Low energy ($E > 100$ MeV) galactic cosmic rays in the prolonged activity minimum of the 24th solar cycle according to stratospheric measurements

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***Abstract*. The low energy galactic cosmic ray (GCR) fluxes in the 24th solar activity minimum differ from the sharply peaked fluxes during the 1965 and 1987 minima in the sense that they reached the level of the preceding minima fluxes in April of 2007 and then were constant within a few (2–3) per cent till October of 2008. Since November of 2008 a certain growth of cosmic ray intensity was observed which was continued up to April of 2009. The data of balloon measurements at the stratospheric stations Mirny (Antarctica), Murmansk and Moscow confirm the cosmic ray growth. Cosmic ray fluxes in the present solar minimum were compared with solar wind velocity and heliospheric magnetic field as well as with the heliospheric current sheet inclination.**

***Keywords*: cosmic rays in the atmosphere, modulation, solar minimum**

I. Introduction

The current solar activity minimum is special in many ways. The sun was blank during many days in the last two years [1], the heliospheric magnetic field (HMF) is the weakest since the beginning of measurements in 1963 [2], the density and temperature of solar plasma reduced near the Earth and along the Ulysses orbit [2], [3].

The fluxes of $E > 100$ MeV galactic cosmic rays, in turn, have also shown a noticeable increase during the last few months. Below we present data on the cosmic rays in the current minimum using for that the monthly averaged data on particle fluxes obtained in balloon measurements in the atmosphere. The cosmic ray variations in the 24th solar activity minimum can be a good test to verify the cosmic ray modulation theory and to determine the solar plasma parameters which are directly relevant to the GCR modulation. A significant cosmic ray increase at the midlatitudes, as it was seen at the stratospheric station Moscow, can have effect on ionization in the troposphere. Thus it gives a chance to test a suggestion [4] about the link between cosmic ray fluxes and cloudiness on the Earth.

II. Stratospheric data sets on cosmic rays

Long-term data sets on cosmic ray fluxes were obtained in balloon measurements at the stratospheric stations Murmansk (Rc = 0.6 GV), Moscow (Rc = 2.4 GV) and Mirny (Antarctica, Rc = 0.03 GV). Gas-discharge counters were used in measurements of the omnidirectional and vertical fluxes of charged particles from the ground level up to 30–35 km in the atmosphere. The measurements were carried out since 1957 on daily basis (at Mirny since 1963), and three sonde launchings per week were made over the last decade. More detailed description of the long-term stratospheric balloon experiment on cosmic rays is elsewhere [5].

The current solar activity minimum is the fifth one, for which the stratospheric data on cosmic rays are available. During more than fifty years a cosmic ray monitoring was carried out of the same type gas-discharged counters and methods of counters calibration were the same. So one can hope that the long-term data sets are quite homogeneous and the data of measurements, shown on Fig. 1 [6], confirm the homogeneity. As it is seen on Fig. 1, cosmic ray fluxes were practically equal during four previous solar activity minima both at north and south high-latitude stations and at middle-latitude station Moscow.

In the middle of 2007 cosmic ray fluxes have reached the flux level of the previous solar activity minima. Approximately in that time the heliospheric magnetic field and solar spot numbers Rz have decreased to the typical for the previous minima levels. The monthly averaged solar wind speed has not changed much, but it has shown stable four-sector structure with very low minimal speed [1]. Only the tilt of the heliospheric current sheet (HCS) has remained sufficiently large (approximately 15°), whereas in the 1976, 1987 and 1997 minima the tilt had decreased to 4° [7].

So it would be expected that the cosmic ray fluxes began to decrease since the middle of 2007. In spite of that the particle fluxes began to increase since 2008, at first at the station Moscow and than at high-latitude stations. The increase is continuing up to now (April 2009), and as a consequence of that we have seen now the highest particle fluxes since the beginning of cosmic ray monitoring in the atmosphere.

