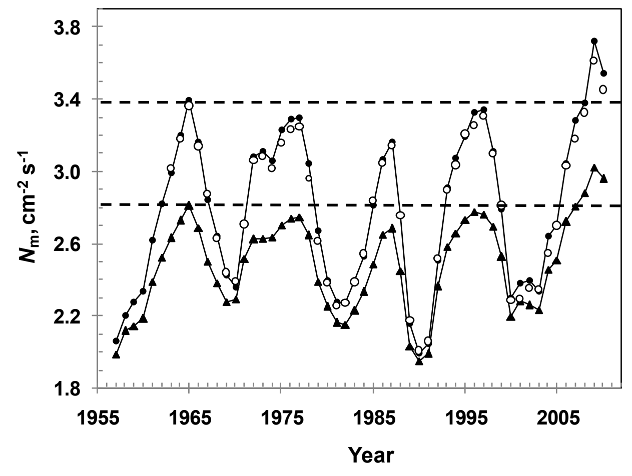

Fig. 1. Time variations of CR fluxes measured at the Pfotzer maximum in the atmosphere, N_m, at the northern polar latitude (geomagnetic cutoff rigidities $R_c = 0.6$ GV, filled circles), southern polar latitude ($R_c = 0.04$ GV, open circles) and at the middle northern latitude ($R_c = 2.4$ GV, triangles). Yearly averages of N_m are presented. Standard deviations have the sizes of points. The horizontal dashed lines show the highest cosmic ray fluxes observed in 1965 (Stozhkov et al., 2007, 2009).

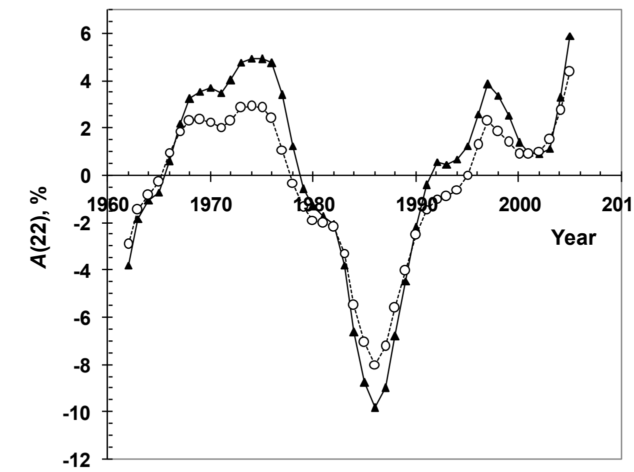

Fig. 2. The 22-year wave A_{22} vs. time. The triangles show the values of A_{22} for particles with $E > 0.2$ GeV (measurements at a northern polar latitude). The circles show the values of A_{22} for particles with $E > 1.5$ GeV (measurements at a latitude with $R_c = 2.4$ GV)

effects of particles in the heliosphere. The amplitudes of the 22-year wave in the cosmic ray fluxes, A_{22}, do not exceed 10%. The same values of A_{22} were obtained when we used the smoothed data with the 22-year period in contrast to the linear approximation of the 11-year smoothed data.

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

4 The unusual increase of the cosmic ray flux in 2009

From Fig. 1, it is seen that the highest flux of CRs was observed in 2009 in the history of the regular cosmic ray measurements (Svirzhevsky et al., 2009; Krainev and Kalinin, 2009; Svirzhevskaya et al., 2010; Bazilevskaya et al., 2011). From the data on CR fluxes obtained in our experiments, one can get the flux of primary CRs falling on top of the atmosphere. The monthly data of primaries presented in Fig. 3 show that the increase of primary CR flux for particles with $E > 0.2$ GeV in 2009 was about 20% in comparison with the highest flux observed in the solar activity minimum of 1965. Also in Fig. 3, the monthly averages of primary CR fluxes detected with the spectrometer PAMELA from the middle of 2006 to 2009 are shown (Mayorov et al., 2011). Without any normalization, good agreement between the two sets of data obtained with different instruments and methods occurred. The PAMELA data confirm the increase of CR flux observed in the polar atmosphere in 2009.

