Properties of Forbush Decreses on Daily Proton Flux with the AMS Data

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Abstract

A Forbush decrease (FD) is a sudden reduction of Galactic Cosmic Rays (GCRs), due to disturbances in the interplanetary magnetic field, usually caused by intense transient solar activities such as Interplanetary Coronal Mass Ejections (ICMEs) and Corotating Interaction Regions (CIRs). With the high-precision daily proton data measured by the Alpha Magnetic Spectrometer (AMS-02) on the International Space Station from May 2011 to October 2019 (Aguilar et al. 2021), we identified **146** FD events, with an automatic method. The properties of **49 ICME-caused and 55 CIR-caused FD events** were analyzed, using proton data with 30 rigidity bins from 1 GV to 100 GV. The rigidity dependence of fluxes during FDs are studied, separately for ICME and CIR FDs. The correlation between FD properties such as magnitude and maximum affected rigidity and synchronous solar wind parameters are studied separately for ICME and CIR FDs.

Introduction

ICMEs are large-scale magnetized plasma structures ejected from the solar surface to the interplanetary space. They usually contain a magnetic cloud with a shock in the front followed by a turbulent sheath. ICMEs are barriers for GCRs whose intensities are suppressed for short time periods. In solar wind data, ICMEs can be identified with rapidly increasing solar wind speed and magnetic field, and its magnetic cloud can be identified with depressed temperature and rotating magnetic field (Cane 2000).

CIRs, or stream interaction regions, are caused by fast corotating solar wind streams originating from coronal holes (Richardson 2018). The high speed streams create a forward shock when it surpasses the slow ambient solar wind and form an interaction region, called corotating interaction regions (CIRs). CIRs can cause FDs with a gradual decrease and are usually followed by a symmetric recovery.

FD identifying Method

A significant daily decrease was identified if at least one rigidity bin from 1 to 10 GV shows a suppression greater that a 2-σ threshold. This σ is rigidity and time dependent and was computed in the following way: we calculated the flux difference between each day and its previous day for 180 days before the day of interest: $\{\Delta\Phi_d \mid \Delta\Phi_d = \Phi_d - \Phi_{d-1}, d = 1, 2, ..., 180\}$, where Φ_d is flux value at day d , and $\Delta\Phi_d$ is the flux different between day d and the day before. The 2-σ threshold on the day of interest is calculated as twice the standard deviation of the 180 flux differences. To be conservative, 2-σ is also restricted to be no larger than 4% of the flux of the previous day. This method is explained in Figure 1.

