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Solar modulation of galactic cosmic rays during 2006-2015 based on PAMELA and ARINA data

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Abstract

Solar modulation of galactic protons with energies from 50 MeV up to dozens of GeV during July 06 – February15 studied based on a data of the magnetic spectrometer PAMELA and scintillation spectrometer ARINA. This period is interesting because it covers the end of 23rdand current 24thcycles of solar activity, including the abnormally long transient period and change of the polarity of solar magnetic field.

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*Keywords:*Solar modulation, magnetic spectrometer PAMELA, scintillation spectrometer ARINA.;

1. Introduction

In accordance with modern notions, the propagation of galactic cosmic rays (GCR) in the heliosphere depends on following processes: diffusion and drift in the interplanetary magnetic field (IMF),drift along the heliospheric current sheet (HCS), convection in solar wind (SW) plasma, adiabatic cooling and polarity of solar magnetic dipole(M. S. Potgieter[1] and references within). Each physical process can be associated with at least one actual physical parameter, for example, roughly, the diffusion coefficient is inversely proportional to the square of the IMF and drift along the HCS depends on its tilt angle. But they are vary in time because of dependence on phase of solar cycle and level of solar activity, which entail a change of GCR flux inside heliosphere (so-called effect of solar modulation).

Despite the large number of currently existing theoretical models, the scarcity of continuous precision measurements of the cosmic ray fluxes of different energies does not allow to understand a contribution of a particular process in the modulation in different phases of solar cycle. Therefore, it is very difficult to predict the flux of galactic particles inside heliosphere if based only on indirect measurements of heliospheric parameters, although today they are performing quite accurately.

Magnetic spectrometer PAMELA (P. Picozza et al. [2]) and scintillation spectrometer ARINA (A.V. Bakaldin, et al.[3]) are modern space experiments, which give us new opportunities to study a transport of cosmic rays in the heliosphere and the effect of solar modulation. The results of measurement the galactic proton flux are present in this paper.

2. PAMELA and ARINA experiments

Both instruments were installed onboard the Russian satellite Resurs-DK1 [4] and launched on June 15th 2006 in a near-Earth orbit. PAMELA and ARINA are carry out a precise measurements of the fluxes of charged cosmic rays (electrons, positrons, protons, antiprotons and heavier nuclei) from the launch date up to present time. The duration, an energy interval and energy resolution along with the main tasks of experiments (see P. Picozza et al. [2] and A.V. Bakaldin et al. [3]) allows to study the solar modulation of galactic cosmic rays.

Scintillation spectrometer ARINA registers protons with energies from ~30 to ~100 MeV with and an energy resolution about 10-15%. Magnetic spectrometer PAMELA registers protons in energy range from ~80 MeV up to hundreds GeV with an energy resolution about 2-5% for particles with energy below 10 GeV (solar modulation affected).

The algorithms for the energy spectra reconstruction gives in works O. Adriani, et al. [5] (PAMELA) and L.A. Grishantseva et al. [6] (ARINA).

The following conditions to select a galactic component of cosmic ray protons were use:

- $L>15$ (whereL - L-shell) in ARINA experiment; and
- $R>1.2R_C$ (where R_C - geomagnetic cutoff rigidity in the point of event registration with rigidity R) in PAMELA experiment.

3. Results and discussion

The instruments operation time includes the end of 23rd, beginning and development of current 24th solar cycles. The past solar activity minimum period was abnormally long and almost complete absence of sunspots since the beginning of 2008 to the end of 2009 have been observed (see Fig. 1a) [7]. Therefore, the transition to the new solar cycle was occurring with a large delay: in January of 2010instead of expected 2008 (assuming a ~ 11-year periodicity). As a result, the consequent modulation conditions for galactic particles were unusual. For example, this period was characterized by a much weaker IMF and solar wind speed compared to previous cycles [8]; the tilt angle of the HCS also reached a minimum value at the end of 2009[9].

Large event statistics collected by PAMELA and ARINA instruments allow us to measure the galactic particle fluxes for each Barlets rotation (BRN).

In Fig. 1b we have plot the time profiles of proton intensities *I* from July 2006 to the beginning of 2015 for different energies with a normalization of them on the first data point in June 2006 $I_{06.2006}$: $(I/I_{06.2006} - 1)\cdot 100\%$. By other words, this picture shows a time variations of galactic proton intensities with energies from 50 MeV (ARINA, to exclude solar component below this value) up to hundred GeV (PAMELA); the color shows different energies according to the color bar at the right side of the picture.

