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Rigidity dependence of two-step Forbush decreases

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Abstract. For the comparison of theoretical models on Forbush decreases (Fds) with experimental data, investigations of the rigidity spectrum parameters of the galactic cosmic ray (GCR) intensity variation during Fds are of importance. From the period 1971-1991 we examined 5 almost isotropic events with a clear two step decrease. Although the onset of the individual decreases as seen by different stations was a function of local time, the time of minimum intensity of the shock related and ejecta related decreases was a global phenomenon. We discuss a model that describes the relative isotropic intensity variation during the selected Fds. Using hourly data of neutron monitor stations and of the Nagoya meson telescopes (median rigidity 60 - 120 GV) we determined the parameters of the rigidity spectrum for the different steps of the Fds. We found evidence that the upper rigidity limit of GCR modulation is higher for the shock related decreases than for the ejecta related decreases. Also, in all cases examined, the spectral parameters for the two steps indicate a tendency for a softer spectrum during the first step. These results reflect the differences between the mechanisms of GCR propagation in the media with coronal mass ejections (CMEs) and interplanetary magnetic shocks.

1 Introduction

The rigidity (energy) dependence of Fds is discussed in many papers (see e.g. Lockwood, 1971; Nachkebia and Shatashvili, 1983,1985; Nachkebia, 1986; Lockwood et al.,1991; Hofer and Flückiger, 1997, 2000 and references therein). There are some difficulties to fit results received by different authors, especially when one compares results received by using hourly and daily data. It is possible to solve this problem, partially, by taking into account that Fds generally consist of two steps (Barnden, 1973; Flückiger, 1985; Sanderson et al., 1990; Cane et al., 1994) caused by the combination of shocks and CMEs.

According to Wibberenz et al. (1997,1998), Cane et al. (1994,1996) and Cane (2000) the first step is connected to the turbulence structure behind the shock, and the second step is connected to the enhanced magnetic field and loop-like field configuration of the CMEs. The component related to the shock shows a gradual decrease and slow recovery with a duration about 8 days, the ejecta component starts with the ejecta arrival and its total duration is about 24 hours. CMEs interact with the background solar wind and create a shock wave. The superposition of the CMEs and shock effects leads to rather complex structures in the intensity profiles of Fds. Since shocks are more extended in longitude that ejecta, one finds that Fds without the second step when the ejecta is not intercepted. Different types of Fds are observed on the Earth in accordance with various heliocoordinates and rate of CME. In this respect a variety of Fds could be explained. For the comparison of the theoretical models on Fds with experimental data, it seems very valuable to investigate the rigidity spectrum parameters of the CR intensity variation during Fds, taking into account different structures of decreases. But, usually, only one step of Fds, the most powerful, or entire decreases are discussed. There are some reasons for this: to separate shock and CME related components are very difficult because of the variability which occurs between stations. The large directional anisotropy during Fds leads to an enhanced diurnal variation and it is difficult to use data from a single neutron monitor or meson telescope (particle observations from spacecraft, in particular anticoincidence guard counters are free from the diurnal variation, but guard counters give only low channels of energy). Apart of this we suggest that the upper rigidity limit of variation of components related to the shocks and CMEs are different, which leads to observe only one step of Fds at the low latitude neutron monitor stations and especially with meson telescopes. In the above-mentioned respects there are not too many specific articles about the rigidity dependence of two-step Fds. However Wibberenz et al. (1997) defined the

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rigidity dependence of shock related decreases for 6 two-step Fds at two characteristic channels - > 60 Mev/amu particle data from Helios 1 and Helios 2 (characteristic rigidity 1.5 GV), and high latitude neutron monitor data (characteristic rigidity 10 GV). They found good agreement with the theoretical model for propagating diffusive barriers. Despotashvili et al. (2001) investigated the rigidity spectrum parameters of shock related and entire decreases of 12 two-step Fds with range of rigidity up to about 120 GV (using data of low latitude neutron monitors and meson telescopes). These results are not opposite to results of Wibberenz et al. (1997), but both articles mentioned above don't carry information about the rigidity dependence of CME related decreases.