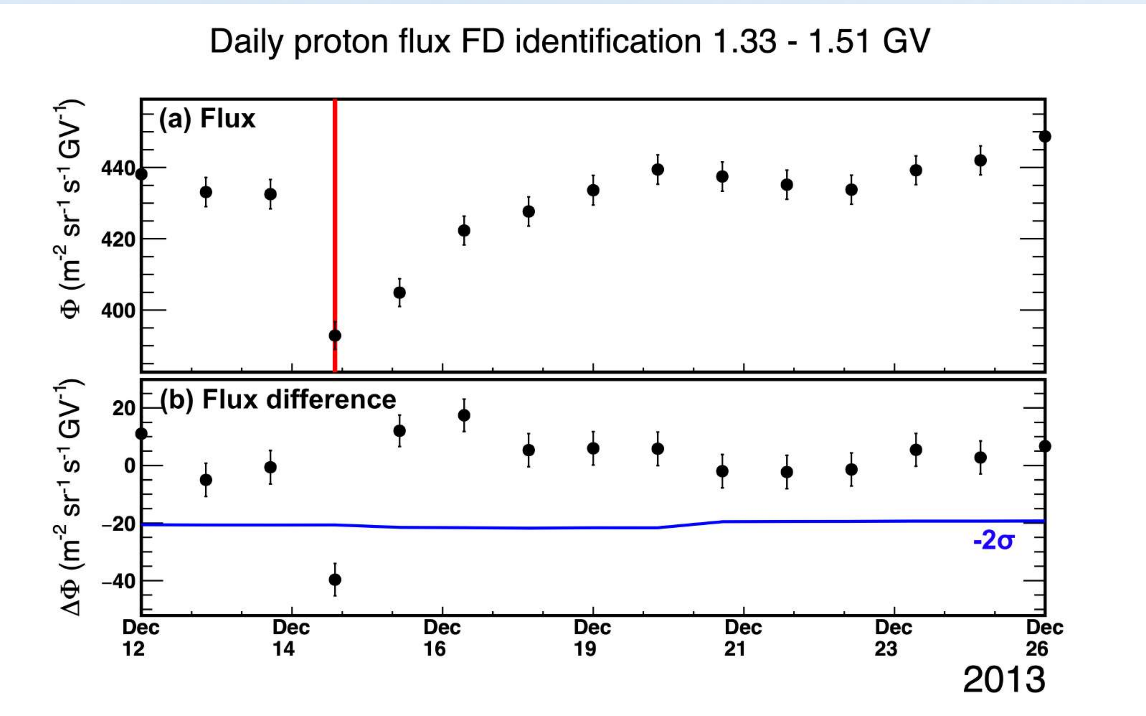

Figure 1. An example of FD identification at the 1.33 to 1.51 GV rigidity bin. Red line marks the day recognized as significant decreases on 2013/12/15.

With this method, 146 FD events were identified from May 20, 2011, to October 29, 2019, including 59 ICME FD events, 69 CIR FD events, 7 events caused by combination of ICMEs and CIRs, and 11 not categorized.

Analysis Method

The analysis was done in following steps:

1) Determine the **date of FD onset in AMS flux**.
2) Determine the **date of disturbance** of the corresponding ICME or CIR event according to Richardson & Cane (2010), Kilpua et al. (2017) or Maris Muntean et al. For ICME events, it is the time of the associated geomagnetic storm sudden commencement, typically related to the arrival of a shock at Earth. For CIR events, it is when magnetic field and solar wind speed start to rapidly increase.
3) Determine **date of minimum**: the day when the the fluxes of majority of rigidity bins below 10 GV reach minimum.
4) Calculate **normalized flux on date of minimum**, normalized by the day before disturbance.
5) Fit normalized flux with exponential fit:

$$\Phi_{norm} = C - a \cdot e^{-\alpha \cdot R} \quad (1)$$

and power law fit:

$$\Phi_{norm} = C - b \cdot R^{-\beta} \quad (2)$$

Among 146 FD events identified, **49 ICME FDs and 55 CIR FD events are included by event lists mentioned in 2) and comply with shape of Eq. (1) or Eq. (2).** These events are used for further studies.

