# Time Dependence of the Electron and Positron Components of the Cosmic Radiation Measured by the PAMELA Experiment between July 2006 and December 2015

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Cosmic-ray electrons and positrons are a unique probe of the propagation of cosmic rays as well as of the nature and distribution of particle sources in our Galaxy. Recent measurements of these particles are challenging our basic understanding of the mechanisms of production, acceleration, and propagation of cosmic rays. Particularly striking are the differences between the low energy results collected by the space-borne PAMELA and AMS-02 experiments and older measurements pointing to sign-charge dependence of the solar modulation of cosmic-ray spectra. The PAMELA experiment has been measuring the time variation of the positron and electron intensity at Earth from July 2006 to December 2015 covering the period for the minimum of solar cycle 23 (2006–2009) until the middle of the maximum of solar cycle 24, through the polarity reversal of the heliospheric magnetic field which took place between 2013 and 2014. The positron to electron ratio measured in this time period clearly shows a sign-charge dependence of the solar modulation introduced by particle drifts. These results provide the first clear and continuous observation of how drift effects on solar modulation have unfolded with time from solar minimum to solar maximum and their dependence on the particle rigidity and the cyclic polarity of the solar magnetic field.

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*Introduction.*—Electrons and positrons are a natural component of the cosmic radiation. Both cosmic-ray electrons and positrons are produced in the interactions between cosmic-ray nuclei and the interstellar matter. Additionally, since the observed electron flux is about an order of magnitude larger than the positron one (e.g., Ref. [1]), a majority of electrons must be of primary origin, probably accelerated to high energy by astrophysical shocks generated at sites like supernova remnants (e.g., Ref. [2]).

The recent results on the positron fraction measured by PAMELA [3–5], Fermi [6], and AMS-02 [7,8] elicited enormous interest because of the significant discrepancy with the expected secondary behavior (e.g., Ref. [9]) of this fraction with energy. While most of the excitement was due to the high energy ($> 10$ GeV) results and their connection with possible new sources, such as pulsar (e.g., Refs. [10,11]) or dark matter particles (e.g., Refs. [12–14]), the differences at low energies also attracted considerable interest. These differences were particularly intriguing because previous measurements [15–17], which were both statistically and systematically significant, agreed at low energies ($< 5$ GeV) with the theoretical modeling (e.g., Refs. [9,18,19]). This discrepancy was explained as an effect of charge-sign dependence of the solar modulation (e.g., Refs. [20,21]), since these older measurements were taken during the 1990s, i.e., in a period of opposite polarity of the heliospheric magnetic field (HMF) with respect to PAMELA results.

Traversing the heliosphere, galactic cosmic rays (CRs) are scattered by the irregularities of the turbulent HMF embedded into the solar wind, and undergo convection and adiabatic deceleration in the expanding solar wind. As a consequence, the intensity of CRs at Earth decreases with respect to the local interstellar spectrum [22]. Solar modulation has large effects on low energy CRs (less than a few GeV) and has negligible effects above energies of a few tens of GeV. Moreover, due to the 11-year solar activity cycle, the intensity of CRs inside the heliosphere changes with time. During solar minimum periods, the intensity of CRs is higher with respect to periods of solar maximum. This feature is well represented in the bottom panel of Fig. 1, where the counting rate of the Oulu neutron monitor between July 2006 and the end of 2015 is shown (data are normalized to July 2006). This quantity describes well the time variations of the CR intensity at Earth since the neutrons are produced by the interaction of CRs with the atmosphere and the apparatus.

