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Precision measurements of cosmic ray electron and positron spectra above 50 MeV with the PAMELA magnetic spectrometer

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Abstract. The PAMELA experiment with magnetic spectrometer operated almost ten years on board of the Resurs DK1 satellite. The satellite was launched on 15 June 2006 on polar orbit with an inclination of 70° and an altitude of 350–610 km. The spectrometer continuously measured charged cosmic ray particles in wide energy range from about 50 MeV up to several TeV. In this work the spectra of electrons and positrons averaged over one year were obtained from July of 2006 until January 2016, i.e. from the end of 23th and at the beginning of 24th solar cycle including the period of interplanetary magnetic field polarity reversal. These precise long duration time-dependent measurements of the electron and positron spectra are important to estimate possible contributions of exotic cosmic ray sources such as dark matter annihilation or decay.

1. Introduction

The PAMELA magnetic spectrometer was launched onboard the Resurs-DK1 satellite to Earth polar orbit with altitude of 350-600 km to study the fluxes of cosmic ray particles and antiparticles in a wide energy range from ~ 50 MeV to hundreds of GeV. First measurements of electron and positron spectra were reported in papers [1-3], for which data taken in 2006-2009 during 23th solar cycle were processed.

The magnetic spectrometer had been collecting data until 23 January 2016 when satellite downlinks were terminated. To evaluate the electron and positron spectra for all periods of observations, the same approach [3] was applied to the whole data set. This extended period of observations covers the end of the 23th solar cycle and the beginning of the 24th cycle. The reversal of the heliospheric magnetic field direction occurred in this period, causing a significant increase of the electron to positron ratio [4]. These measurements were extended with high accuracy by the AMS magnetic spectrometer that also demonstrated these new features in the ratio after 2016 [5]. This paper reports preliminary measurements

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of electron and positron fluxes by the PAMELA magnetic spectrometer for the whole period of operation.

