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 - January ’16 studied based on a data of the magnetic spectrometer PAMELA and scintillation spectrometer ARINA. This period is interesting because it covers the end of 23rd
and current 24th cycles of solar activity, including the abnormally long transient period and change of the polarity of solar magnetic field.

1. Introduction
In accordance with modern notions, the propagation of galactic cosmic rays (GCR) in the heliosphere depends on following processes: a convection in the solar wind (SW) plasma, a drift along the heliospheric current sheet (HCS), a diffusion and a drift in the interplanetary magnetic field (IMF), adiabatic cooling and the polarity of the solar magnetic dipole ([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 vary over 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 at the different phases of a solar cycle. Therefore, it is very difficult to predict the flux of galactic particles inside the heliosphere based solely on indirect measurements of heliospheric parameters, although today they are obtained with high accurateness. Magnetic spectrometer PAMELA [2] and scintillation spectrometer ARINA [3] are space experiments, which give new opportunities to study transport of cosmic rays in the heliosphere and the effect of the solar modulation. In this article we present measurements of proton and helium fluxes during 2006-2016 years.

2. PAMELA and ARINA experiments
Both instruments were installed onboard the Russian satellite Resurs-DK1 [4] launched on June 15th 2006 in a near-Earth orbit and took data up to January 2016 year. PAMELA and ARINA carried out precise measurements of the fluxes of charged particles in cosmic rays. The duration, an energy interval and energy resolution along with the main tasks of experiments (see [2, 3]) allow to study the solar modulation of galactic cosmic rays.

From June 2006 onwards on the basis of data obtained in the experiments PAMELA and ARINA examines the effect of the solar modulation. Received from spectrometers information differs from all existing experiments: wide total energy range (from a few dozens of MeV to several hundreds of GeV), the precision measurement of the energy of the particles, and the reliable identification of particles and anti-particles including isotope separation of light nuclei. It is worth noting the measurement period, which includes the end of the 23-th cycle of solar activity, moving to 24-th cycle (minimum of solar activity), which turned out to be an unusually long, as well as the starting and maximum 24-th cycle of solar activity.

Spectrometer ARINA is a tower of scintillation detectors C1-C10 and can detect electrons with energies from 3 to 30 MeV and protons with energies from 30 to 100 MeV determining their energy by path. The geometric factor of the spectrometer is 10 sm^2sr.

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, determining their energy by deviation of the trajectory in the magnetic field of the spectrometer. The geometric factor of the instrument PAMELA equals 21.6 sm^2sr.

The algorithms for the energy spectra reconstruction were given in works [5] (PAMELA) and [6] (ARINA).

3. Results and discussion
Here we want to focus on spectra of protons and helium for each month from 2006 to 2016 years were reconstructed based on data from PAMELA and ARINA spectrometers in energy range from 80 MeV to ~ 100 GeV for protons (ARINA and PAMELA) and for 60 MeV/n to 25 GeV/n for helium (PAMELA). We leave these results and analysis for future publications and here lets focus on the helium to proton fluxes ratios.
3.1 \textit{He}/p fluxes ratios for fixed energies per nucleon

It was achieved for different rigidities and energies per nucleon. In the figure 2 helium to proton ratio variations over time for \(E = (0.8 \text{ -- } 1.25 \ \text{GeV/n})\) and \(E = (2.5 \text{ -- } 3.4 \ \text{GeV/n})\) are shown. One can see periodic changes with time: value of the ratio decreased with decreasing of solar activity at the start of measurements then after passing the solar minimum in 2009-2010 rose until it reach its maximum in 2014. So in general it repeats the shape of sunspot number vs time, see figure 1. It is also seen that range of variation between solar minimum and solar maximum decrease with increasing of energy.

\textbf{Figure 2.} Helium to protons ratio measured with the PAMELA experiment for fixed kinetic energies.
3.2 He/p fluxes ratios for fixed rigidities

In the figure 3 helium to proton ratio variations over time for rigidity R=1.7 and R=4.7 GV are shown. It is seen that it doesn’t vary over time but that can be explained by the propagation of cosmic rays in the heliosphere which mostly depends on deflection in the interplanetary magnetic fields (deflection is rigidity$^{-1}$). Though one can see that there are features in the shape: e.g. steep rise of ratios in low rigidities at winter between 2009 and 2010 year, at start of 2012 year and sharp decrease at start of 2015 year. We leave explanation of them for future analysis.

![Figure 3. Helium to protons ratio measured with the PAMELA experiment for fixed rigidities.](image)

4. Conclusion

We got helium to proton fluxes ratio for different energies per nucleon and rigidities during 2006 – 2016 years. Data analysis and processing continue.

Acknowledgments

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