On top of the time dependence, a charge sign dependence of the solar modulation is expected. The gradients and curvatures present in the HMF induce drift motions that depend on the particle charge sign. During so-called $A < 0$ [25] polarity cycles such as solar cycle 23, when the heliospheric magnetic field is directed toward the Sun in the northern hemisphere, negatively charged particles undergo drift motion from the polar to the equatorial regions and outwards along the heliospheric current sheet. Positively charged particles drift in opposite directions. The situation reverses when the solar magnetic field changes its polarity at each solar maximum. Drift effects are expected to be particularly important during periods of minimum solar activity and have less impact during solar maximum [26]. Indeed, solar minimum activity is the ideal condition to study the global modulation processes that affect the CR propagation inside the heliosphere because very few solar-created transients disturb the modulation region. The coincidental study of positively and negatively charged particles allows us to understand the contribution of drift motion to the propagation of CRs. Furthermore, extending these measurements to solar maximum conditions and reversal of the magnetic field polarity allows us to study how drift effects evolve with solar activity and if they actually account for the differences in the experimental results.

In addition to the positron fraction results discussed above, charge-sign effects were invoked to explain the electron ($e^- + e^+$) and proton measurements from a few hundred MeV up to the GeV region by the KET instrument on board the *Ulysses* spacecraft [27] that explored the high latitude regions of the inner heliosphere from 1990 to 2009 and the antiproton results by the BESS experiment [28]. Clem *et al.* [29] reported a world summary of the positron abundance measurements as a function of energy for different epochs of solar magnetic polarity together. All these results point at charge sign dependence of the solar modulation but are affected by large statistical and systematic uncertainties. A precise understanding of the effects of solar modulation, which significantly affects the cosmic-ray particle spectra below a few GeV, is fundamental to fully exploit the precise experimental data available nowadays. Low energy positron data, dominated by the contribution of secondary particles, can be used to constrain propagation models and have a strong impact on indirect dark matter searches (e.g., Ref. [30]). Similarly, low energy antiproton data can be used to test models like annihilation or decay of dark matter particles (e.g., Ref. [31]) and evaporation of primordial black holes (e.g., Ref. [32]). Furthermore, the experimental and theoretical investigation of the heliosphere provides information that can be easily applied to larger astrophysical systems (e.g., Ref. [33]).

PAMELA (Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics) is a satellite-borne experiment [34,35] designed to make long duration measurements of the cosmic radiation. Results on the effects of the solar modulation on the energy spectra of galactic cosmic-ray protons [36] and electrons [37] for the 23rd solar cycle minimum (July 2006–December 2009) have already been published by the PAMELA Collaboration. In this Letter we present a comprehensive study on the long-term variation of the low energy cosmic-ray positron fraction and of the cosmic-ray positron to electron ratio between 500 MeV and 5 GeV from July 2006 to December 2015, covering the period for the solar minimum until the middle of the maximum of solar cycle 24, through the polarity reversal of the heliospheric magnetic field, which took place between 2013 and 2014. The process of polar field reversal is relatively slow, north-south asymmetric, and episodic. Sun *et al.* [23] estimated that the global axial dipole changed sign in October 2013; the northern and southern polar fields reversed in November 2012 and March 2014, respectively, about 16 months apart.

The analysis presented in this Letter is the first extensive study of CR modulation during an unusual period of solar activity. It was expected that the increase in the activity for the 24th solar cycle would begin early in 2008. Instead,

