LONG-TERM CHANGES OF COSMIC RAYS INTENSITY AND SOLAR WIND TURBULENCE FOR THE LAST FOUR SOLAR ACTIVITY CYCLES

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We have analyzed the energetic part of the spectrum of solar wind turbulence in the frequency range between $2.2\cdot10^{-6}$ and $1.39\cdot10^{-4}$ Hz for the last four solar cycles (1964-2009). We have shown that the turbulence spectrum of the last cycle No.23 is essentially different from the three preceding ones Ns.20-22. While the mean power of fluctuations was roughly constant for the interplanetary magnetic field strength as well as for the velocity and density of solar wind plasma, the level of small-scale irregularities of the solar wind was, and still remains, greatly reduced. We discuss implications of these peculiar features for the observed variations of cosmic ray intensities during the solar cycle No.23

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INTRODUCTION

Variations of cosmic ray intensities near Earth are continuously monitored by the ground-based network of neutron monitors for almost sixty years. This provides a unique series of data to probe the solar and heliospheric conditions since the flux of galactic cosmic rays is modulated by the solar magnetic activity. The main features of the cosmic ray modulation, including the 11-year and 22-year cycles, are well understood and can be properly modeled for the last solar cycles.

However, the present minimum of cycles 23/24 is very unusual and does not fit the generally accepted picture. In particular, the bulk of data implies that the cosmic ray intensity during years 2007-2009 significantly exceeds that for all the previous minima of solar activity (Fig. 1). This unusual feature of the recent solar cycle 23 has raised great interest in the solar-heliospheric scientific community.

In particular, special attention to this problem was paid during the 31-st International Cosmic Ray Conference.

Main observational facts concerning cosmic rays during the unusual minimum of cycle 23 can be briefly summarized as follows:

1. ***Intensity of cosmic rays measured by the ground-based neutron monitors (E>1 GeV) exceeds that for the previous cycles 19-22 by 5-6 % for polar stations.***

2. Cosmic rays measured by balloon-borne detectors (E>100 MeV) depict even higher excess of up to 15 % in Murmansk and Mirny.

3. A significant excess of helium (E~265 MeV/nuc) flux recorded onboard Voyager 1 and 2 missions is observed up to the heliodistance of 110 AU, i.e. even beyond the termination shock.

4. On the contrary, the intensity of anomalous cosmic rays (oxygen with E~8-27 MeV/nuc) is suppressed.

Such an unusual behaviour of cosmic rays cannot be described using the common models in the framework of standard assumptions. In this letter we try to reveal the uncommon solar and heliospheric features of the solar cycle 23 which are reflected in the cosmic ray variations.

