Sharp increasing of positron to electron fluxes ratio below 2 GV measured by the PAMELA

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\textbf{Abstract.} Magnetic spectrometer PAMELA was launched onboard a satellite Resurs-DK1 into low-Earth polar orbit with altitude 350-600 km to study cosmic ray antiparticle fluxes in a wide energy range from $\sim 100$ MeV to hundreds GeV. This paper presents the results of observations of temporal variations of the positron and electron fluxes in the 2006-2015. The ratio of the positron and electron fluxes below 2 GV shows sharp increasing since 2014 due to changing of the polarity of the solar magnetic field.

1. Introduction
High energy electrons are produced mainly in accelerating processes in supernova remains. Small number of electrons together with positrons are produced also in the inelastic interaction of...
cosmic ray nuclei with the interstellar medium. Recent measurements of the ratio of positron
flux to total flux of electrons and positrons in PAMELA and AMS02 experiments [1, 2, 3] have
shown that it increases with energy beginning from 5-10 GeV in opposition to the standard
diffuse cosmic ray propagation model with secondary production mechanism for positrons.

But also at low energy new data are clearly lower then results of previous experiments made in
90th [1, 3]. Diffusion, drift, convection processes in the Heliospheric Magnetic Field (HMF) and
solar wind affect cosmic-ray fluxes with energies less than about 10 GeV modifying their energy
spectra. The effect of this modulation depends on solar activity level. At Solar minimum fluxes
suppression is minimal and cosmic rays have maximum intensity near the Earth. Moreover drift
process depends from sign of particles charge and this lead to charge dependent modulation
which defined by HMF polarity. Tilt angle is important parameter to characterize drift of
particles along of neutral sheet of HMF [4].

The PAMELA apparatus is mounted on-board the Resurs-DK1 satellite which was placed
into near Earth elliptical orbit with an altitude of 350 - 600 km and an inclination of 70.4
°
on June 15, 2006. The experiment observations cover period from the end of last long 23th solar
minimum till the maximum of next 24th cycle including the HMF polarity change interval from
A<0 to A>0. Preliminary results of the solar modulation influence on the positron fraction of
galactic cosmic-ray for period between June 2006 and December 2015 have been published [5].
Here the results of the long-term variation in the positron fraction of galactic cosmic-ray are
presented at 1 AU since June 2006 till January 2016 with increased statistical accuracy.

2. PAMELA experiment
The instrument includes magnetic spectrometer, electromagnetic imaging calorimeter, time-of
flight system, anticoincidence system, shower scintillator and neutron detector and it is capable
to measure particle speed $\beta$, charge $Z$, rigidity $R$ and total energy $E$. The electron and positron
identification is provided by the imaging calorimeter which consist of 22 double side silicon strip
detectors interleaved by tungsten planes (16.3 radiation and 0.6 nuclear interaction lengths deep).
The instrument allows extracting electrons and positrons and measuring their energy from 50
MeV up to several hundred GeV. Details about the experiment and the particle identification
can be found in papers [9, 10].

Figure 1 shows Heliospheric condition before and during measurements. $F_{10.7cm}$ flux is
perfect index for solar activity. The PAMELA started observations when solar activity was
decreasing. It reached the minimum at the end of 2009. The highest proton flux was observed
by PAMELA at that period [6]. The drift effects also had maximum in 2009 [4]. Polarity of
HMF was changed from positive sign $A>0$ to negative $A<0$ in 2002 and between 2012 and 2014
it was changed again.

3. Data analysis
In this paper the analysis based on data gathered from June 2006 to January 2016. To increase
statistical accuracy more soft selection criteria for magnetic spectrometer were applied to data
then in paper [5] with additional geometrical checking of tracks in tracker of the spectrometer and
calorimeter. Total accumulated statistic for electrons and positron is about $4\times10^6$ events with
energy more then 100 MeV. Primary cosmic ray particles were selected by vertical geomagnetic
rigidity cut-off $R_{cut}$ in point of observation requiring particle rigidity $R>1.2\times R_{cut}$. This selection
was then verified with special program which calculate trajectory of all detected electrons and
positrons in the Earth magnetosphere using known particles rigidity, coordinates and direction.

An efficiency of the instrument was changed with time. It was verified from experimental
data itself by using information from different combination of detectors: calorimeter, magnetic
spectrometer and time of flight system. Figure 2 shows the comparison of the PAMELA data
Figure 1. PAMELA observations are related to different periods of solar activity. Top panel shows projection of heliospheric magnetic field, middle panel shows tilt angle (data of the Wilcox Solar Observatory, http://wso.stanford.edu ) and bottom panel shows F10.7 cm flux (http://www.spaceweather.gc.ca/solarflux/sx-5-mavg-en.php).

Figure 2. Average positron to electron ratio as function of energy on measurements of PAMELA and AMS02 from 05/2011 till 11/2013.

with the AMS02 measurements. The PAMELA ratio of positron flux to total electron and positron flux as function of energy was plotted exactly for the same period as in paper [3]. Good agreement of results for positron fraction is evident from the figure. Other possibility to cross check efficiencies is derived from the observations of secondary fluxes of positrons and electrons produced by high energy cosmic rays in the Earth residual atmosphere. Part of those secondaries can be detected on the satellite orbits as so-called reentrant albedo. In near equatorial region
albedo fluxes don’t undergoes solar modulation because they mainly originated from protons with rigidities more then 16 GV. Positron fraction of secondary albedo component is shown in figure 3 for energy range 0.5-2 GeV. Between 2006 and 2016 it vary not more then 7% giving a limit of possible systematic error.

Figure 3. albedo positron to electron ratio vs time (Lshell ≤ 3, B>0.23 G), <E>=1.25 GeV.

4. Results
Figure 4 shows measured positron fraction in energy interval 0.5-2.2 GeV as function of time. High statistical precision of data allows us to limit the role of statistical errors and to see the variations of ratio even they are relatively small in period before 2014. While large solar modulation of electrons, positron and proton fluxes was observed, variation of positron fraction were relatively small till 2012. Maximum of the ratio was reached at the end of 2009, during minimum of solar activity, because of more fast increasing of the positron flux comparing to electron at that period. Between 2011 and 2013 ratio of positron to sum of electrons and positrons remained practically constant. Sharp increasing of positron fraction started at the end of 2013 soon after epoch of HMF polarity change.

Several attempts were made to estimate electron and positron fluxes variations during solar cycle. All models show the different behavior occurring in periods with different magnetic field polarity. During periods with A> 0 the positrons ratio is quite similar to the interstellar one. During periods with opposite field polarity instead there is a relevant reduction of the cosmic ray positron fraction in comparison with the interstellar one[8, 4, 7]. Meanwhile, quantitative agreement with observations is less perfect. For example, the results of PAMELA spectrometer shows that the modeled magnitude [8] is somewhat too large during whole solar cycle.

5. Summary
Electron and positron fluxes and their ratios measured in the PAMELA experiment provide a matter for the detailed study of modulation effects during 9-th year period due to large accumulated statistics.
Figure 4. Cosmic ray positron to electron ratio vs time, $<E>$=1.2 GeV.

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