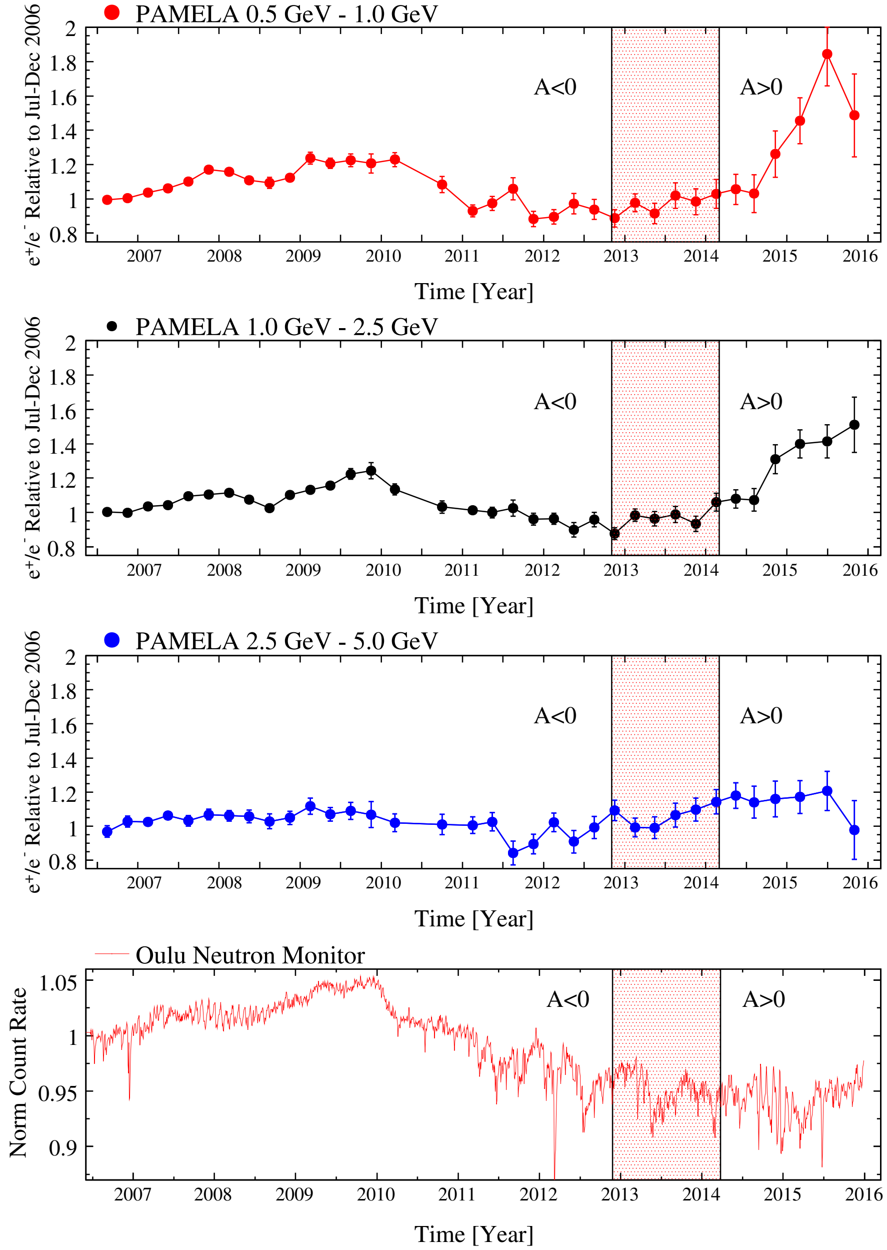

FIG. 1. The positron to electron ratios relative to July–December 2006 measured at Earth by the PAMELA experiment for three different energy intervals. The colored lines provide connection among the points. Data were selected on three month time intervals between July 2006 and December 2015. For 2010 only two time intervals were considered since the instrument was switched off from April to August. The shaded area corresponds to the period with no well-defined HMF polarity [23]. The bottom panel shows the Oulu neutron monitor count rate (data taken from Ref. [24]). Data are normalized to July 2006.

solar minimum modulation conditions continued until the end of 2009 when the largest fluxes of galactic cosmic rays since the beginning of the space age were recorded [38,39]. The subsequent maximum condition of solar cycle 24 continues to be unusual, with the lowest recorded sunspot activity since accurate records began in 1750.

*PAMELA instrument and data analysis.*—The PAMELA experiment was launched on June 15 2006 from the Bajkonur cosmodrome on-board the Resurs DK1 satellite and, since then, it has been almost continuously taking data.