In current work we tried to define the rigidity spectrum parameters of shock and ejecta related decreases separately for two-step Fds in wide range of rigidities up to about 120 GV.

2 The Data and Method

From the catalogue of Fds (Cane et al., 1996) all cases connected with CMEs and shocks for period 1971-1991 are discussed. We found only 5 events with well expressed two steps and almost isotropic changes of intensity from considered Fds. Hourly data of a minimum of 12 neutron monitors with different cut off rigidity and asymptotic directions were used. Apart from the data of neutron monitors, hourly data of 7 Nagoya (Japan) meson telescopes with median rigidity from 60 GV to about 120 GV were used. Since the large directional anisotropies during Fds, especially during the initial phase, lead to enhanced diurnal variation, it is difficult to determine even the non disturbed level of Fds. We define it as the nearest plateau on 25 hourly moving averages (horizontal dashed line at the Fig. 1) of the hourly intensity for each station. 3 hourly moving averages of hourly relative intensity were used to remove short time variations for each station.

The method of definition of decreases, related with shock and ejecta, is based on the analysis of the intensity profiles of the selected Fds – fitting arbitrary functions to the data. We assume that the variation of the relative intensity $U(t)$ near the minimum of the Fd can be described as:

$$U(t) = Z_0 \cdot t \cdot e^{-z_1 \cdot t} + Z_2 \cdot e^{-\frac{(t-z_3)^2}{2 \cdot z_4^2}} \tag{1}$$

where

$$U(t)_{Sh} = Z_0 \cdot t \cdot e^{-z_1 \cdot t} \tag{2}$$

and

$$U(t)_{Ej} = Z_2 \cdot e^{-\frac{(t-z_3)^2}{2 \cdot z_4^2}} \tag{3}$$

describe shock and ejecta related decreases respectively. The parameters z_0, z_1, z_2, z_3 and z_4 are chosen so that the function $U(t)$ is a best approximation of the data of the CR relative intensity at the near minimum phase of the Fd – at least during 60-120 hours from the beginning of the Fd. We should define only the onset of the Fds and the initial value of the parameters z_0, z_1, z_2, z_3 and z_4, which is easy if we take into account the following conditions:

$$\hat{U}_{Sh} = \left| \frac{Z_0}{e \cdot Z_1} \right| \tag{4}$$

$$\hat{U}_{Ej} = \left| Z_2 \right| \tag{5}$$

$$T_{Sh} = \frac{1}{Z_1} \tag{6}$$

$$T_{Ej} = Z_3 \tag{7}$$

$$DT_{Ej} = 4 \cdot \left| Z_4 \right| \tag{8}$$

where Eq(s). (4) and (5) describe the amplitude of decreases related with shock and ejecta; Eq(s). (6), (7) and (8) –the moments of minimum intensity of shock and ejecta related decreases and the duration (in hours) of ejecta effect respectively. The method of fitting arbitrary functions to data does not need a definition of ejecta effects and it depends only weakly on the amount of points outside the ejecta effect. This is very important for our investigation, because we used the data of single neutron monitors and meson telescopes for calculations of the rigidity dependence of ejecta or shock related decreases separately. Fig.1 demonstrates the method of fitting the arbitrary function to the data during the Fd of 28 Oct. 1991, according to Tbilisi neutron monitor.

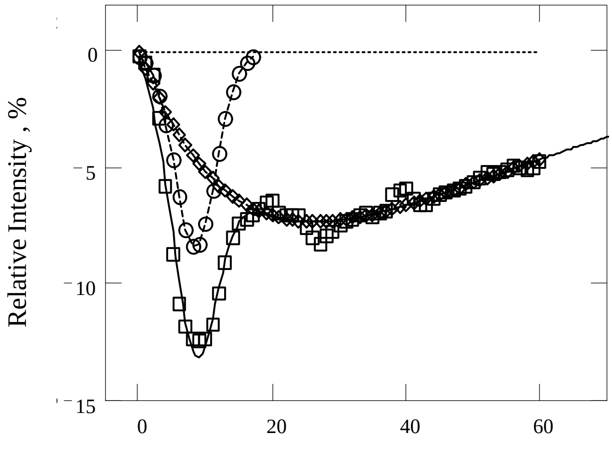

Fig.1. Decreases connected with shock (diamonds) and ejecta (circles) effects defined using the method of fitting arbitrary functions to the data. Solid line – best approximation to the data (boxes) for Fd on 28 October 1991, according to Tbilisi (Georgia) neutron monitor.