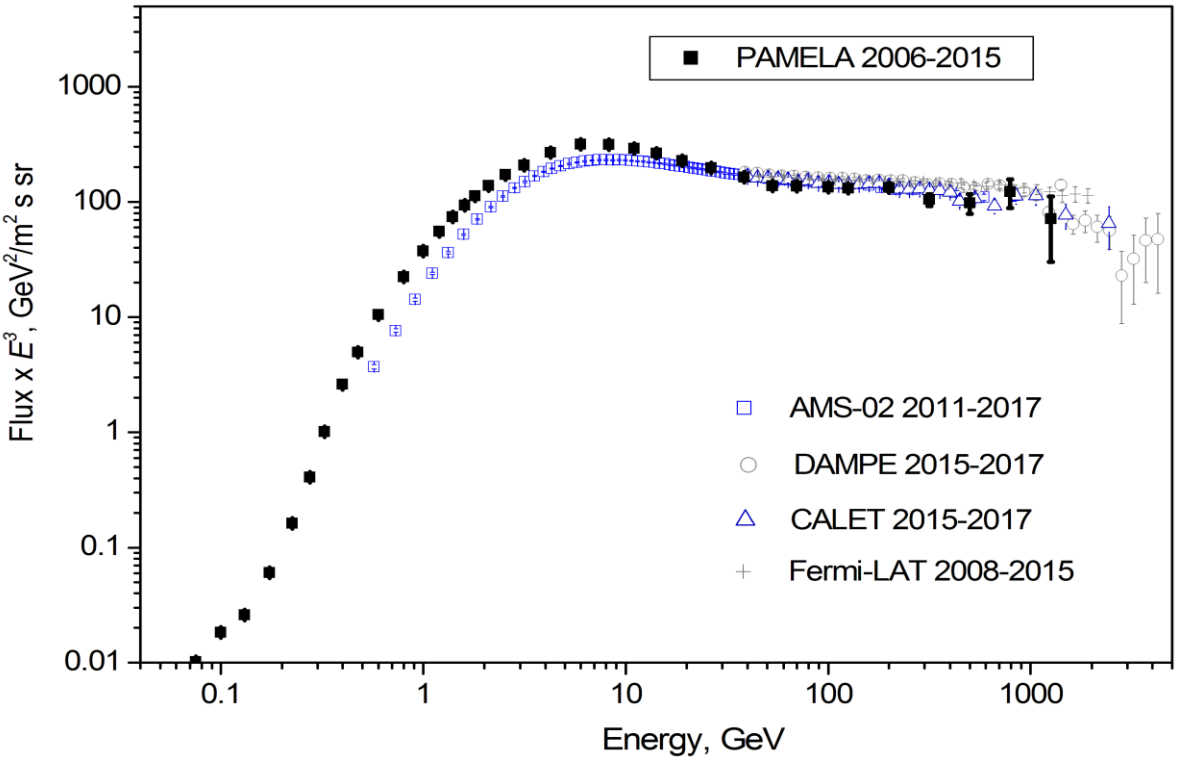


Figure 1. Differential energy spectra of total electron and positron fluxes (xE^3) above 50 MeV measured by PAMELA and recent experiments as indicated in [6-9].

2. Measurements of electron fluxes at high energy

Combined spectrum of electron and positron flux for the period 06/2006-01/2016 is presented in figure 1 in comparison with other recent measurements. The measurements of cosmic ray electron and positron fluxes by AMS-02 [6] Fermi-LAT [7], DAMPE [8] and CALET [9] all report about features of the energy spectra over this large energy range. In particular, DAMPE observed a break of the total electron and positron spectrum at ~ 700 GeV and a peak at about 1 TeV. The break was confirmed by CALET and Fermi-LAT data, but not the peak. Another problem is that the data of AMS-02 and CALET are noticeably lower than that of DAMPE and Fermi-LAT above several hundred GeV. The reason for this difference has not been clarified, yet. It could be some systematic aspect in the instrument calibration but it is also not possible to exclude that the difference deals with different experimental environments. For example, in [10] it is argued that when primary cosmic ray electrons and positrons enter the top of the atmosphere, their energy spectra may be changed by an anomalous bremsstrahlung effect. Both AMS and CALET are on board the international space station at about 400 km height, while Fermi-LAT and DAMPE were orbiting the Earth at 500 ~ 560 km altitude leading to a complex structure of the measured spectra [10]. In 2006–2010, the "Resurs DK1" satellite had an elliptical orbit between 350–610 km. Figure 2 presents energy spectra of electrons and positrons for different altitudes in the magnetosphere and their corresponding ratio. From this figure it is difficult to notice an influence of the residual atmosphere on measured fluxes.