The apparatus comprises the following subdetectors (from top to bottom): a time-of-flight (TOF) system; a magnetic spectrometer; an anticoincidence system; an electromagnetic imaging calorimeter; a shower tail catcher scintillator, and a neutron detector. A detailed description of the instruments and data handling can be found in Refs. [34,40].

To select a clean sample of low energy electrons and positrons, a first selection on the goodness of the reconstructed track, expressed in terms of the $\chi^2$ of the fit, was made. Only single track events were selected.

Furthermore, the track was required to be reconstructed inside a fiducial volume bounded 0.15 cm from the magnet cavity walls to increase the spectrometer performance. The ionization losses in the TOF scintillators and in the silicon tracker layers were used to select minimum ionizing singly charged particles. Albedo particles were rejected using the TOF velocity information. Reentrant albedo particles were rejected, comparing the particle rigidity with the vertical cutoff corresponding to the PAMELA orbital position. Only events with a measured rigidity greater than 1.3 times the vertical cutoff were selected.

In the energy range between 500 MeV and 5 GeV the major source of contamination for positrons is represented by protons. The positron to proton ratio is about $10^{-3}$. On the other hand, antiprotons account just for a few percent of the electron signal. Another important source of contamination for both electrons and positrons is represented by pions, which are created locally by the interaction of primary protons and nuclei with the PAMELA structure or pressure vessel. According to simulations, this background reaches a maximum value around 300–500 MeV and rapidly decreases with energy, becoming negligible above a few GeV. Around 400 MeV the pion background is about 2 times the positron signal and ∼30%–40% of the electron signal. Finally, a non-negligible fraction of high rigidity ($>10$ GV) protons are reconstructed as low rigidity ($<1$ GV) positively or negatively charged particles. This is due to the presence of spurious hits in the tracker planes, which cause a wrong curvature reconstruction of the track. These events are significant at energies below 1 GeV and amount to a few percent of the electron and positron signal. All these hadron background were rejected using a combination of calorimeter variables defined in order to emphasize the different topological development of the electromagnetic and hadronic shower inside the PAMELA calorimeter. For more details on the analysis see Refs. [5,37,41].

For this study, galactic positrons and electrons were selected between 0.5 and 5 GeV. The positron to electron ratio was measured on three-month time periods between July 2006 and December 2015. This energy and time division was chosen as the best balance between the statistics, the energy resolution, and the time resolution. A total of 35 time intervals were obtain. For 2010 only two time intervals were considered since the instrument was switched off from April to August because of satellite problems.

*Results.*—Figure 1 shows the results on the time dependence of the positron to electron ratio. Each of the three panels represents a different energy interval. Data were normalized to the values measured between July and December 2006. Note that the statistical errors on the positron to electron ratio increase with time. This decrease in statistics was due to a reduction in the tracker efficiency with time [37]. The red shaded area represents the time interval during which the process of polar field reversal took place.

The results clearly show a time dependence of the positron to electron ratio. In the first two energy intervals of Fig. 1 (0.5–1 and 1–2.5 GeV) an increase of the ratio was observed up to the end of 2009. During this time period positrons at Earth increased about 20% more than electrons. For the third energy interval (2.5–5.0 GeV) this increase was ∼10%. From Fig. 1, bottom panel, it can be noticed that minimum modulation was reached at the end of 2009, when the neutron monitor count rate reached its maximum values. After 2009 the solar activity started to increase and the CR intensity decreased up to the middle of 2013 where it remained constant until late 2015. At the same time the ratio $e^+:e^-$ decreased until the middle of 2012. This means a stronger decrease in the positron intensity at Earth with respect to electrons. Until the middle of 2013 the ratio remained constant and slowly increased up to the middle of 2014 when a sudden rise was observed up to late 2015 for the first two panels of Fig. 1, where positrons increased, respectively, about 80% and 50% more than electrons. This sudden rise is not observed for the highest energy interval, where the positrons increased only about 20% more than electrons. The sudden rise measured during this period appears to be a consequence of the polarity reversal of the HMF.