Detailed cosmic ray variations at Murmansk station in the three sunspot minima with the same direction of the heliospheric magnetic field N^-S^+ ($A < 0$) are shown in Fig. 2. The choice of the data for comparison allows to exclude the differences resulting from the different drift contribution to cosmic ray fluxes depended on the HMF direction. In Fig. 2 as key months were chosen May

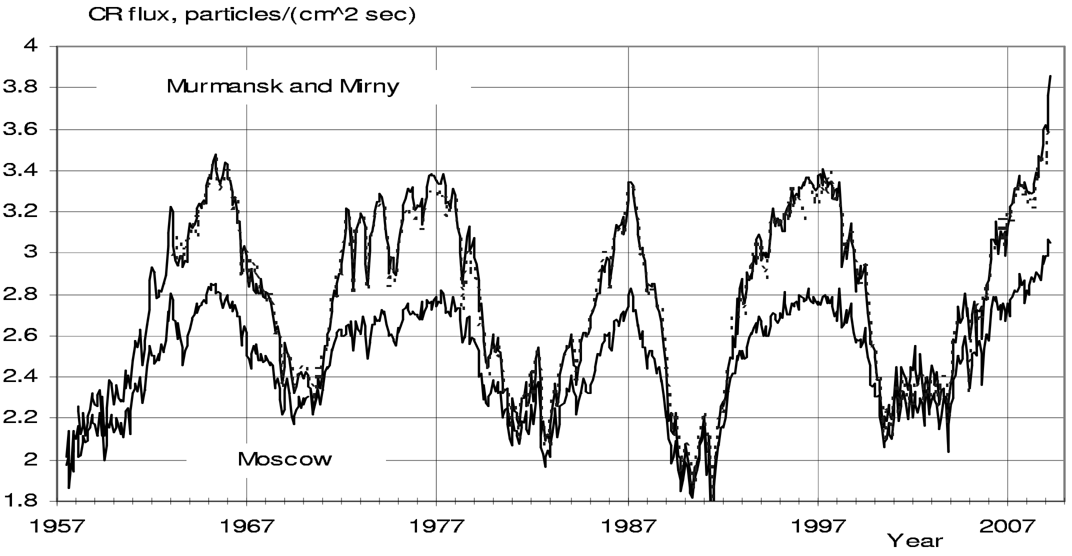

Fig. 1: Time variations of the cosmic ray fluxes at Pfotzer's maximum in the atmosphere ($\sim$ 25 km at Murmansk and Mirny, $\sim$ 20 km in Moscow). Two upper curves for high-latitude station Murmansk and Mirny (the fluxes at Mirny is shown as dotted line) almost coincide.

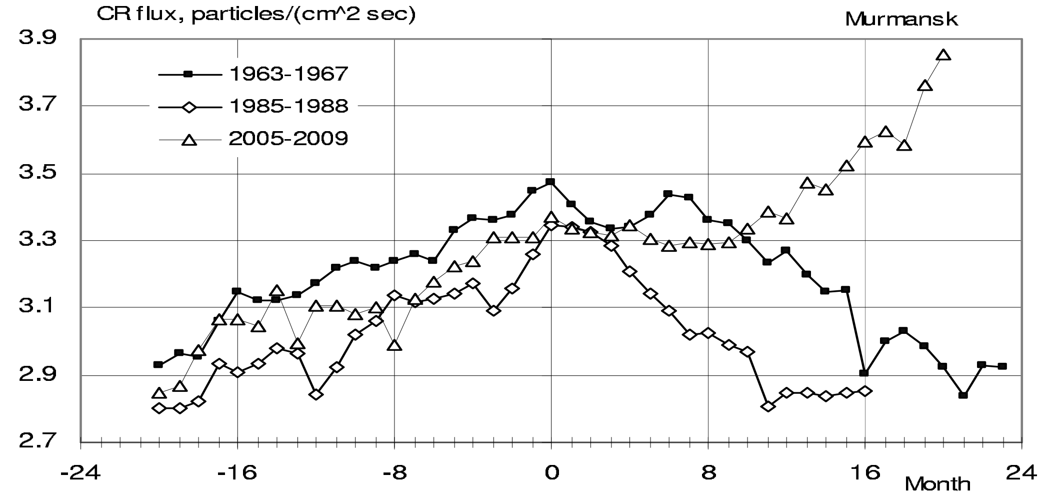

Fig. 2: Cosmic ray fluxes at Pfotzer's maximum in the atmosphere in time periods close to solar activity minima with the same direction of the heliospheric magnetic field.