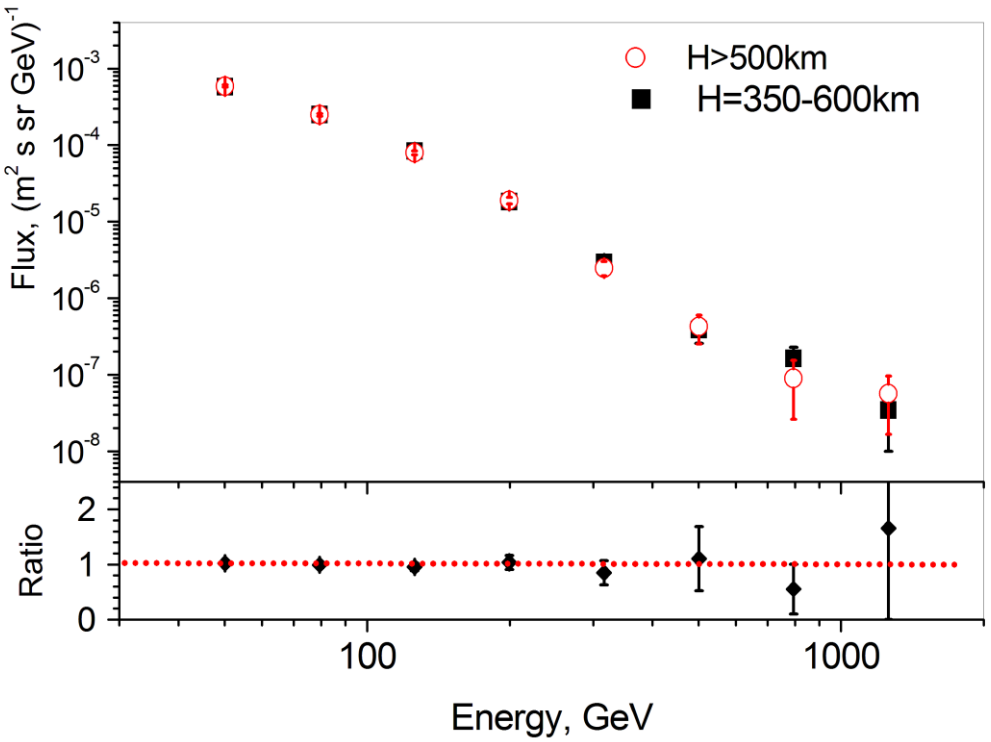
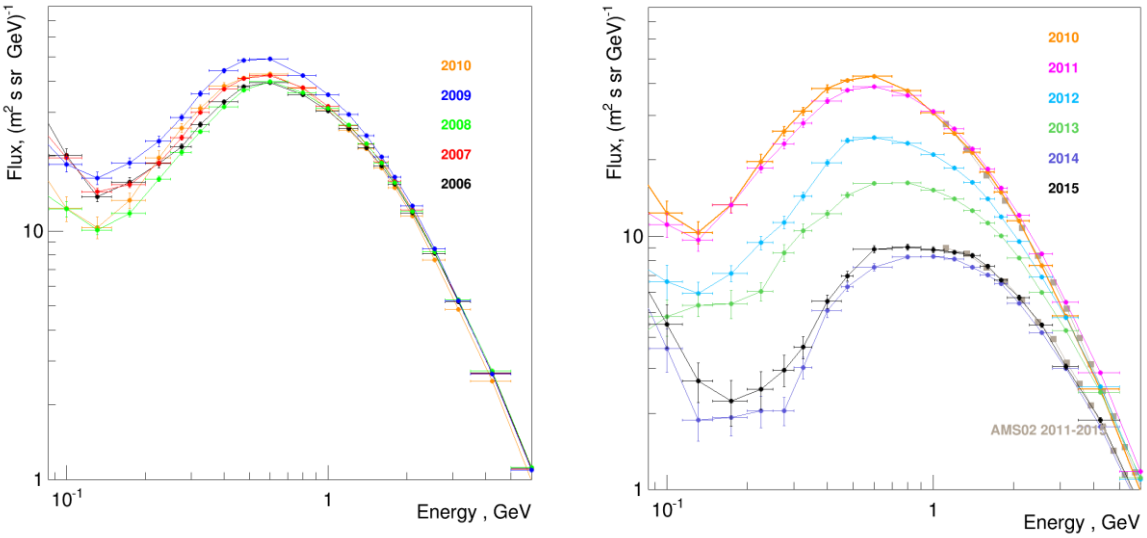


Figure 2. Fluxes of electrons above 30 GeV as measured by the PAMELA magnetic spectrometer at different altitudes in the Earth magnetosphere.



(a) (b)

Figure 3. The differential fluxes of cosmic ray electrons obtained the PAMELA experiment during the 23th solar cycle minimum 2006-2010 (a) for the negative polarity (A<0) of the HMF and from 2010 to 2015 (b) as the beginning of the 24th cycle until the HMF polarity reversal in 2014 and AMS-02 data in 06/2011 and 06/2015 [5].