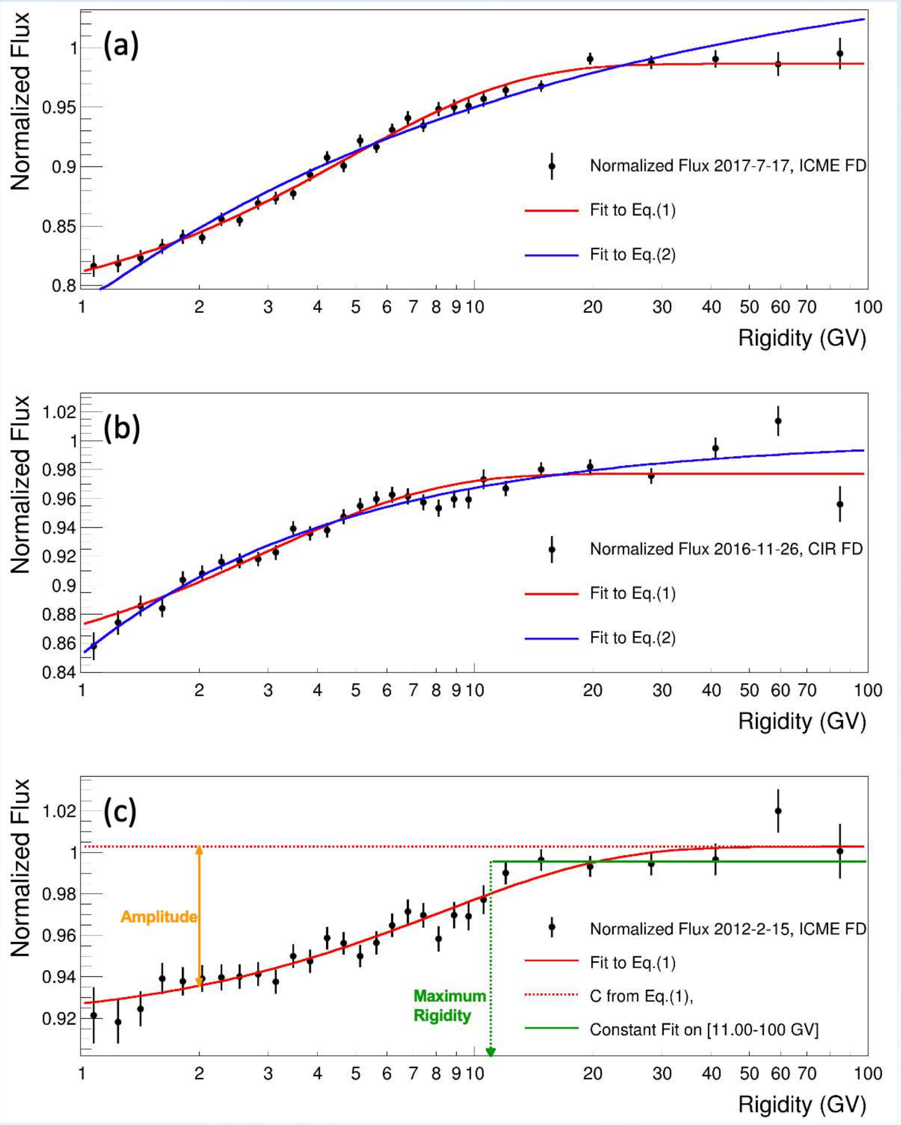

Figure 2. (a) Flux on date of minimum, 2017/7/17, of an ICME FD, normalized by flux on 2017/7/15, the day before the onset of the ICME on 2017/7/16. **The χ^2 of Eq.(1) is smaller than the χ^2 of Eq.(2).** (b) Flux on date of minimum, 2016/11/26, of a CIR FD, normalized by flux on 2016/11/20, the day before the beginning of the CIR on 2016/11/21. **The χ^2 of Eq.(2) is smaller than the χ^2 of Eq.(1).** (c) Flux on date of minimum, on 2012/2/15, of an ICME FD, normalized by flux on 2012/2/13, the day before the onset of the ICME on 2012/2/14.

Decrease Amplitude: extrapolated from the exponential fit Eq. (1) of the normalized flux on the date of minimum at 2 GV.

$$\text{Decrease Amplitude} = C - \Phi_{norm|R=2GV} = a \cdot e^{-\alpha \cdot 2}$$

Maximum Affected Rigidity: discrete values chosen from the edges of AMS proton flux binning, determined by comparing the χ^2 of constant fits, on a set of rigidity ranges ending at 100 GV, with the χ^2 of the exponential fit Eq. (1) in the same rigidity range. Figure 2. (c) explains this as an example: the green line is a constant fit from 11.0 to 100 GV, with a χ^2 smaller than the χ^2 of Eq.(1); for lower rigidities, the χ^2 of a constant fit is worse than the χ^2 of Eq.(1), thus 11 GV is the Maximum Rigidity of this FD.

Results

As shown in Figure 3, **for ICME FD events, the exponential function generally fits better than the power law function** as most of the data points are above the diagonal; **for the CIR FDs**, the data points are almost evenly distributed around the diagonal, which means that some cases fit better with the exponential function, while others fit better with the power law function and **the overall difference is not significant**.