1965, March 1987 and August 2007 when the particle fluxes were the largest. At Murmansk (threshold proton energy is 100 MeV) the cosmic ray increase began in 10 months after the key month, as well as at station Mirny, Antarctica (in June–July 2008). The cosmic ray increase in Moscow (threshold proton energy is 1600 MeV) began in 5 months after the key month (January 2008). Monthly averaged cosmic ray fluxes in Pfotzer's maximum at stations Murmansk and Moscow in five spot minima are shown in Table 1. Exceeding over averaged fluxes in April 2009 was 23.5% at Murmansk and 8.2% at Moscow. At the top of the atmosphere at Murmansk mean cosmic ray intensity in 20–23 minima was 3662 $\pm$ 40 particles/(m^2 s $\cdot$ sr) whereas in April 2009 it was 4521 $\pm$ 80 particles/(m^2 s $\cdot$ sr).

III. Cosmic ray comparison with the HMF and the inclination of the HCS

In the beginning of 2007 the strength of the HMF near the Earth has reached the level of the previous activity minima (Fig. 3), and since that it has weakened by more than 20% to March 2009. Obviously the magnetic field decrease began earlier, likely since the end of 1990s. In evidence of that we can point out on the cosmic ray

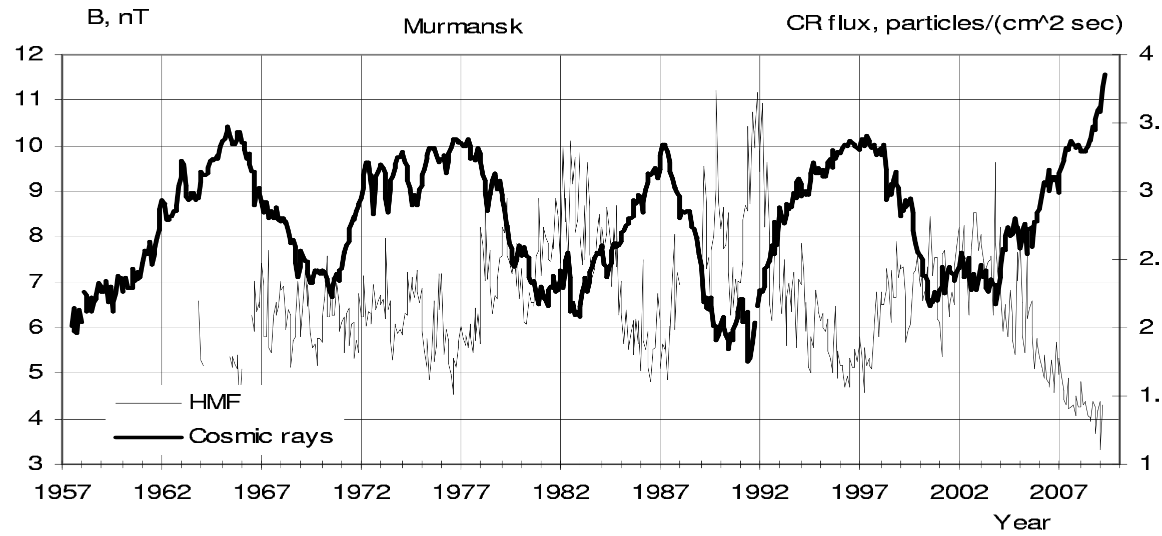

Fig. 3: Cosmic ray fluxes at Pfotzer's maximum in the atmosphere (Murmansk) and the heliospheric magnetic field near the Earth.