Rigidity spectrum parameters were determined using the least square method according to Despotashvili et al. (2001). Below we describe in detail the selected Fds. The time of minimum intensity of ejecta/shock related decreases are given relative to the start of the decrease at the Deep River (Canada) neutron monitor. It is necessary to define the amplitude of shock and ejecta related decreases for each station to define the rigidity spectrum parameters of shock and ejecta related decreases separately. To be sure that we have isotropic changes of the intensity during Fds, we checked the time of minimum intensity (T_{Sh} , T_{Ej}) for each station (see Fig.2 – shown as an example).

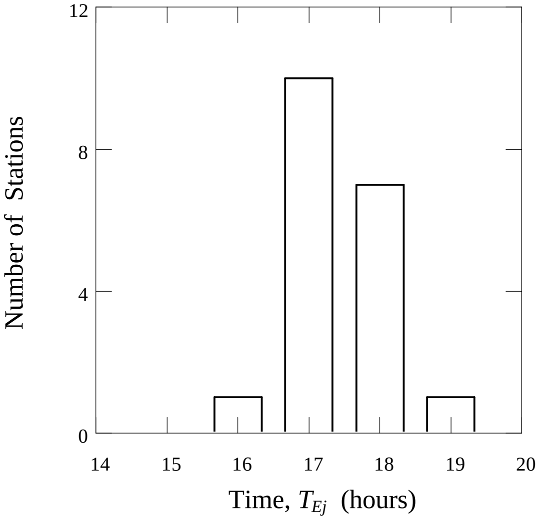

Fig.2. Histogram of the times of minimum intensity of ejecta related Fd on 15 February 1978 relative to the start of the decrease at the Deep River (Canada) neutron monitor. Although the onset of the individual decreases as seen by different stations is a function of local time, the time of minimum intensity of the ejecta related decreases is a global parameter.

3 Discussion of the Results

We determinate the rigidity spectrum parameters of shock and ejecta related decreases separately (for the moments T_{Sh} and T_{Ej}) for two-step Fds in a wide range of primary particle rigidities up to about 120 GV (see Tab.1). Here *Sh* and *Ej* represent the shock and CME connected steps of Fds; R_{max} - the upper rigidity limit of GCR modulation during Fds; *r* - rigidity spectrum index; *P* – Fds rigidity spectrum power; *T* –the time of intensity minimum of Fds; *DT* – duration of the ejecta connected step of the Fds.

Our results confirm recent findings of Wibberenz et al. (1997,1998) about relation of two effects not only for high latitude neutron monitors, but even for meson components.

We found a simple formula, which describes the relative isotropic intensity during the discussed Fds and is able to reveal separately shock and ejecta related decreases.

The rigidity spectrum power for both components is almost the same. The difference is significant only for the Fd on 15 February 1978. In spite of the fact that upper rigidity limit of Fds is not defined accurately, we found evidence that the upper rigidity limit of GCR modulation is higher for the shock related decreases than for the ejecta related decreases. We suppose that this effect is very important to check theoretical models of Fds, especially for models describing particle propagation in media with CMEs.

Table 1. Rigidity Spectrum Parameters for Two Steps of FDs.

Date	Step	R_{max}, GV	- 0.01*r*	10 *P*, % / GV	10 *T*,h	10 *DT*, h
Aug.4, 1972	*Sh*	1000	94 ± 6	126 ± 3	139 ± 3	
	Ej	30	74 ± 6	166 ± 9	45 ± 1	48± 2
Feb.15, 1978	*Sh*	30	114 ± 10	87 ± 8	204± 24	
	Ej	50	50 ± 24	244 ± 11	177± 2	126± 6
Feb. 12, 1982	*Sh*	1000	82 ± 16	55 ± 1	212± 9	
	Ej	20	38 ± 36	62 ± 3	54 ± 2	134± 8
March 24, 1991	*Sh*	900	70 ± 6	120 ± 3	441± 13	
	Ej	100	46 ± 10	166 ± 6	114± 2	214± 22
Oct. 28, 1991	*Sh*	60	62 ± 6	151 ± 2	226± 11	
	Ej	50	54 ± 6	168 ± 5	71± 2	125± 5

It was found that the correlation between the experimental data and theoretical values is better for shock related decreases than for ejecta related ones, however both have high value - >0.8-0.9.

