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A study of Forbush Decreases effects with DAMPE experiment

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Forbush Decrease (FD) is a rapid decrease and slow recover in the observed galactic cosmic ray intensity, caused by active solar events sweeping low energy galactic cosmic rays (GCRs) away from Earth. Differnet properties of FDs have been observed by different scientific experiment but mostly from worldwide ground based Neutron Monitors (NMS), they focus on secondary neutron from the atmosphere. The Dark Matter Particle Explorer (DAMPE) is a satellite-based cosmic-ray experiment that has been stably operated for more than 7 years. Precise measurements of cosmic ray electrons and positrons from DAMPE make it possible to directly study FDs from a new perspective. We analyze the FD properties, such as decrease amplitude and recover time as a function of energy, observed by DAMPE from 2017 to 2021. Finally we simulate the FDs with a numerical model, and successfully reproduce the FDs. The preliminary result shows that the head-on events causes energy related recover time, while edge-on events causes energy unrelated recover time of FDs.

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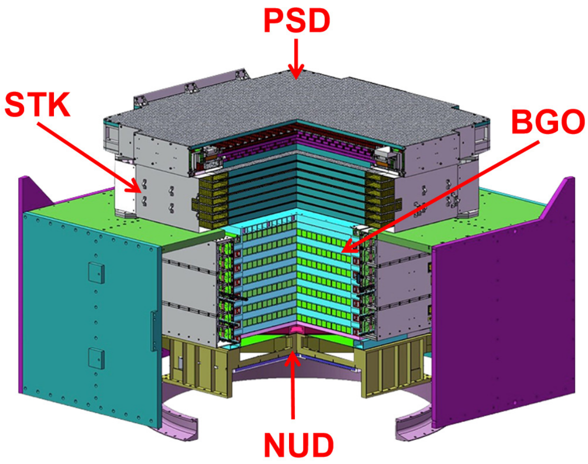

Figure 1: Schemetic diagram of DAMPE payload

1. Intorduction

GCRs are the energetic particles originate from outside the solar system and are likely accelerated by explosive events such as supernova. The charged components interact with and are influenced by magnetic fields. Extreme solar activities such as coronal mass ejection (CME) and solar flare could produce high intensity particle flow together with large magnetic field, blocking the propogation of GCRs and cause steep decrease in GCR flux with a slow recover. This phenomon was called Forbush Decrease [1, 2].

FDs have been extensively studied for decades, mainly by ground-based neutron monitors NMs located from equator to poles covering geomagnetic verticle rigidities cutoff (VRC)[3] range from 0.1 GV to less than 30 GV. However, NMs only measure secondaries neutrons produced in the atmosphere and gives flux variation at median energy E_m as defined by function 1 [4, 5], P_c is the VRC of the NM station. This restricts the ability of a wide energy range detection.

$$E_m = 0.0877P_c^2 + 0.154P_c + 10.12 \tag{1}$$

As reported before [6], FDs can be separated into two kinds showing energy related recover time and energy unrelated recover time respectively, the author mention that this can be explained by differnet location of earth inside the CME, the head-on events will cause energy related recover time of FD, for example.

In this work, we study the GCR electron FD events associated with extended CME or solar flare observed, including three FDs with one shows energy unrelated recover time while the other two FDs have a energy related recover time. Finally we try to reproduce the FDs with a therical model and figure out new features of FDs.

2. FDs selections from DAMPE and NMs

DAMPE is a space-borne detector for observations of cosmic ray electrons and positrons (CREs), nuclei, and gamma ray photons [7, 8]. With a large acceptance and high resolution, DAMPE is suitable for high energy resolution measurements of CREs. The DAMPE payload is composed of four sub-detectors: a Plastic Scintillator strip Detector (PSD) [9] on the top of the detector in order to measure the charge of a particle precisely. A Silicon-Tungsten tracKer-converter (STK) [10] is placed next, in order to reconstruct the trajectory of GCRs and provide extra charge reconstruction. The Bismuth-Germanium Oxide (BGO) imaging Energy CALorimeter (ECAL) [11] is the main detector to measure the deposited energy. Finally a NeUtron Detector (NUD) [12] is placed to serve as a powerful electron-proton separation instrment. A schemetic view of the DAMPE payload is shown in Figure 1.