The unusual increase of fluxes of nuclei in 2009 was also recorded by the ACE spacecraft (Mewaldt et al., 2010; McDonald et al., 2010). During the same year neutron monitors also recorded increases in the CR fluxes (Moraal and Stoker, 2010). But in comparison with 1965, the excess of CRs was rather small, about a few percent or less. Besides, an anomalous increase of the 2.5 GeV electron flux was observed in 2008 by Ulysses (Heber et al., 2009) and the authors predicted that the proton intensity would also increase by a factor 1.3 if the tilt fell below 10°(which occurred in 2009).

A decrease of CR fluxes is observed in 2010, but until the beginning of 2011 rather high CR fluxes persisted. The neutron monitor data show the same effect (see, for example, http://pgia.ru/lang/ru/data/nm/).

To our mind, the unusual increase of CR flux in 2009 was mainly due to the very weak interplanetary magnetic field (IMF) strength (http://omniweb.gsfc.nasa.gov/; http://spaceweather.com). In the previous solar activity minima the strength of IMF of the Earth's orbit was about 5 nT. In 2009, the IMF strength decreased to 3.5 nT and varied between 3.5 and 5.0 nT up to the beginning of 2011. The very low solar wind velocity (~ 350 km/s) and the sharp decrease in the tilt of the heliospheric current sheet to the solar equator were observed in 2009 (http://sun.stanford.edu/~wso/wso.html).

These factors are also very important for the theory of CR modulation.

5 Conclusions

The data on galactic cosmic ray fluxes measured in the atmosphere from the middle of 1957 to the present time are presented.

In 2009, the highest flux of galactic CRs during the whole history of the regular monitoring of CRs in the atmosphere was measured. The flux of CRs with $E > 0.2$ GeV was about 20% higher than the maximum flux observed in 1965.

From our cosmic ray data an evaluation of the 22-year wave amplitude was made and it was shown that drift effects give $\sim 25-30\%$ of the total 11-year CR modulation of the Earth's orbit. The physical cause of the unusual galactic CR increase in 2009 was very low solar activity, namely, the IMF strength at 1 AU was ~ 3.5 nT (in the three previous solar activity minima this value was ~ 5 nT), the solar wind velocity was the lowest for the last 40 yrs. Furthermore, a very low sunspot number was observed.

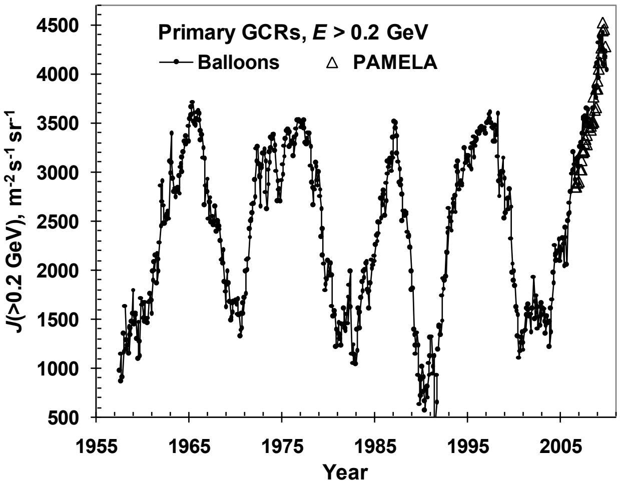

Fig. 3. The monthly averages of CR fluxes falling on top of the atmosphere derived from the regular measurements of CRs in the northern polar atmosphere (particles with $E > 0.2$ GeV, circles) and fluxes of primaries measured with the PAMELA spectrometer (particles with $E > 0.2$ GeV, triangles) (Mayorov et al., 2011). The PAMELA data are given without any normalization. The horizontal dashed line shows the highest cosmic ray fluxes observed in 1965 (Stozhkov et al., 2009).

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