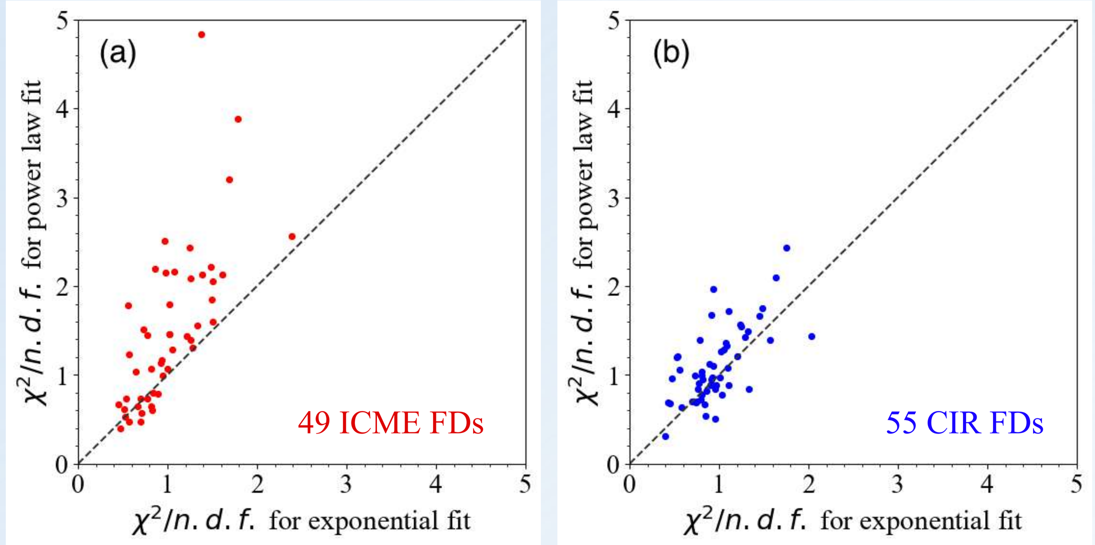

Figure 3. Comparison of exponential and power law fits for FD normalized flux on date of minimum for (a) 49 ICME FDs, and (b) 55 CIR FDs. Dashed black lines indicate same χ^2 /n.d.f. values.

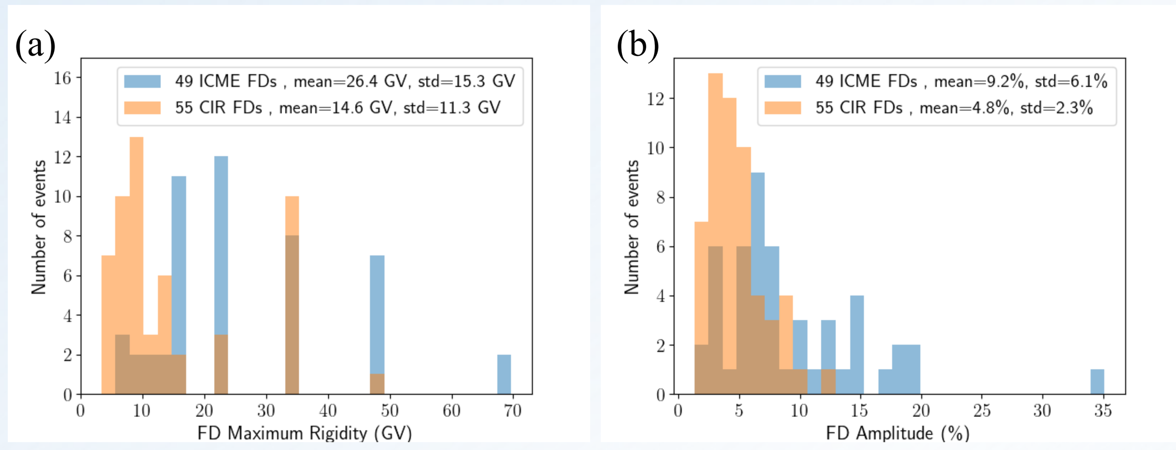

Figure 4. FD Maximum Rigidity and Amplitude distribution for ICME FDs and CIR FDs.

The Amplitudes of CIR FDs are generally much smaller than ICME FDs. The Amplitude of CIR FDs are ranging from ~1% to ~12% , centered around 4%, while the amplitudes of ICME FDs are distributed between ~2% and ~20%, with one extreme case of amplitude ~35% happened on March 8, 2012. **The maximum rigidities of the CIR FDs are also generally smaller than the ICME FDs**, ranging from ~3 GV to ~50 GV, while the Maximum Rigidities of ICME FDs are starting from ~8 GV, reaching ~70 GV.

