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# Observation of time evolution of cosmic ray electron and positron fluxes with the Dark Matter Particle Explorer

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In this analysis, we measure the time-dependence of the primary cosmic ray electron and positron (CRE) fluxes using over 3 years of data from the Dark Matter Particle Explorer (DAMPE). The monthly CRE fluxes show clear variabilities due to the solar modulation effect. We also investigate the short-term structures of the CRE fluxes in September, 2017 when an X level solar flare event occurred. Energy-dependent Forbush descreases have been observed. The Forbush decrease amplitude and recovery time of the CRE fluxes depend on energies, which may have interesting implication in understanding the disturbances of interplanetary environment due to solar activities. All these results indicate that the DAMPE has a great potential to probe the interplay between particles and the heliosphere environment.

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## 1. Introduction

Before arriving at the Earth, Galactic cosmic rays (GCRs) propagate in the interplanetary space with continuous interaction with solar winds and their associated magnetic fields. As a consequence, their fluxes get modulated by the solar cycle. In addition, violent solar activities such as flares and coronal mass ejections (CME) can disturb the interplanetary environment substantially and rapidly. The intensities of GCRs are affected by these transient disturbances and experience short-time variabilities, known as Forbush decrease (FD) after Scott E. Forbush who firstly observed this phenomenon [1]. Solar energetic particles (SEPs) can also be produced by the solar flares, with maximum energies reaching a few GeV [2]. Precise measurements of time variations of GCR fluxes can thus be very useful in understanding the particle transport and interaction in the heliosphere.

For a long time, ground-based neutron monitors (e.g., [3]) and muon detectors play important roles in monitoring the time evolution of GCRs, through detecting the neutrons or muons produced when GCRs (mostly protons and Helium nuclei) hit the atmosphere. The advantages of the neutron monitors or muon detections are the large acceptance of ground-based detectors and hence a high time resolution can be achieved. However, disadvantages of these measurements are also obvious. The energy resolution of primary GCRs inferred from the neutron or muon measurements is poor since the neutron or muon fluxes are the convolution of the primary GCR spectrum and the hadronic interaction cross section. Second, the neutron or muon fluxes just reflect the total fluxes of primary GCRs with all elements and are lack of composition information.

Direct measurements of the GCR flux variations with the space particle detectors are therefore superior in overcoming the above mentioned problems. Observations of the long-term evolution of GRC intensities can date back to 1950s [4], with significantly improved measurements by PAMELA [5] and AMS-02 [6, 7] recently. The FD behaviors of different particle species were also observed for the first time by PAMELA [8].

The Dark Matter Particle Explorer (DAMPE) is a space-borne detector for observations of cosmic ray electrons and positrons (CREs), nuclei, and $\gamma$-ray photons. Here we study the time evolution of the CRE fluxes using the DAMPE data. Compared with other experiments, the DAMPE has two unique advantages in measurements of the CRE fluxes. The inclination angle of the DAMPE orbit is 97 degrees [9], meaning that the DAMPE can reach the polar region which is less affected by the geomagnetic rigidity cutoff. In addition, a relatively large acceptance ($\sim 0.35$ m$^2$sr) for CRE observations enables a high time-resolution. In this analysis, we study both the long-term evolution of the CRE fluxes since the launch of DAMPE, as well as an FD event in September, 2017 when an X-level solar flare occurred.

## 2. DAMPE detector

The DAMPE mission was launched into a sun-synchronous orbit at 500 km altitude on December 17, 2015. The DAMPE detector system consists of four sub-detectors, as illustrated in Figure 1. At the top is a plastic scintillator array detector (PSD) for charge measurement. The second part is a silicon strip detector (STK) aiming to measure track of charged particles and to convert $\gamma$-rays into $e^+e^-$ pairs. The third one is a BGO calorimeter which is the key sub-detector to measure the energy and direction of particles, to identify the particle species and to provide trigger primitives. At the bottom is a neutron detector (NUD) for assist of particle identification. The four sub-detectors work together to measure the charge, direction, and energy of cosmic ray particles. Detailed performance of each detector and the on-orbit calibration can be found in [10].

