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Study of solar modulation of galactic cosmic rays with the PAMELA and ARINA spectrometers in 2006-2012

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Abstract. Spectrometers PAMELA and ARINA, mounted on the spacecraft Resurs-DK1, carried out precision measurements of galactic cosmic ray (GCR) flux near the Earth from 2006 to present. Combining these instruments gives the possibility to study the effect of solar modulation in the energy range from 30 MeV to dozens of GeV. This report presents
experimental results concerning the time interval from the end of the 23rd solar cycle (noted by an prolonged minimum) to the beginning of the 24th cycle. The cosmic ray flux raised up to the end of 2009, then it began to decline, which is in coincidence with the sunspot number and evidence of the solar activity increasing. Some additional features were noted in the time profile of galactic cosmic ray flux, which, as shown by analysis of the correlation, correspond to a change of such heliospheric parameters as the tilt angle of the heliospheric current sheet (HCS), the solar wind velocity and the intensity of interplanetary magnetic field (IMF).

1. Introduction
The measurements of the galactic cosmic ray (GCR) intensity over the full cycle of solar activity led to the discovery of its relation to the number of sunspots (solar activity) and this effect was called solar modulation. Further development of this school, active research of the Sun and interplanetary space led to the conclusion that the modulation of galactic particles is mainly influenced by such physical processes as diffusion, drift, convection and adiabatic cooling during the propagation in Heliosphere. To date, this mechanisms failed to be fully understudied, in spite of the fact that there were created the adequate methods for their description. The contemporary physics experiments PAMELA and ARINA carrying out precision measurements of the GCR flux on the near Earth orbit from June 2006 till present time can promote the development of solar modulation models. It is important to note that at the end of 2009 there was a transition from the 23rd solar cycle, whose minimum was abnormally long and was accompanied by a prolonged lack of sunspots [1], to the 24th cycle. In this regard, experimental data are unique, obtained in an unusual period of solar activity. The correlation analysis of GCR intensity time profile with such heliospheric parameters as the intensity of IMF $B$, the tilt angle of the heliospheric current sheet $\alpha$ and solar wind velocity $V_{sw}$, defined in the experiments ACE and OMNI was carried out.

2. Scientific equipment and processing of experimental data
Experiments PAMELA [2] and ARINA [3] are carried out from 15 June 2006 on board of the Resurs DK-1 satellite launched on near Earth quasi polar orbit with altitude from 350 to 600 km and inclination of 70°. One of the objectives of these experiments is long-term GCR flux measurements, the joint energy range of devices is 30 MeV – hundreds GeV.

Spectrometer ARINA is a tower of scintillation detectors C1-C10. It can detect electrons with energies from 3 to 30 MeV and protons with energies from 30 to 100 MeV. Energy is determined by range of the particles. The geometric factor of the spectrometer is 10 sm$^2$. To separate the protons in the spectrometer ARINA the events were used with signals in the detectors C1C2C3 forming aperture of the instrument. Lack of signal in the bottom counter C10 allows excluding from the analysis the events moving in the opposite direction to the zenith axis of the spectrometer. Protons and electrons are separated by analysis of energy release in scintillation detectors. The galactic component of CR was distinguished by the condition: geomagnetic L shell > 15.

Magnetic spectrometer PAMELA consists of a set of detector systems which allows to identify the particles in the energy range from 100 MeV to hundreds GeV. The energy is determined by deviation of the trajectory in the magnetic field of the spectrometer. The geometric factor of the instrument PAMELA equals 21.6 sm$^2$. To select particles passing through in the aperture of the instrument, the rigidity and the velocity of which can be measured, the following selection criteria were used: single track without interactions in the magnetic spectrometer, which does not touch the magnet, triggered in the time-of-flight system detectors, the lack of signal in the anticoincidence system. Protons separation is based on the dependence of the average ionization losses in the tracking system on the measured rigidity. The galactic component of CR was distinguished by the geomagnetic selection $R>1.2R_c$, $R_c$ - cutoff rigidity at the point of the event registration.

Particle detection efficiency was determined by the Monte Carlo method using the software package based on GEANT3 [4], and also was estimated from the experimental data using various combination of detectors.
3. Results and Discussion

Figure 1 shows the intensity of galactic protons in the energy ranges 45-100 (ARINA), 200-220, and 870-1030 MeV (PAMELA) in the period from July 2006 to April 2012 obtained by both spectrometers.

![Figure 1. Galactic protons intensity measured by the PAMELA and ARINA spectrometers.](image)

Until the end of 2009 particle flux was increasing. Subsequent measurements have shown changes in trends associated with the beginning of the new, 24th, solar cycle and the growth of the solar activity. However, at last minimum the maximum CR flux was higher than in previous SA minima by 10-15% [5, 6, 7]. In the time profile of the intensity several features marked by dashed lines and digits could be distinguished: features 3 and 7 correspond to decrease in flux, 1, 2, 4, 5 and 6 - flux increase. These features are traced in the experiment STEREO [8] and observations of neutron monitors network [9] that suggests of the general nature of their formation.

The particle drift in the heliosphere consists of 2 components: namely, in a regular solar magnetic field and in the heliospheric current sheet - a surface that separates the heliosphere into two regions with the opposite directions of interplanetary magnetic field (toward the Sun and from the Sun). HCS is characterized by the tilt angle of its surface relatively to the solar equatorial plane. The angle varies according to the 11-year solar cycle from about 3°-4° at the minimum of solar activity to 65°-70° during the maximum. Figure 2 shows the time dependence of the inverse tilt angle of HCS calculated for "classic" and the "radial" models of the magnetic field on the Sun surface [10].

Correlation analysis between the tilt angle of HCS for both models and intensity of the GCR protons measured by ARINA and PAMELA was realized. Used experimental data set covers energy range from a few tens MeV up to 10 GeV.

![Figure 2. Inverse dependence of the angle of HCS versus time for the "classic" and the "radial" models of the solar magnetic field [10].](image)
It was found that there is a correlation between the flux of galactic protons and the tilt angle of the current sh. Changes of the flux lag behind at some time for a change of the tilt angle of HCS. In average the flux of cosmic rays with energy from ~ 50 MeV up to several GeV changes about 100 days after tilt angle change. Previously similar lag has been reported, for example, in [11] and references therein on base of neutron monitor data. In this work it was found that the time shift between the changes of the tilt angle and the intensity of galactic protons exists for all energies from 30 MeV to ~ 10 GeV. The duration of lag depends on the energy, probably, due to the different influence of the drift on the distribution of particles with different energies in the heliosphere. This item is now under investigation. Correlation analysis between the intensity of interplanetary magnetic field measured according to OMNI database [12] and intensity of the GCR was also realized using the same data set. But the time shift is not found in this case.

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