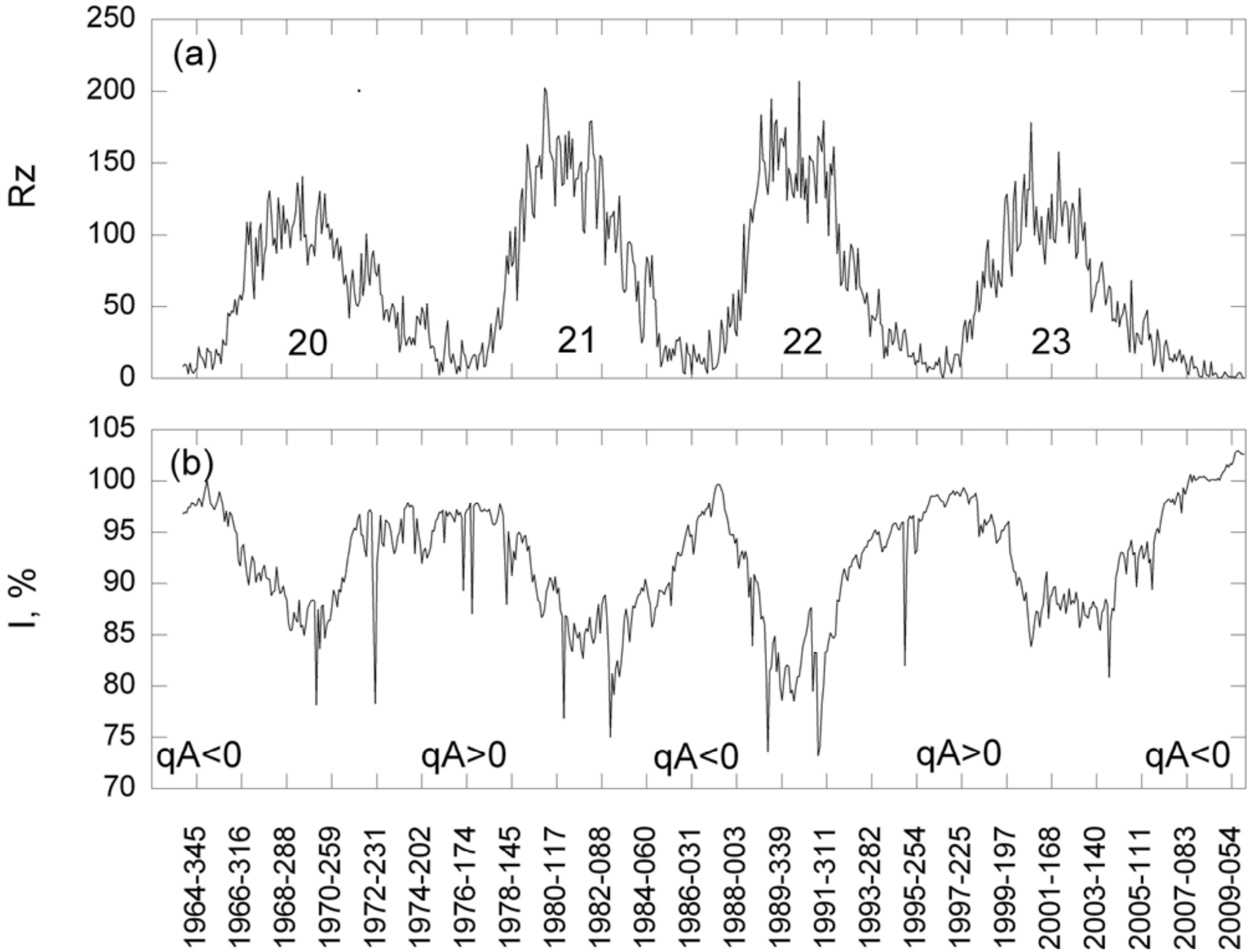

Fig. 1. *a) Temporal variability of the sunspot numbers. Solar cycles are numbered; b) Cosmic ray intensity measured at Oulu cosmic ray station. The sign of IMF polarity qA is indicated.*

DATA AND METHOD

Cosmic rays (CR) are charged particles which interact with the interplanetary magnetic field (IMF) carried by solar wind. Depending on their energy CR are scattered on different scales IMF irregularities that are defined by the turbulence level of the interplanetary medium. The turbulence level varies in the course of solar cycle leading to the solar modulation of cosmic rays in the heliosphere. In this way variations of CR intensity are related to the parameters of irregularities (or turbulence) of the interplanetary medium.

Studying of the solar wind (SW) turbulence, IMF disturbances with the characteristic scale of 1 AU and smaller, which defines main processes in the heliosphere, is a key problem for space physics. Since direct measurements of the turbulence are not possible, it is common to use the method of spectral analysis to study parameters of the irregularities (turbulence) in SW. In a general case, the turbulence spectrum is described by a descending power law: $P(\nu) = P_0\nu^{\alpha}$, where P is the spectral power estimate, ν is frequency, P_0 and α are the constant and the spectral index of the spectrum.

The power spectrum of IMF data at the Earth's orbit has a wide frequency range, which can be roughly separated in three ranges with different parameters of the fluctuations.

The first energetic range between frequencies of $\sim 10^{-7}$ - 10^{-4} Hz and is characterized by the spectral index $\alpha \approx -1$. Next inertial range between $\sim 10^{-4}$ and $\sim 10^{0}$ Hz and has the spectral index $\alpha \approx -5/3$. The third dissipative zone ($\nu > 10^{0}$ Hz) is described by $\alpha \sim -2$.