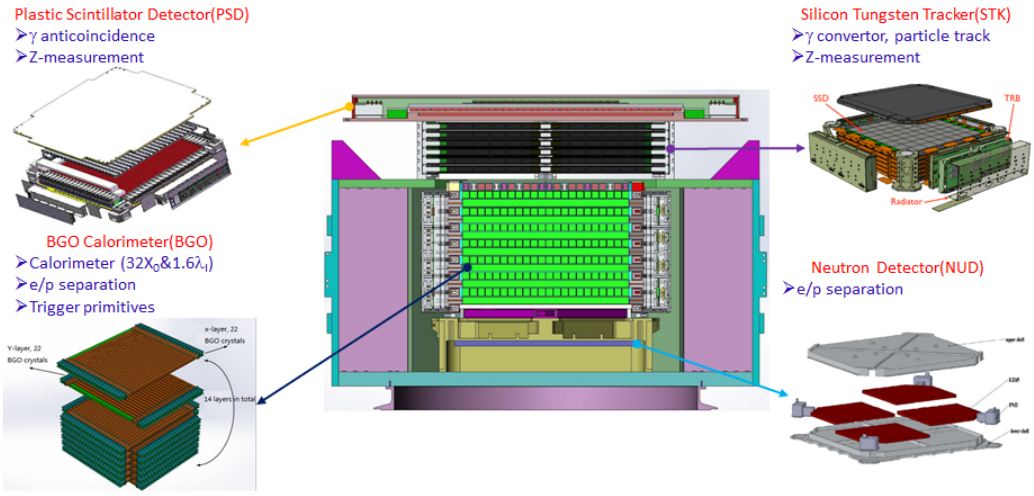


**Figure 1:** Exploded view of the DAMPE detector.

## 3. Data analysis

The data used in this analysis were recorded between April 1, 2016 and June 30, 2019. The pre-selection of events includes the exclusion of the SAA region, the triggers with either High Energy Trigger or Low Energy Trigger, the charge selection to exclude heavy nuclei and photons, the full containment of the shower development, the geometry cut with track crossing the PSD, and the energy cut with corrected energies [11] between 2 GeV and 20 GeV and higher than 1.2 times of the vertical rigidity cutoff (VRC).

Cosmic ray protons are rejected based on the shower development in the BGO calorimeter [12]. The background contamination is estimated according to a fitting of the Monte Carlo (MC) simulation templates in each energy bin. The primary abundance ratios between CREs and protons vary with time due to the solar modulation. It is found that the proton background decreases by about 2% per year. The trigger efficiency is determined from the MC data and validated by the flight data. Due to the radiation damage and electronics aging, the light yield of the crystal and the gain of the PMTs change slightly with time. Their impacts on the trigger efficiency is investigated through modifying the trigger threshold of the MC data, which results in a variation of within 1% per year. Due to the VRC, the exposure time varies with energy. We calculate the exposure time bin-by-bin through adding the time when the satellite travels in the regions with VRC values smaller than 1/1.2 of the lowest rigidity of the energy bin, and subtracting the SAA passage time, the dead time of the data acquisition system, and the calibration time. On average the exposure time is $1.9 \times 10^6$ seconds per month for energies above 15 GeV and $8.8 \times 10^5$ seconds at 2 GeV.

The CRE flux at time bin $j$ and energy bin $i$ can be calculated as

$$\Phi_{j,i} = \frac{N_{j,i}(1-\sigma_{j,i})}{A\eta_{j,i}\Delta T_j \Delta E_i}, \tag{3.1}$$

where $N_{j,i}$, $\sigma_{j,i}$, $\eta_{j,i}$ represent the number of CRE candidates, the fraction of the background contamination, and the trigger efficiency, $A$ is the effective area of the detector, $\Delta T_j$ is the live time, and $\Delta E_i$ is the width of the energy bin.

## 4. Result

### 4.1 Long-term evolution of CRE fluxes

We first study the long-term evolution of the CRE fluxes. The monthly CRE fluxes are derived, with results of four selected energy bins being shown in Figure 2. Here the relative fluxes with respect to that of April, 2016 are shown. To avoid influences from short-term solar activities, the data collected during two FD events occurred in July, 2017 and September, 2017 are excluded. An overall trend that the CRE fluxes increase with time can be clearly seen, due to that the Sun approaches to the quiet state in these years (see the bottom panel for the variation of the total monthly sunspot numbers [13]). We also observe relatively significant monthly variations of the CRE fluxes, indicating that the interpanetary environment changes at relatively smaller time scales. For energies higher than $\sim 10$ GeV, the CRE fluxes become less affected by the solar activities.

### 4.2 Forbush decrease

The behaviors of CRE fluxes corresponding to an FD event associated with the solar flare occurred on September 7, 2017 have been studied. The time bin is adopted to be 6 hours to study the short-term variabilities of the fluxes. The results are shown in Figure 3. With about 36 hours after the solar flare, the CRE fluxes decrease to the minimum values and then recover in several days. To characterize the recover behavior, we use the function, $R_\Phi = 1 - p_0 \exp[(t-t_0)/p_1]$, to fit the time profile after the minimum, where $p_0$ represents the decrease amplitude and $p_1$ represents the recovery time. Both the amplitudes and the recovery time depend on energy, as shown in Figure 4.

## 5. Summary

Monthly evolution of CRE fluxes is studied with more than three years of DAMPE data. An overall anti-correlation between the CRE fluxes and the solar activities (characterized by the numbers of sunspots) is observed. With a time resolution of 6 hours, we obtain the time profiles of CRE fluxes of an FD event occurred in September, 2017. Both the FD amplitudes and recovery time decrease with energy. This analysis illustrates that the DAMPE is well suitable to study the time variations of CRE fluxes with very high energy resolution and time resolution, and can definitely shed new light on the understanding of the particle transport in the heliosphere as well as the interplanetary space environment.