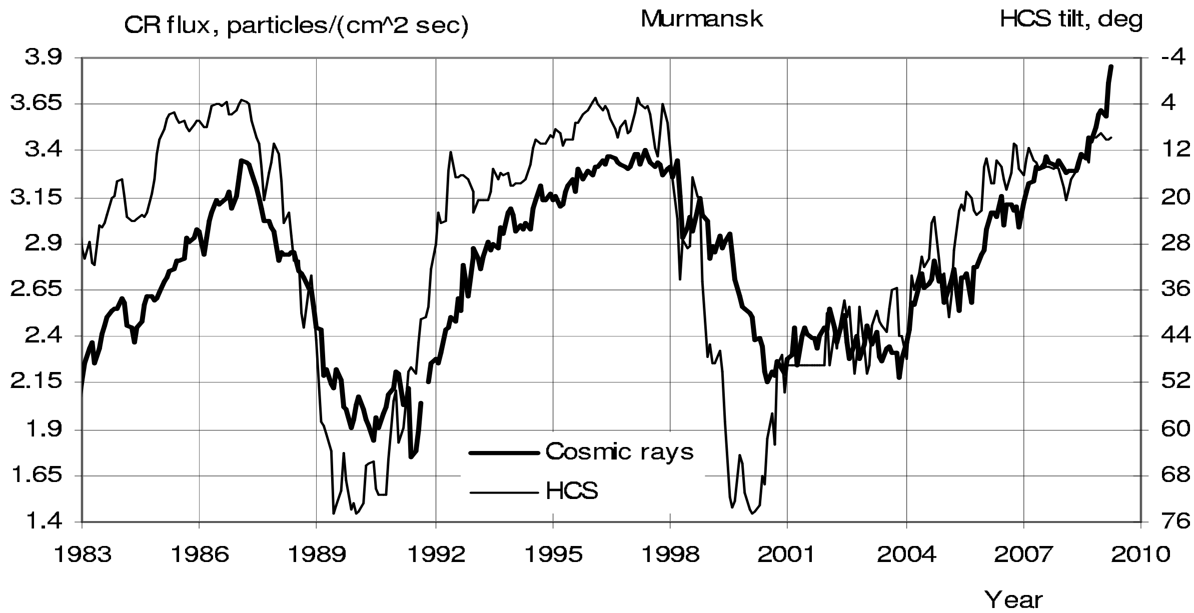

Fig. 4: Cosmic ray fluxes at Pfotzer's maximum in the atmosphere (thick) and the heliospheric current sheet tilt.

fluxes in the 2000–2003 sunspot maximum, which were not so low as during the two previous (1980–1983 and 1989–1991) maxima with more strong magnetic fields. Observations at Ulysses have shown that during 2006–2007 solar activity decrease the magnetic fields were weaker in comparison with that in the same solar cycle phase in 1993–1995 not only near the ecliptic but all over the heliosphere [8].

The HMF is one of the main factors defining the GCR modulation. As is the convention the radial diffusion coefficient is inversely proportional to the magnitude of the HMF, thus the same cosmic ray fluxes are expected at the same magnitude of the HMF. We make a comparison of cosmic ray fluxes and magnetic fields during the last solar activity maximum and the 1969–1970 maximum (Fig. 1, Fig. 3). The cosmic ray fluxes were 2.39 $\pm$ 0.08 and 2.34 $\pm$ 0.06 cm^{-2} s^{-1}, and the magnetic fields were 6.25 $\pm$ 0.60 and 7.37 $\pm$ 0.56 nT in the 1969–1970 and 2000–2003 solar activity maxima, correspondingly. Data on the cosmic rays and the magnetic fields do agree with each other, and we can conclude that in 2000-2003 sunspot maximum the weak magnetic fields were not

TABLE I: Monthly averaged cosmic ray fluxes in Pfotzer's maximum (Nmax, $cm^{-2}s^{-1}$) at the stratospheric stations Murmansk (Rc = 0.6 GV), Moscow (Rc = 2.4 GV) in five solar activity minima.

Solar cycle number	Month year	Nmax, Murmansk	Nmax, Moscow
20	05.1965	3.474 ± 0.006	2.851 ± 0.010
21	05.1977	3.383 ± 0.008	2.803 ± 0.013
22	02.1987	3.346 ± 0.015	2.799 ± 0.013
23	05.1997	3.405 ± 0.013	2.789 ± 0.016
24	04.2009	3.856 ± 0.028	3.048 ± 0.015

unique, and the data on the magnetic fields in the 1969–1970 are true.

At present (May 2009) a favourable conditions remain for further cosmic rays increase. First, the time lag between variations of the solar plasma parameters and the GCR has always existed and has been equal at least a few months. Second, the tilt the HCS has not reached a minimum in $3°$–$5°$, typical for the three previous minima, and is equal now nearly $10°$ (Fig. 4). In the heliosphere the HCS produces the so-called sector zone [9] with enhanced disturbance of the magnetic fields, a decreased diffusion coefficient and suppressed cosmic ray diffusion [10]. At a solar activity minimum the GCR modulation is proportional to the sector zone angular size [11], and if the HCS tilt decreases it will be followed by an increase in the GCR intensity (with a delay of two-three months).

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