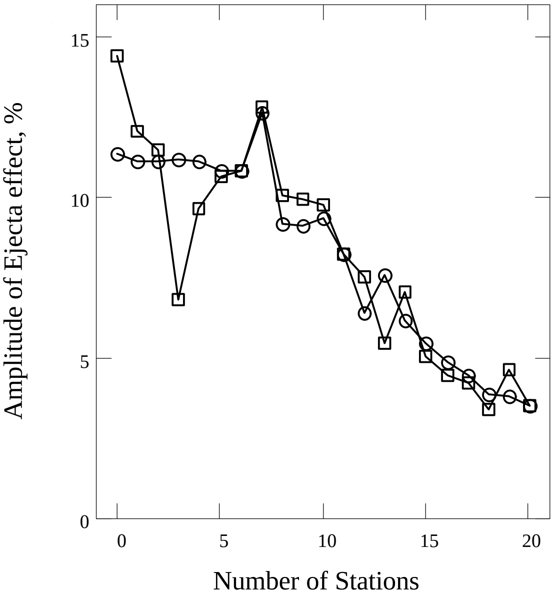

Fig.3. Amplitude of the ejecta related decreases during 24 March of 1991. Boxes – results of fitting arbitrary function to experimental data according to neutron monitors (0-13) and Nagoya meson telescopes (14-20). The station number is given in accordance with increasing cut off rigidity or median rigidity. Open points - calculated values with R_{max}= 100 GV, r = -0.46 (best fit to the data).

In terms of rigidity spectrum indices, it is noted that 25-hourly averaged data describes approximately the shock connected decreases.

Analyzing plots of theoretical and experimental amplitudes shock and ejecta related decreases (Fig.3 - is provided as an example), a difference between the correlation of theoretical and experimental data for neutron monitors with cut off rigidities < 3 GV and > 3 GV for ejecta related decreases was noted. When we exclude the data of neutron monitors with cutoff rigidities less than 3GV, the correlation becomes better, notwithstanding the number of used stations was reduced. Probably the reason of this is not changes in the cutoff rigidity during the magnetic storm, because the effect is large at mid-latitudes, but for stations with low cutoff rigidity the effects are small. Perhaps we couldn't fully exclude anisotropy effects from the data of stations with low cutoff rigidity. This effect has less influence over shock related decreases.

However, there might be another reason – according to Vanhoefer (1996), particles enter in the interior of the ejecta via perpendicular diffusion; the size of the maximum depression is a function of the geometric parameters of CMEs and the perpendicular diffusion coefficient; according to Bieber (1998) the perpendicular diffusion coefficients are different from low to intermediate $(K_{\wedge} \sim V R_L^2)$ and at high rigidities $(K_{\wedge} \sim V)$, where $K_{\wedge}$ is the perpendicular diffusion coefficient, R_L – Larmor radius, V-particle's velocity**.** This might be the reason of the different correlation between theoretical and experimental data at high and low latitude neutron monitors.

Wibberenz et al. (1997) found that the size of the shock related decreases scale with the radial gradient. According to Belov et al. (1993,1997) and Munakata et al. (1997) the radial gradients at 10 GV and 60 GV vary in the range of *2-4 %/AU and 0.4-0.6 %/ AU* respectively. In terms of rigidity spectrum index, this gives $-1.28 < r < -0.67$, which is in good agreement with our results.

In all cases examined the spectral parameters for the two steps indicate a tendency for a softer spectrum during the shock related step. These results reflect the differences between the mechanisms of GCR propagation in the media with coronal mass ejections and interplanetary magnetic shocks.

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