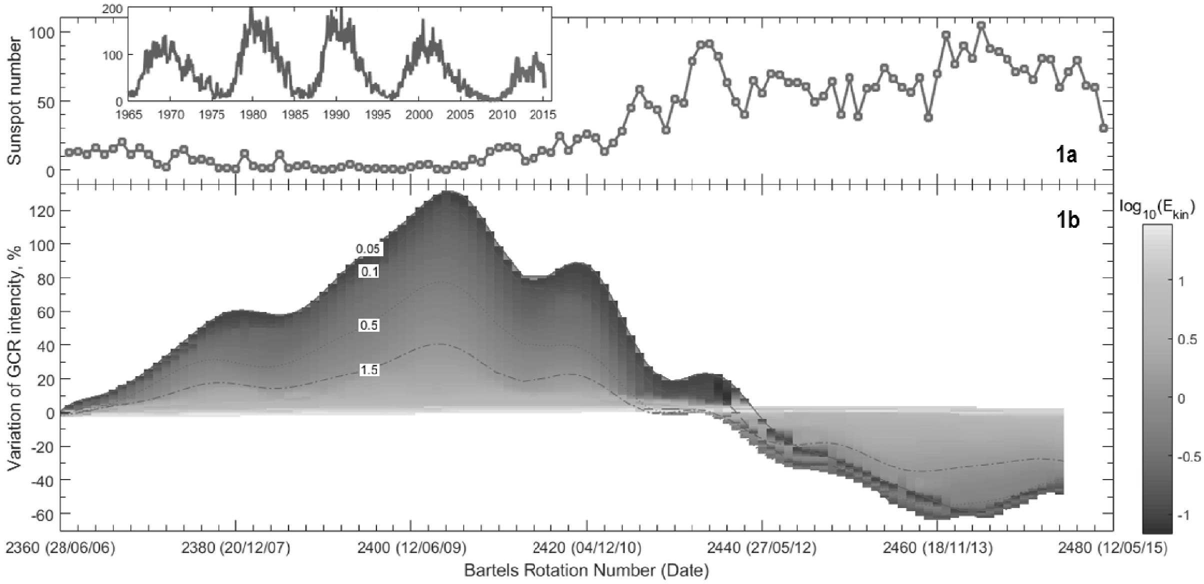

Fig. 1. (a) Sunspot number during the solar cycles; (b) Time variations of galactic proton intensities from 01/06/2006 up to 20/02/2015 measured by PAMELA & ARINA spectrometers in energy range 0.05-100 GV.

The record high flux of galactic particles among the last four minima of solar activity was observed in December 2009 and it cannot be explain uniquely in the framework of existing theoretical models (for examples, M. S. Potgieter, et al. [10] and references within). In particular, during previous negative polarity cycles, proton spectra were always lower than for positive cycles at kinetic energies less than a few GeV, i.e. in a good agreement with drift models of solar modulation (M. S. Potgieter et al. [10]).

From the July 2006 up to January 2010, the flux of low energy galactic protons has increased more than 2 times or ~ 130% of increase in terms of fig. 1b.Then, the solar activity started to grow up and the proton intensity began to decrease. Today there is a maximum of 24thsolarcycle, which probably close to the end (see 1a) and intensity decrease more than 60% relative to the intensity in the middle of 2006. A total amplitude between minimum and maximum fluxes depends on particle's energy and it monotonically decrease from ~ 190% at 50 MeV up to few-ten percent at high energies (at about 15-20 GeV, that is in a good agreement with a neutron monitor measurements [11]).

Many of features in presented time profiles repeated at all energies; they caused by a time variations of different heliospheric characteristics, listed in Introduction. The correlation analysis which was done before (O. Adriani et al. [5], M.A. Bzheumikhova et al. [12]) show that the time-shift between variations of heliospheric parameters and proton fluxes is depending on energy. Now when PAMELA and ARINA measurements cover a wider time interval it seen much better this phenomenon. The fluxes at high energies return to the zero level of July 2006 before low energies ones comes back. They were higher of zero level for at least several months. It is clear to see if compare proton fluxes with energies 0.05 GV and 1.5 GV in figure 1b. Therefore, a shape of the energy spectra would change interesting during this period.

This conclusion is also illustrated in figure 2 where the energy spectra of galactic protons for different Barlets rotations shown. ARINA data points are below 100 MeV, PAMELA data points are above 100 MeV.

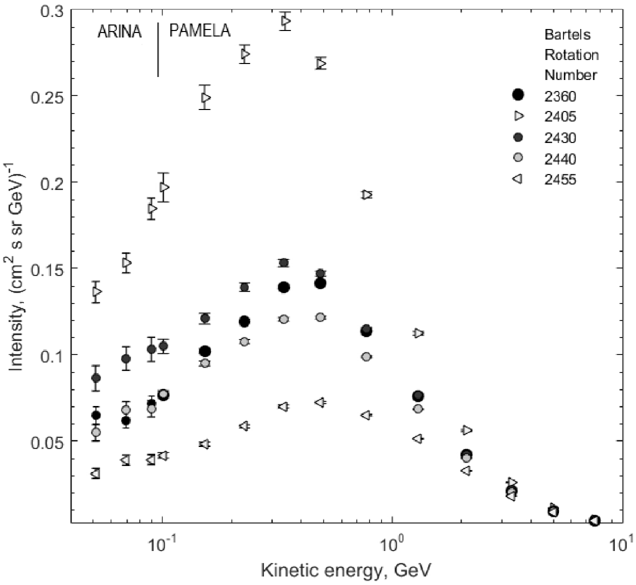

Fig. 2. Galactic proton spectra measured by PAMELA and ARINA spectrometers during different Barlets rotations.

The spectrum measured during July 2006 (BRN 2360) is shown by black circles; open right and left triangles show the measured intensities at the end of 2009 (BRN 2405) and at the middle of 2013 (BRN 2455). It is clear that during BRN 2430 the flux of high-energy particles came back to the values of July 2006, but at the same time the flux of low energy particles is above of similar points. After at about ten Barlets rotations, proton flux at low energies back to the values of July 2006, but at the same time, the flux of high-energy particles became below of similar points. So clearly that there is a time shift in variations of particle fluxes with different energies.

4. Conclusions

We measure variations of galactic proton intensities from 01/06/2006 up to 20/02/2015 by PAMELA & ARINA spectrometers. During this period, we measured variations of fluxes of galactic cosmic rays with energies ranging from 50 MeV to tens of GeV, which decreases monotonically with increasing energy. Special features in the time profiles of particle fluxes associated with changes in different heliospheric parameters. Long-time measurements of PAMELA & ARINA will allow for a more detailed analysis of the correlation for the effect of solar modulation. Especially note the previously detected and reliably confirmed a time delay in the change of fluxes of galactic particles, depending on their energy.

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