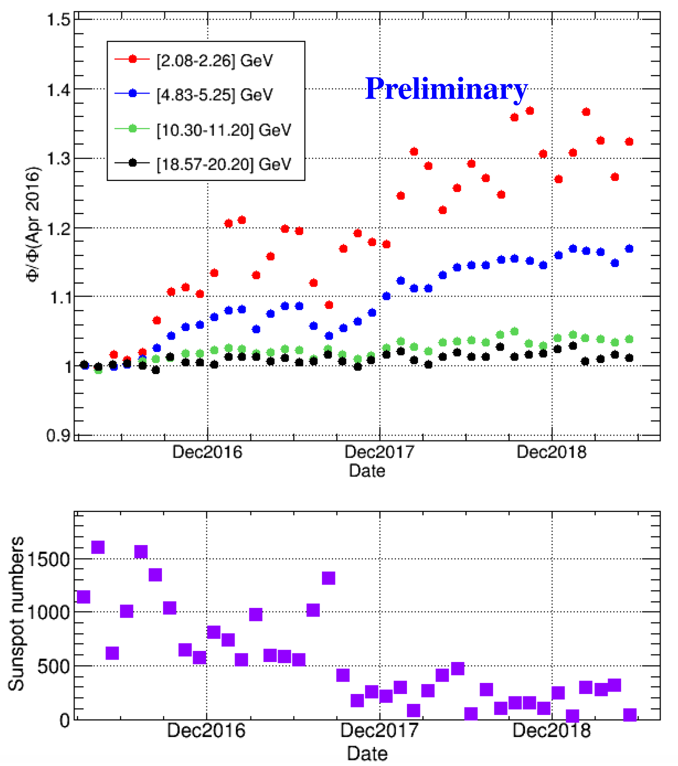


**Figure 2:** *Top*: Variations of CRE fluxes in four chosen energy bins. Error bars (too small to be visible) are statistical errors only. *Bottom*: total number of sunspots of each month [13].

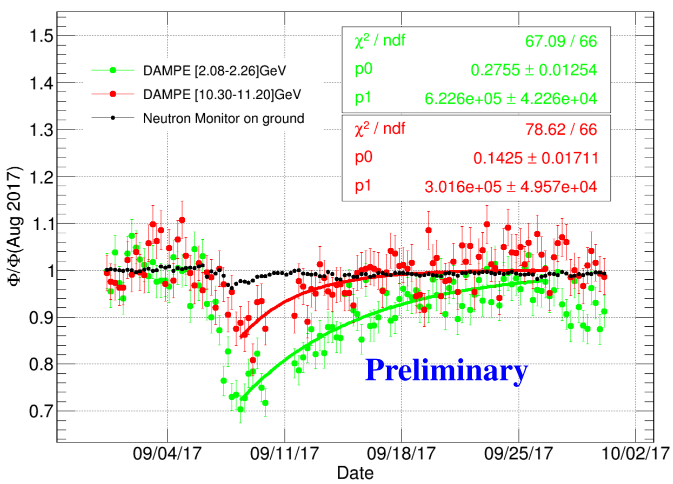


**Figure 3:** Time profile of relative CRE fluxes in September, 2017 with respect to the average flux of August, 2017, for two energy bins, [2.08-2.26] GeV and [10.30-11.20] GeV. The neutron monitor data from the Oulu station is also shown [3].

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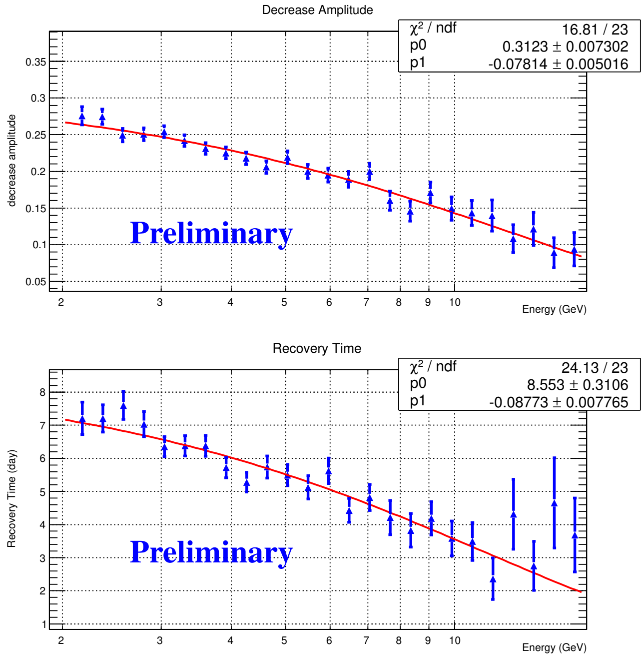


**Figure 4:** Decease amplitudes (top) and recovery time (bottom) as functions of energy. Both are well fitted by an exponential function $y = p_0 * \exp(p_1 * x)$ (red solid lines).


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