As a result of resonant interaction between particles and IMF irregularities of Alfven (or MHD) type wave, particles of CR are effectively scattered. The resonant condition can be reached when the particle's Larmor radius is close to the wavelength $\rho \sim \lambda$. This makes it possible to estimate the spatial scale of the IMF irregularities studying CR particles. Larmor radius ρ of a particle with momentum E in magnetic field B is proportional to E/B. On the other hand, $\lambda \sim U/\nu$, where U is the SW speed. For typical values of $U=4\cdot10^{7}$ m/s, $B=6\cdot10^{-5}$ Gs and the effective energy of CR measured at ground-based neutron monitors $E\sim 10^{10}$ eV, one can estimate the resonance frequency $\nu \sim 7\cdot10^{-5}$ Hz. This corresponds to the energetic part of the power spectrum of SW turbulence, which is analyzed here to study the relations of the amplitude of CR variations and heliospheric parameters in the course of solar cycle.

Here we study spectral characteristics of different parameters of SW in the frequency range between $\nu_1=2.2\cdot10^{-6}$ and $\nu_2=1.39\cdot10^{-4}$ Hz. We use hourly data of the IMF strength as well as speed and density of SW as adopted from the OMNI database (http://nssdc.gsfc.nasa.gov/omniweb/ow.html). In order to exclude possible effects of the solar rotation, we have averaged all the values over 27 day periods linked to the Bartels rotations.

RESULTS

Fig. 2 shows the measured IMF strength B(a) as well as the mean power P_B (b) and spectral index α_B in the analyzed frequency range of the IMF fluctuation spectrum for the last four solar cycles.

One can see that both IMF strength B and the power of IMF fluctuations P_B vary in a cyclic manner with the 11-year solar cycle. The IMF strength reached the lowest ever observed values of 3--4 nT during the minimum of solar cycle 23 in 2008-2009.

This phenomenon, related to the unusually weak minimum of solar cycle 23, is widely discussed nowadays and calls for revision of many established views.

On the other hand this result offers another surprise – the spectral index α of the IMF spectrum (Fig. 2c) depicts significant and systematic steepening (from -1.5 to -2) of the spectra after 1995, i.e. during the entire solar cycle 23.

Keeping in mind the usual strength and fluctuation power of IMF (Fig. 2a and b), one can interpret this as a reduced level of small-scale turbulence accompanied by an enhanced power of large scale inhomogeneties (MHD-waves) in SW.

In order to verify this interpretation, we have analyzed in a similar manner fluctuations of SW parameters, as shown in Fig. 3. Here one can see a similar pattern - almost constant level of the fluctuation power but a sudden systematic steepening of the spectrum of fluctuations of both speed and density of SW. Such behaviour confirms the idea of a strong suppression of small-scale turbulence in solar wind during the entire solar cycle 23, not only around its minimum time.

