Observation of Complex Time Structures in the Cosmic-Ray Electron and Positron Fluxes by the Alpha Magnetic Spectrometer on the ISS

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Abstract. We present high-statistics, precision measurements by AMS of the detailed time and energy dependence of the primary cosmic-ray electron and positron fluxes over 79 Bartels rotations from May 2011 to May 2017 in the energy range from 1 to 50 GeV. For the first time, the charge-sign dependent modulation during the solar maximum has been investigated in detail by leptons alone. We report the observation of short-term structures on the timescale of months which are not visible in the positron-to-electron flux ratio. The precision measurements across the solar polarity reversal show that the ratio exhibits a smooth transition over $\sim 800$ days from one value to another.

1. Solar modulation of cosmic rays

Galactic cosmic rays (GCR) entering the heliosphere from outer space interact with a turbulent magnetized plasma, the solar wind. Such interaction results in convective, diffusive, drift and adiabatic energy losses, which significantly reshape the spectra of GCR and introduce time-dependent effects correlated with the dynamic activity of the Sun. Investigating the mechanisms of solar modulation has implications beyond solar astrophysics. The finite understanding of these phenomena limits in fact the sensitivity of model predictions to study for new GCR sources with long-duration experiment data. The development of predictive models for the variations of GCR fluxes has also applications for the planning of future deep-space missions \cite{1}.

Curvature drifts introduce charge-dependent effects in solar modulation \cite{2}. Electrons ($e^-$) and positrons ($e^+$) represent a unique probe to investigate such charge-dependent mechanisms: $e^+$ and $e^-$ differ in fact only in charge sign, and their absolute and relative abundance in CRs opens for precision measurements by detectors currently operating in space. The large acceptance and the long exposure time of the AMS-02 detector allowed us to monitor the time dependence of $e^\pm$ with unprecedented accuracy over more than 6 years of continuous data taking in low Earth orbit, providing novel information for the understanding of solar modulation and its charge-dependent mechanisms.
2. AMS-02 measurements of $e^+$ and $e^−$

The core of the AMS-02 apparatus is the spectrometer composed of micro-strip silicon tracker planes with 10 µm resolution in the bending direction placed within a 0.14 T dipolar magnetic field. AMS-02 is integrated with additional subdetectors for precise identification of the properties of different species of CRs. The AMS-02 detector is fully described in [3]. The identification of $e^±$ and their separation from the overwhelming proton background is obtained by the combination of the hadronic rejection capabilities of the independent Transition Radiation Detector (TRD) and Electromagnetic Calorimeter (ECAL) subdetectors. The TRD measures the TR X-ray emission over 20 layers and combines the samplings in a TRD classifier based on the likelihood properties of the $e^±$ and proton hypotheses. The 3-D imaging ECAL samples the energy deposits of $e^±$ in 18 layers over 17 $X_0$ to reconstruct the topological development of the electromagnetic and hadronic showers and to measure the energy of $e^±$. The spectrometer finally provides an independent evaluation of the $e^±$ energy by the rigidity measurement and measures the sign of the charge to separate $e^+$ from $e^−$.

![Figure 1. Measurement of the $e^+$ flux (red, left axis), the $e^−$ flux (blue, right axis) and the positron-to-electron ratio $R_e$ (green) as function of time (in units of BRs) measured by AMS-02 from May 2011 to May 2017 for 5 different energy bins. Error bars represent the statistical uncertainties. The vertical lines mark distinct time structures for the $e^±$ fluxes. The shaded azure area marks the transition from negative polarity ($A<0$) to positive polarity ($A>0$) of the heliospheric magnetic field. The continuous red line shows the best fit parametrization of the time dependence for $R_e$ described in the text. The graphs are extracted from [5].](image)

The $e^±$ fluxes have been measured from 1 GeV to 50 GeV over 79 Bartel rotations (BRs, 27 days) from May 2011 to May 2017. The determination of the $e^±$ fluxes is based on the procedure used for the measurement of the time-averaged fluxes with improved acceptance at low energies, whose details are presented in [4]. Extensive studies have been performed to determine the systematic uncertainties of the measurement. In addition to the systematic studies discussed in [4], the stability in time of the subdetector responses, efficiencies and of the energy scale are taken into account in each time interval for the determination of systematic effects. The systematic uncertainty on the $e^+$ and $e^−$ flux measurements results smaller than 2.5% for all energies and for all time intervals, and is dominated by the finite knowledge of the effective
acceptance for the $e^-$ flux and by charge confusion for the $e^+$ flux. For all BRs, the systematic uncertainty on the $e^+$ flux is smaller than the statistical uncertainty for all energies, while for $e^-$ this holds for energies above 10 GeV.