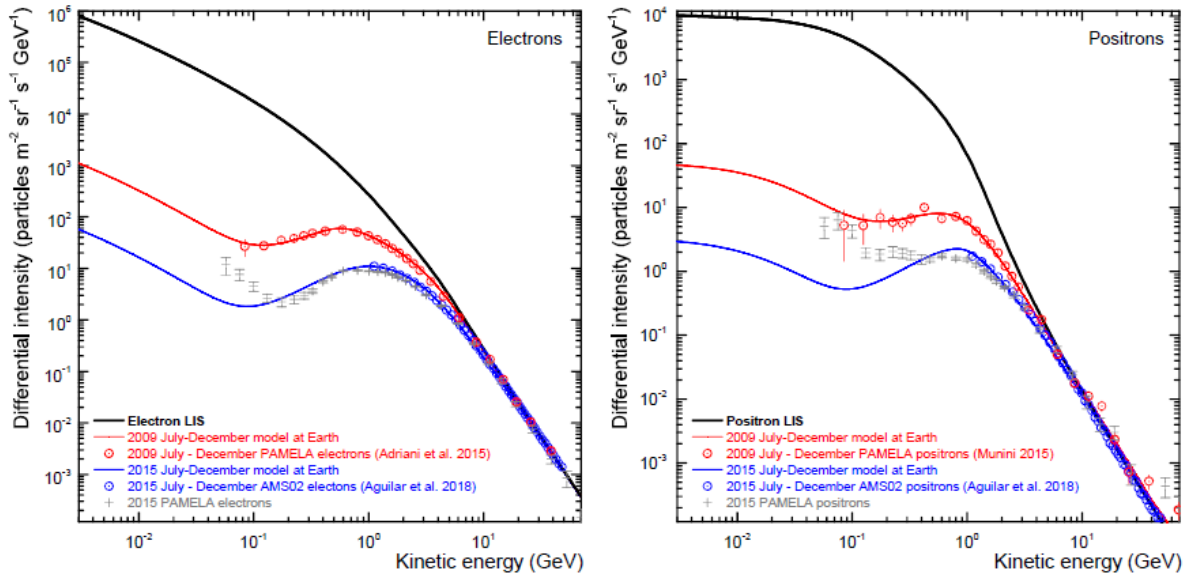
3. Solar modulation of cosmic rays in the heliosphere

Simultaneous and continuous observations of protons, helium, electrons, anti-protons and positrons from the PAMELA experiment have improved our understanding of the major mechanisms driving the modulation of cosmic rays (CRs) in the heliosphere. These observations have confirmed that the principal factors in modelling the modulation of CRs in the heliosphere are the local interstellar spectra (LIS), the heliospheric magnetic field, the solar wind speed, heliospheric boundaries, the tilt of the heliospheric current sheet, and the elements of the diffusion and drift tensor [11]. New results for the low energy part of electron spectra obtained for the period of increasing solar activity and for the HMF polarity reversal are presented in Figure 3. These data sets can be utilized to adjust modulation models to conditions of moderate solar activity in the heliosphere.

Modulation models used to study CRs in the heliosphere are based on solving the transport equation derived by Parker (1965) [13]:

$$\frac{\partial f}{\partial t} = -(\boldsymbol{V} + \langle \boldsymbol{v}_{\mathrm{D}} \rangle) \cdot \nabla f + \nabla \cdot (\boldsymbol{K}_s \cdot \nabla f) + \frac{1}{3}(\nabla \cdot \boldsymbol{V}) \frac{\partial f}{\partial \ln P}, \tag{1}$$

where $f(\boldsymbol{r}, P, t)$ is the omnidirectional CR distribution function, P is rigidity, $\boldsymbol{r}$ is the heliocentric position vector, and t is time, with $\mathbf{V}(r, \theta) = V(r, \theta)\, \boldsymbol{e}_r$ the radial solar wind velocity. The terms on the right-hand side represent convection, gradient and curvature drifts, diffusion, and adiabatic energy losses, respectively. All details of the comprehensive 3D numerical model used in Figure 4 were published by Potgieter and Vos [14] and Aslam *et al.* [11,12].



(a) (b)

Figure 4. Computed electron (a) and positron (b) spectra for 6 month-averaged (July to December) periods between 2009 (A < 0 cycle) and 2015 (A > 0 cycle) at the Earth (coloured solid lines) with respect to the LIS specified at 122 AU (solid black lines). These computed spectra are compared to PAMELA and AMS electron and positron observations indicated by coloured open circles and grey crosses as indicated.

Figure 4 depicts the computed spectra overlaid on the corresponding observed electron and positron spectra from PAMELA and AMS, shown at the Earth with respect to their LIS. The effects of varying solar modulation conditions between 2009 and 2015 on CR electron and positron spectra are clearly noted, at kinetic energies below ~ 10 GeV. This indicates that the PAMELA and AMS measurements of these CR species reveal very little information about the shapes of their LIS. Figure 5

further illustrates that observed electron and positron spectra are well reproduced by the 3D modulation model across kinetic energies above ~ 200 MeV. The discrepancy between the model computations and PAMELA observations below 200 MeV in 2015 needs further investigation.

Acknowledgments

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