The housekeeping system of DAMPE records incident counts of DAMPE events every 4 seconds as so-called T0 counts, to monitor the condition of the data acquisation system. The frequency of T0 trigger varies from several hundred Hz near the equator to several thousand Hz at poles, which means that the T0 counting rate directly gives the intensity of CRs observed by DAMPE. The active solar events such as CMEs can significantly increase the T0 count rate when they arrive near the earth, as we have mentioned before [14]. However, we do not find such phenomen before FD in July 2017 and November 2021, but only the decrease in T0, as shown in Figure 2. Therefore, we find possible FD by a decreas via T0 count rate.

We adapt OULU NM in the comparison, the VRC for the NM station is 0.81 GV. To keep the consistancy, we choos the MacIlwain L-parameter values within 3.8 < L < 4.7 for DAMPE T0 count selection, keeping the cutoff rigidity R_c ranges from 0.65 GV to 1.0 GV which is similar with that of the OULU station. The green line in Figure 2 represents the normalized T0 count rate, while violet line is normalized OULU NM counts.

3. CRE data selection

After T0 trigger and neutron monitor satification, three FDs are confirmed in this analysis, observed in July 2017, September 2017, and November 2021. In order to properly analyze the FDs, we use the Flight Data between 30 days before and after the FD event observed.

In the data selections, following selection cuts similar to γ-rays [15] are applied: firstly, data recorded when DAMPE passes through the South Atlantic Anomaly (SAA) region are excluded. In order to increase the acceptance, we accept particles from high energy trigger (HET) and also low energy trigger (LET). A charge cut is applied, which requires that the average charge reconstructed by two PSD layers should be less than 1.7, which can reject heavy nuclei up to a level of 99%. As for fiducial cuts, shower max of BGO layer is not at the egde in the first six layers, reconstructed track of the particle is required penetrate the first four layers of the BGO detector. In order to get stable GCR electron flux to reduce the flctuations and to eliminate secondary particles generated in the atmosphere, the minimum energy at each geomagnetic latitude is required to exceed 1.2 times of the vertical rigidity cutoff.

The selections above can effectively reject heavy nuclei, the following electron/proton separation identification value as the same method we use before is applied:

$$PID = F(E)[log(R_r) \cdot sin\theta + log(R_l) \cdot cos\theta] \tag{2}$$

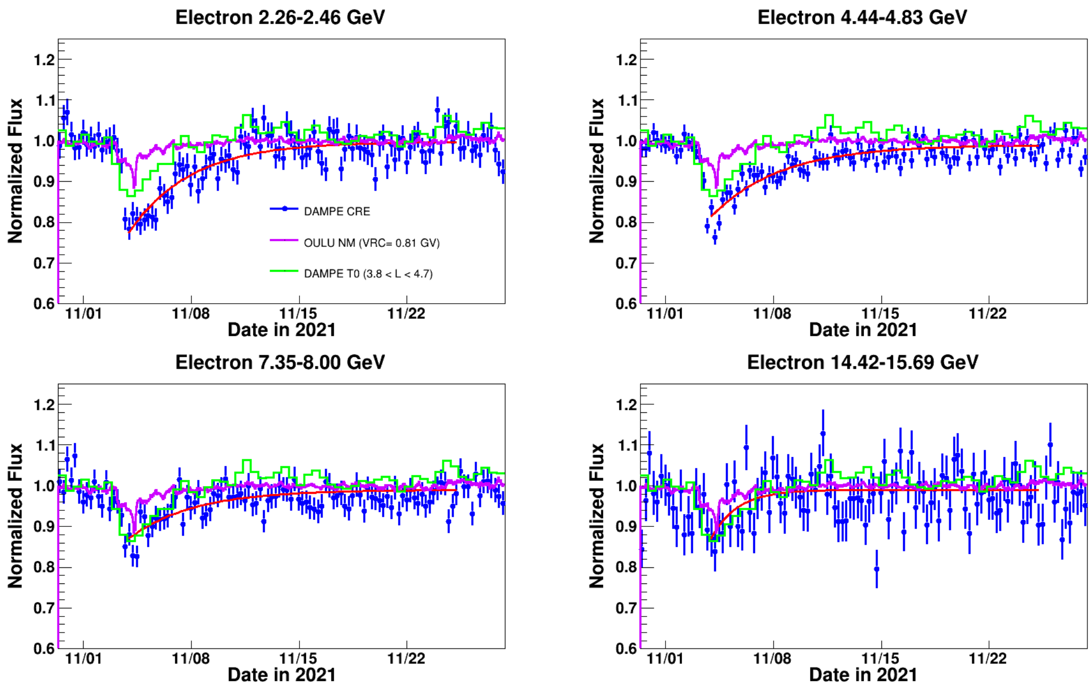

Figure 2: Fit result of FD observed by DAMPE in November 2021, violet line is the OULU NM normalized counts, red line represents the best fit result of DAMPE CRE.