Correlation with Solar wind parameters

Correlation between FD properties and extrema and difference of a variety of solar wind parameters during the events are studied. Solar wind parameters were extracted from NASA OMNIWEB 5-minute averaged data (https://omniweb.gsfc.nasa.gov/). **There are weak to moderate correlation between ICME FD Amplitude and several solar wind parameters**, listed in Table 2, also see examples in Figure 5. **No visible correlation was found between ICME FD Maximum affected Rigidity and the solar wind parameters. For CIR FDs, there are no correlation between Amplitude or Maximum Rigidity and most solar wind parameters tested.** Weak correlation were found for values in Table 1.

Solar Wind Parameter	CIR FD amplitude	
	Correlation coefficient	95% confidence interval
Max magnetosonic mach number	-0.27	[-0.49, -0.01]
Max Alfvén mach number	-0.29	[-0.51, -0.04]
	CIR FD max rigidity	
Temperature increase	0.29	[0.03, 0.51]

Table 1. Correlations between CIR FD properties and selected solar wind parameters.

Correlation with Solar wind parameters

Solar Wind Parameter	ICME FD amplitude	
	Correlation coefficient	95% confidence interval
Minimum dst index	-0.50	[-0.68, -0.26]
Maximum magnetic field	0.50	[0.26, 0.68]
Maximum temperature	0.49	[0.25, 0.67]
Minimum B_z value	-0.48	[-0.66, -0.24]
Maximum pressure	0.46	[0.22, 0.65]
Solar wind speed increase	0.42	[0.17, 0.62]
ICME speed	0.36	[0.09, 0.57]
Maximum solar wind speed	0.32	[0.05, 0.54]

Table 2. Correlations between ICME FD amplitude and selected solar wind parameters.

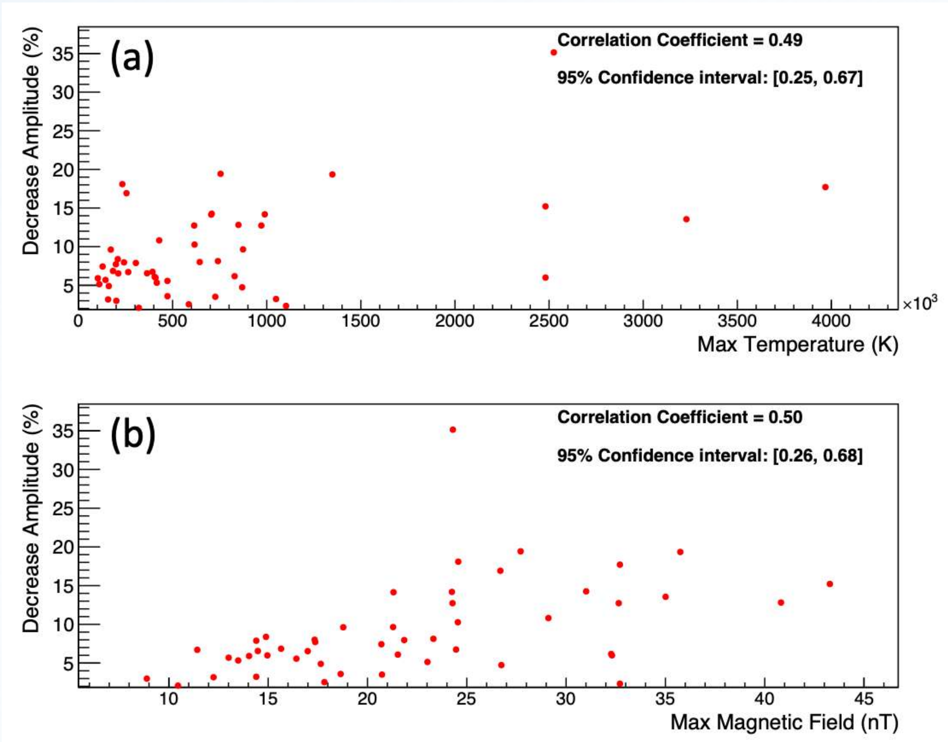

Figure 5. Examples of correlations between ICME FD amplitude and selected solar wind parameters.

References

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