Cosmic ray modulation in the current 24th solar cycle from the measurements in the atmosphere

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Abstract. Experimental data on cosmic ray fluxes measured in the stratosphere of polar and middle latitudes and their consistency with the heliospheric magnetic field strength and the solar wind velocity are discussed. During the last solar minimum the highest cosmic ray fluxes in the atmosphere were observed in 2009-2010. After prolonged solar minimum between the cycles of 23 and 24 the heliospheric magnetic field and the solar wind velocity recovered more slowly as compared with the values in the previous solar minima and remained substantially reduced in 2009-2012. As a result the cosmic ray fluxes are at present significantly higher than fluxes in the similar phases of previous solar activity cycles. The possible reasons of the existence of the long-term high fluxes of cosmic rays are discussed.

1. Introduction
Lebedev Physical Institute (LPI) of the Russian Academy of Sciences together with Polar Geophysical Institute of the Russian Academy of Sciences carry out the regular monitoring of cosmic ray fluxes in the atmosphere at the middle and polar latitudes: at the middle latitude – near Moscow, from July of 1957 till present, geomagnetic cutoff rigidity \( R_c = 2.4 \text{ GV} \); at the northern latitude – Murmansk region, from the middle of 1957 till present, \( R_c = 0.6 \text{ GV} \); and the southern one – Antarctica, Mirny station, from March of 1963 till present, \( R_c = 0.03 \text{ GV} \). The charged particle fluxes are measured at the different altitudes from the ground level up to 30-35 km. The standard radiosounds have been used for these experiments. More than \( \sim 8 \cdot 10^4 \) of these radiosounds were launched since 1957 till present time. Now we have unique and homogeneous set of data on cosmic ray fluxes and its temporal and spatial variations at the different altitudes in the atmosphere for the period more than 50 years [1, 2].

Below we will discuss the time variations of cosmic ray fluxes at its maximum in the atmosphere (so-called Pfotzer maximum) \( N_m \). In the polar regions the maximum values of \( N_m \) are observed at the altitudes 20-22 km and in the middle regions at altitudes 18-20 km.

2. Experimental data on cosmic ray fluxes
Here the data on omnidirectional fluxes of charged particles will be discussed. These data were obtained with single gas-discharged tubes. These tubes are sensitive to electrons with energies \( E_e > 200 \text{ keV} \), to muons with \( E_m > 1 \text{ MeV} \), and to protons with \( E_p > 5 \text{ MeV} \). The detectors were calibrated
to provide the homogeneity of the data. Since the IGY (1957) more than 83,000 of radiosounds were launched at the several latitudes [2].

In figure 1 the monthly averaged values of \( N_m \) are shown. One can see distinct 11-year cycles in cosmic ray flux, alternative sharp and flat maxima of \( N_m \) in the periods of low solar activity. It is worth to note that in 2009 the maximum value of cosmic ray flux was recorded for the whole history of cosmic ray observations (more than 60 years). Also it is seen that modern cosmic ray flux is higher in \(~\) twice as high as ones observed in the previous minima of cosmic ray fluxes.

![Figure 1. Time dependence of maximum cosmic ray fluxes \( N_m \) (monthly averages) measured in the stratosphere of the northern polar latitude (\( R_c = 0.6 \) GV, green curve), the southern polar latitude (\( R_c = 0.03 \) GV, blue curve), and the middle northern latitude (\( R_c = 2.4 \) GV, red curve). Dashed lines show the maximum of \( N_m \) recorded in 1965.](image)

3. Solar activity, interplanetary magnetic field, and solar wind speed

The observed values of \( N_m \) are defined by the level of solar activity and the conditions of interplanetary medium, responsible for the cosmic particle propagation. The data on solar activity and some parameters of interplanetary space are given below in figures 2, 3, and 4.

Now sunspot number \( R_s \) [3] in the current the 24th solar cycle activity is near its maximum. But in comparison with maxima of other cycles the present maximum of sunspot number is (1.5-2) times as low as previous ones. In 2008-2009 the sunspot number was low. Very important feature we have in the present is a time dependence of strength of magnetic field \( B \) measured at 1 a.u. [4]. This dependence is depicted in figure 3.

The main feature in time dependence of \( B \) consists in the very low values of \( B \) during the second half of 2008 and the first half of 2009. Earlier the low values of \( B \) were observed in previous minima of solar activity (~1976, ~1986, ~1996) with the strength of interplanetary magnetic field about 5 nT. But in 2008-2009 it was ~3.5 nT. In figure 4 monthly averages of solar wind velocity \( V \) are given for the period of 1965-2012.
**Figure 2.** Time dependence of sunspot number $R_z$. The values of $R_z$ were averaged per month and smoothed with 5 points [3].

**Figure 3.** Time dependence of interplanetary magnetic field strength $B$ at 1 a.u.: monthly averages of $B$ smoothed with 5 points [4].

**Figure 4.** Time dependence of solar wind velocity $V$ at 1 a.u.: monthly averages of $V$ smoothed with 5 points [4].
The minimum values $V$ were recorded in 2009 but the differences between these values and minimum ones observed earlier in 1969, 1972, 1980, 1988, and 1997 are less than 15%.

3. Discussion
The inspection of data on time dependences of cosmic ray fluxes $N_m$, sunspot number $R_z$, interplanetary magnetic field strength $B$, and solar wind velocity $V$ presented in figures 1-4 shows the following. As it is seen from Fig. 1 in 2012 the observed cosmic ray flux $N_m$ is significantly higher than ones recorded during the previous maxima of solar activity. In comparison with the previous solar cycle maxima now we have low value of sunspot number $R_z$ (see figure 2), although in this cycle the solar activity is close to its maximum. Such conclusion one can get from analysis of the relationship between the sunspot group number and their average heliolatitude [5]. Also the strength of interplanetary magnetic field $B$ is about 5 nT instead of the expected 7-8 nT (see figure 3). The low values of $R_z$ and $B$ are responsible for the high cosmic ray flux in present time.

4. Conclusion
The joint analysis of data on cosmic ray fluxes, solar activity level, and parameters of interplanetary space leads to the conclusion that the current solar cycle is not like other solar cycles. We had long-term solar activity minimum in 2006-2010 and now we observe very low values of sunspot number in the current solar activity maximum and very low strength of interplanetary magnetic field. The observed high cosmic ray fluxes confirm this statement.

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