Where F(E) is energy decoupling polynomial, θ is coordinate rotation angle, R_r and R_l are three-dimentional parameter describing radial shower extension and longitudinal shower in BGO calorimeter respectively.

The background contamination can then be estimated through a fitting with Monte Carlo (MC) templates in each energy bin, the background contamination is estimated to be 2% to 8% for events with deposited energies between 2 GeV and 20 GeV. The PID below 2 GeV is hard to make separation restricted by the BGO calorimeter. After the pre-selections and the PID procedure, the CR electron flux are shown several logarithmically energy bins from 2 GeV to 20 GeV, each point represents six hours of observed flux.

The CR electron flux is described by the following function:

$$I_{i,j} = \frac{N_{i,j}(1 - f_i)}{\Delta E_i A_i T_{i,j} \eta_i} \tag{3}$$

where $N_{i,j}$ and $T_{i,j}$ are the number of selected electrons and exposure time in ith energy bin and jth time bin,, f_i, ΔE_i, A_i and η_i represent background fraction, the energy bin width, acceptance and trigger efficiency of certain energy bin, almost the same as [14].

4. FD analysis and profiles

The GCR electrons flux are calculated with Function 3, with each data point contains data from four DAMPE orbits (about 6 hours). The points are normalized with the flux 30 days before the first point of each histogram. The recover phase of a FD can be described by :

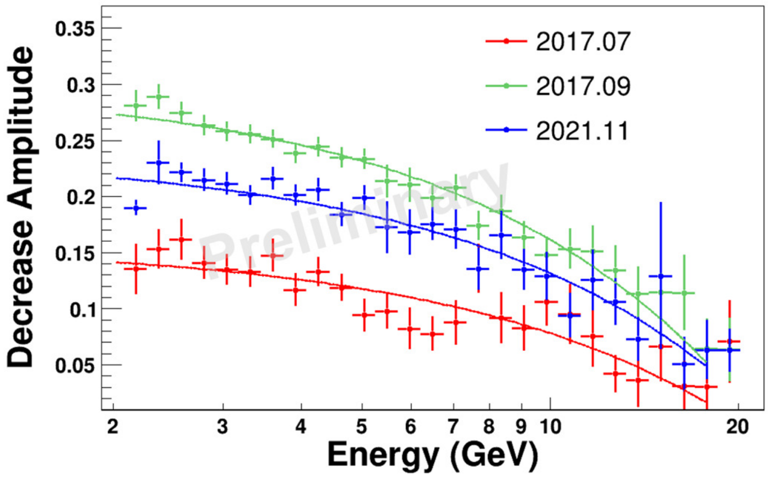

Figure 3: FD decrease amplitude of three FDs as a function of energy, with a liner fit each.

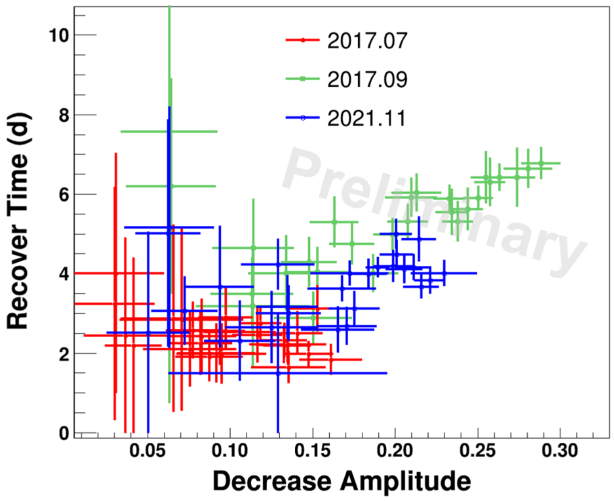

Figure 4: Relationship of decrease amplitue and recover time of the three FDs.

$$\frac{I_t}{I_0} = 1 - A_e \cdot exp(-\frac{t - t_m}{\tau}) \tag{4}$$

where I_t, I_0, are the observed flux and the normalized flux value, A_e, t_m and τ are decrease amplitude, time of the largest decrease and the recover time. As described by the function, we can see that the recover time is defined as the time the decrease recover to $1/e$ of the maximum decrease.