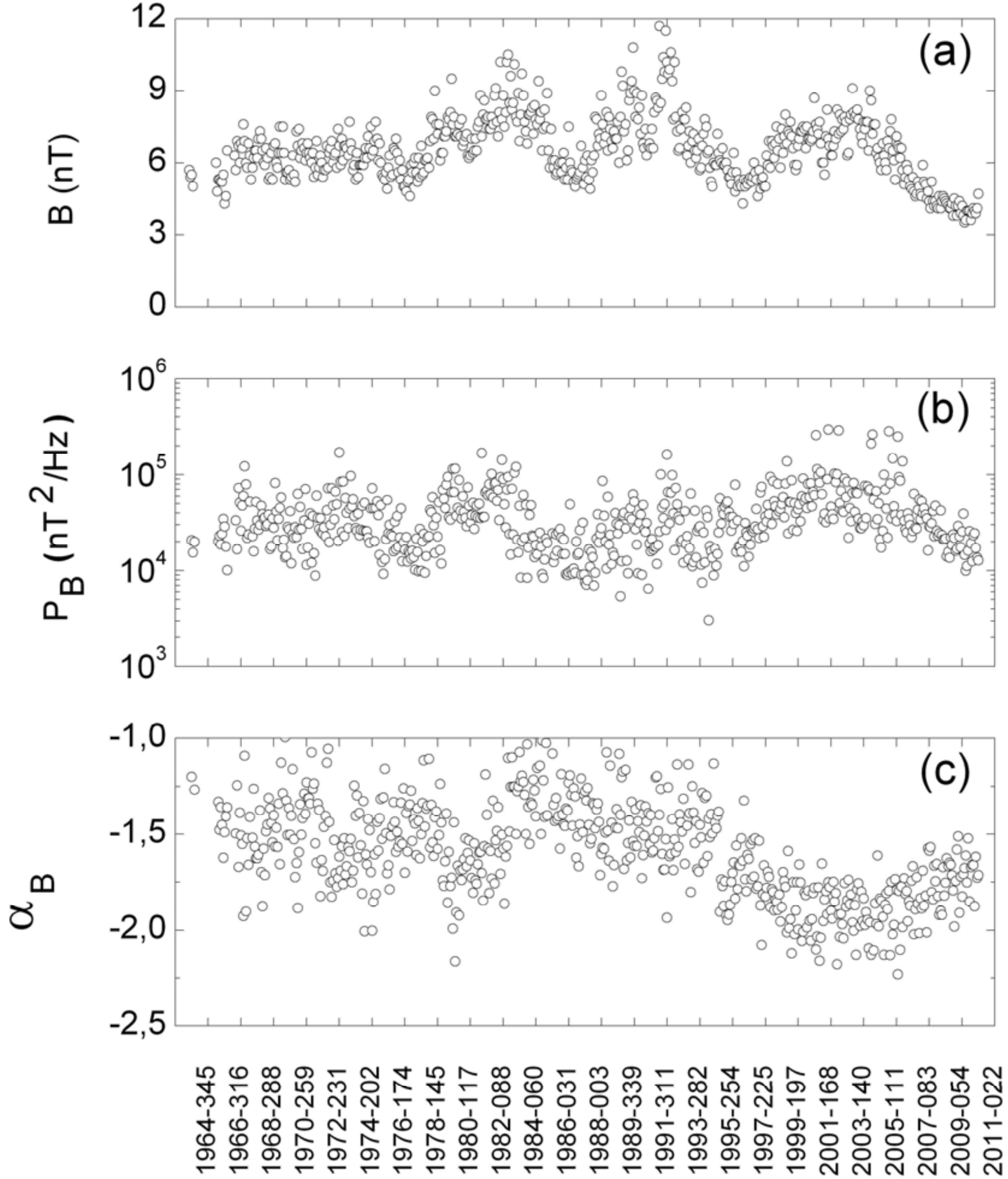

Fig. 2. *Temporal variations of the parameters of the interplanetary magnetic field: IMF strength B (a) as well as the mean power* P_B *(b) and spectral index* α_B *(c) of the IMF fluctuation spectrum. Time is given in years and days of the year.*