3. Time dependence of the $e^+$ and $e^-$ fluxes measured by AMS-02

The measurement of the $e^+$ flux, of the $e^-$ flux and of the positron-to-electron ratio $R_e$ as function time measured by AMS-02 from May 2011 to May 2017 for 5 different energy bins, based on the analysis fully described in [5], is shown in Figure 1. The complete tabulated results are publicly available in the Supplemental Material of [5] and are publicly available for download in different formats from the ASI Cosmic Ray Database [6].

The data reveal long-term and short-term structures in the $e^\pm$ fluxes up to energies below 20 GeV, similarly as observed for the proton and helium fluxes [7]. Both the $e^+$ and $e^-$ fluxes decrease in the ending phase of the positive polarity up to May 2013. Then, the $e^-$ flux continues to decrease while the $e^+$ flux start to increase up to April 2015. After this date, both fluxes rise steeply. The difference in the rate of increase is a clear signature of charge-sign dependent solar modulation. Short-term variations related to peculiar solar events are visible in both fluxes but they cancel out in the $R_e$ ratio, for which a long-term trend appears. The $R_e$ ratio is initially constant. Then, it increases smoothly to reach a plateau at higher intensity after the solar magnetic field reversal. The two plateaus represent two different configurations of solar magnetic fields with different solar modulation effects that depend on the sign of the charge.

![Figure 2](image-url)  
Figure 2. Example of fit to $R_e$ using the parametrization described in the text, together with the energy dependence of the best fit values for $C, t_{1/2}$ with power-law fit (red line) and $\Delta t$ with constant value fit (red line). The graphs are extracted from [5].

To investigate the long-term charge dependent effect of solar modulation on $e^\pm$ in a model-independent approach, the time dependence of $R_e$ has been fitted for each energy bin using a logistic function as reported in Figure 2. The parametrization function is described by the amplitude of the transition $C$, the midpoint of the transition $t_{1/2}$ and the duration of the transition $\Delta t$ to proceed from 10% to 90% of the change in magnitude. The resulting values for $C, t_{1/2}$ and $\Delta t$ as function of energy are also shown in Figure 2. The decreasing trend of $C$ as function of $E$ down to 20 GeV, where it sets consistent with zero, is in agreement with
the expectation based on solar modulation models. The relative distance of the midpoint of the transition to the solar magnetic field reversal changes by $260 \pm 30$ days from 1 GeV to 6 GeV. The transition duration $\Delta t$ amounts instead to $830 \pm 30$ days for all energies. The unexpected energy dependence of $t_{1/2}$, observed for the first time by AMS-02, is a clear probe of the different responses of particles and antiparticles to changing modulation conditions.

4. Outlook and prospects

![Figure 3. Measurement of the positron-to-electron ratio $R_e$ as function of time measured by PAMELA (magenta) and AMS-02 (green). The shaded azure area marks the transition from negative polarity ($A<0$) to positive polarity ($A>0$) of the heliospheric magnetic field. In red, a numerical solar modulation model [8] predicting the flux of CR $e^\pm$ developed on pre-AMS data.](image)

The AMS-02 detector on the ISS is continuously monitoring the flux of CRs since May 2011. The time dependence of the low energy CR fluxes may provide unique insights towards the understanding of solar modulation mechanisms. For the first time, AMS-02 has measured the time dependence of the $e^\pm$ fluxes and of the positron-to-electron ratio $R_e$ in units of BRs from the ascending phase of cycle 24, through its maximum, and the descending phase into the next solar minimum. AMS-02, as of today, is the only detector operating in low Earth orbit capable to separate matter and antimatter CRs: the AMS-02 data is enriching the experimental scenario in terms of accuracy and time extension, providing unique information for the development of predictive models of solar modulation (Figure 3). Together with the monthly dependence of the proton and He fluxes [7], the measurement of the $e^\pm$ monthly fluxes opens a new era for precision monitoring of the time dependence of various components of CRs with AMS-02. The AMS-02 detector is continuously collecting CRs to provide accurate data to benchmark, test and develop models to describe the mechanisms behind propagation of CRs in the complex heliospheric environment.

4.1. Acknowledgments

The authors acknowledge the support from institutions as in [5].

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