The trends in the observational data shown in Fig. 1 can be interpreted in terms of particle drifts. In the context of this charge-sign dependent modulation, the tilt angle [42] of the wavy heliospheric current sheet is the most appropriate proxy for solar activity. For the period 2006 to 2009, this tilt angle decreased slowly to reach a minimum value at the end of 2009. During this $A<0$ magnetic polarity cycle, positrons drifted towards Earth mainly through the equatorial regions of the heliosphere, encountering the changing wavy current sheet, while electrons drifted inwards mainly through the polar regions of the heliosphere and were consequently less influenced by the current sheet. The positron flux therefore increased relatively more than the electron flux with a decreasing tilt angle until the end of 2009, so that the ratio $e^+:e^-$ gradually increased to the point when solar minimum modulation conditions were settled throughout the heliosphere. From 2010 onwards, the tilt angle increased sharply so that the positron flux also decreased proportionally faster than the electron flux and the ratio $e^+:e^-$ decreased. This continued until increased solar activity influenced both fluxes equally and the ratio $e^+:e^-$ became steady. From the end of 2012, the solar magnetic field had gone into a reversal phase, which lasted until the beginning of 2014, when the reversal of both the northern and southern solar magnetic field components was established and the sign of the magnetic polarity in each hemisphere became again clearly recognizable. After this turbulent reversal phase (from $A<0$ to $A>0$) the positrons gradually started to drift inwards through the polar regions of the heliosphere to the Earth while the electrons started to drift inwards through the equatorial regions so

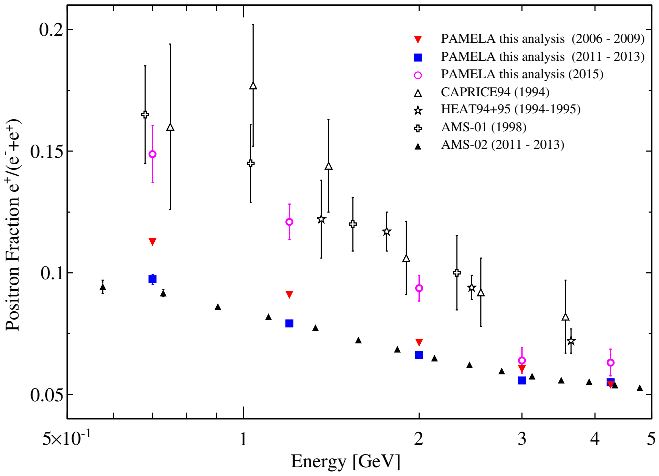

FIG. 2. The positron fraction derived in this work for three time periods: July 2006–December 2009, (solar minimum, as in Ref. [5]), May 2011–November 2013 (as AMS-02 results [8]), January–December 2015, along with other recent measurements: HEAT94 + 95 [15], CAPRICE94 [16], AMS-01 [17], AMS-02 [8]. The results from Refs. [15–17] refer to the previous $A > 0$ solar cycle.

that the positron flux increased proportionally more than for electrons.

This can be observed also in Fig. 2, which shows the positron fraction derived in this work for three time periods: July 2006–December 2009 (solar minimum, as in Ref. [5]), May 2011–November 2013 (as AMS-02 results [8]), January–December 2015, along with previous experimental results. A good agreement between these data and the AMS-02 results can be noticed. Moreover, the positron fraction measured in 2015 draws near to the measurements [15–17] from the previous $A > 0$ solar cycle in the 1990s.

*Conclusions.*—We have presented new results on the positron and electron intensity below 10 GeV obtained by the PAMELA experiment and covering the period from the minimum of solar cycle 23 until the middle of the maximum of solar cycle 24, through the polarity reversal of the HMF. Clear evidence of sign-charge dependent solar modulation was observed. The positron fraction evolves with time as the solar activity varies, approaching in 2015 values consistent with the measurements from the previous $A > 0$ solar cycle 22.

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