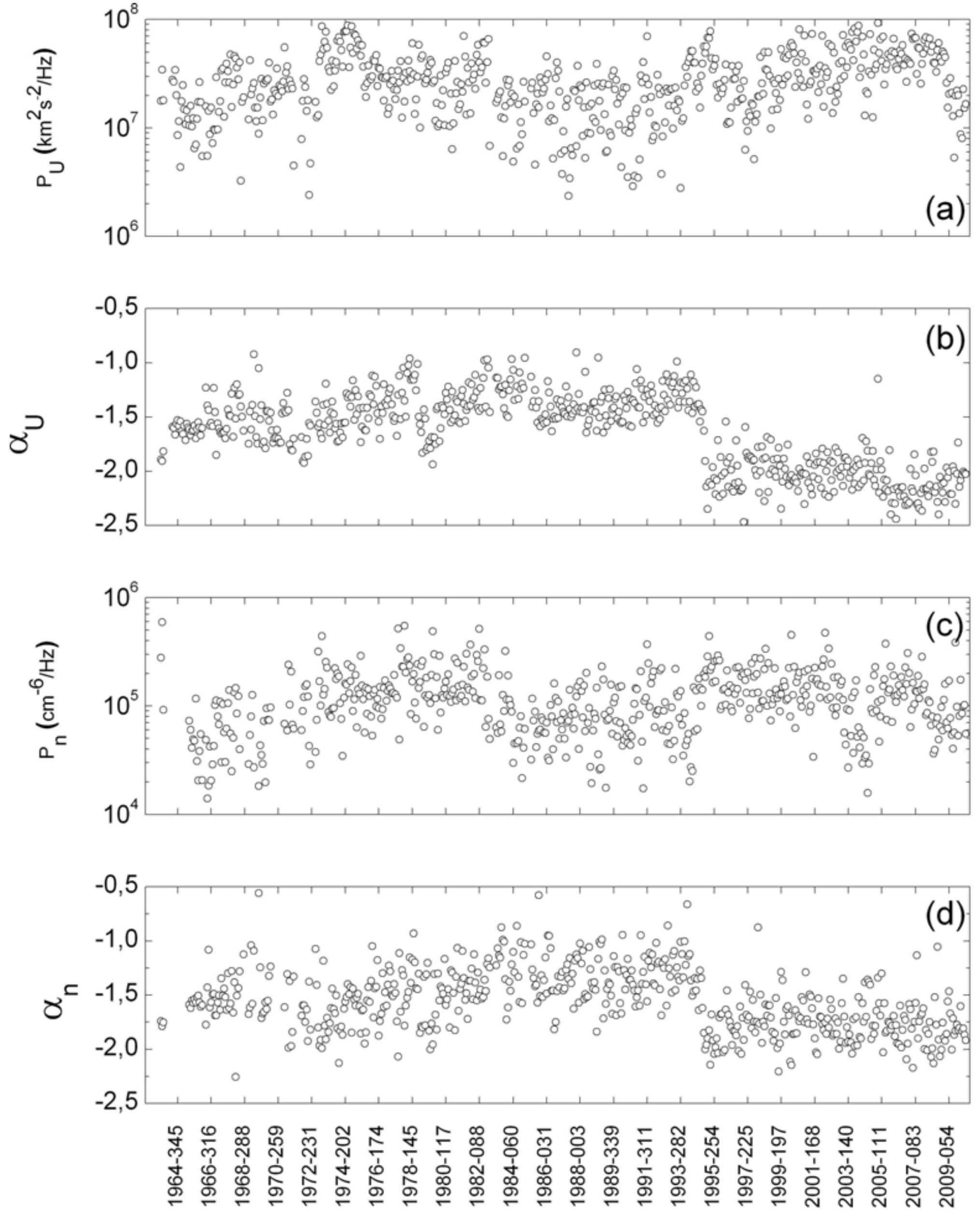

Fig. 3. *Temopral variations of the parameters of solar wind: mean power P_U (panel a) and spectral index α_U (b) of fluctuations of the solar wind speed, as well as the mean power P_n (c) and spectral index α_n (d) of fluctuations of the solar wind density.*

CONCLUSION

Thus, we conclude, based on an analysis of direct measurements of parameters of SW, that the turbulence in interplanetary medium was very unusual during solar cycle 23.
This includes essential suppression of the power of irregularities of SW with the typical spatial scale of $\lambda<0.5\cdot10^{12}$ cm comparing to the previous cycles.

On the other hand, weaker scattering of GCR on these small scale inhomogeneties could lead to the observed very high intensity at high-altitude stations during the solar minimum of cycle 23.

AKNOWLEGEMENTS

This work was supported by the Russian Foundation for Basic Research (project nos. 09-02-00425, 09-02-98507-r_east, and 09-02-98511-r_east), Programs nos. 8 and 16 of the Presidium of the Russian Academy of Sciences, Federal Agency on Science and Innovations (State contract no. 02.740.11.0248), and grant no. NSH-3526.2010.2 from the President of Russia for support of leading scientific schools, and the Academy of Sciences of Finland.