The fit result of FDs is shown in Fig 2, the decrease amplitude as a function of energy of three FDs are shown in Figure 3, and the recover time shows obervious different features in Figure 4. Due to the decrease amplitude is strongly related to the energy, we find that the recover time of FD in July 2017 is not related to the energy, while the other two FDs are energy related.

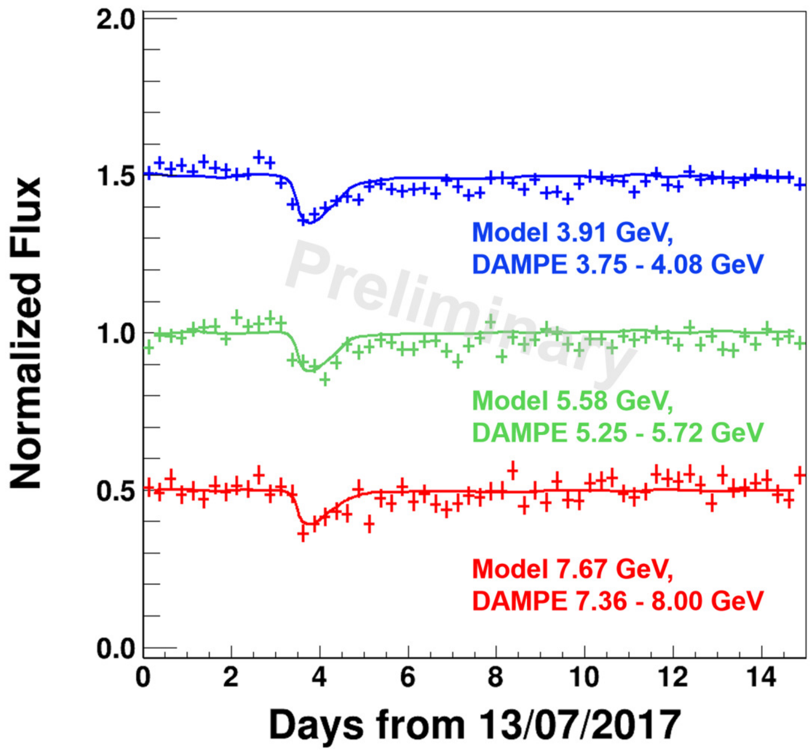

Figure 5: Model reproduction result of July 2017 FDs, shown in three energy ranges.

5. Modeling of the FDs and results

The transportation of a charged particle in the heliosphere can be described by the Parker equation [19]. CMEs and other solar activies can significantly disturb the propogation of CRs, this process can be modelled by a fast-moving diffusion barrier, using different diffusion and drift parameters to depict the interplanetary space [16]. A stochastic differential equation (SDE) method can be used to sovle the Parker's equation[17, 18].

In order to reproduce the FDs, we use parameters from WSA-ENLIL SOLAR WIND PREDICTION[1] data to parameterize the extension of the CMEs, and velocity of the diffusion barrier is given by the CME list[2]. The simulation result in three energy range of the July 2017 FD is shown in Figure 5. The parameters of the FD are: 0.7 AU in width, extensions are 90 degrees in θ angle and 45 degrees in Φ angle.

The model reproduce the FD very well, and the WSA model implies that the FD in July 2017 is a edge-on event, while September 2017 and November 2021 FDs are head-on events. The preliminiary result shows that when earth situated in the central parts of the CME, the recover time shows strong relation with energy, while on the edge the relation vanished. The results gives opposite conslusions as proposed by [6], but satisfies the results from PAMELA, this could be explained that when earth located in the central area of CME, the maximum decrease amplitude is

[1]https://www.swpc.noaa.gov/products/wsa-enlil-solar-wind-prediction
[2]https://cdaw.gsfc.nasa.gov/CME_list/

relative large, but when situated on the edge it causes a small decrease amplitude, and the recover time shows differnet relation with the energy.

6. Conclusion

In this work we study the FDs using CR electrons from DAMPE observations, occurred in July, September in 2017 and November in 2021. The FDs are confirmed from DAMPE T0 trigger and NM data. The high-precision time evolutions of electron fluxes makes DAMPE a sensitive observor, provides a totally different persprctive from NMs and other space experiments. We analyze the relation of FDs amplitudes and recover time, the results show that the recover time of three FDs give differnet relations with energy, two of them are energy related while one is unrelated.

Ultilizing data from WSA weather prediction, the three FDs are well reproduced. We find that the two FDs with energy related recover time require earth locates in the central area of the CME, but the FD with energy unrelated recover time is a edge-on event.

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