Correlations between Cosmic Ray Decreases and Forward Shock Parameters in 2001

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Abstract

Data from 6 cosmic ray detectors ground based with different rigidity cutoffs, and spacecraft measurements have been examined in order to determine the coefficient correlation between percentage changes in cosmic ray decreases and average variations of fast forward shock parameters. For analysis we chose the year 2001. In this period 52 fast and 9 slow forward shocks were identify in the interplanetary medium near the Earth. It was observed that slow forward shocks do not cause perceptible decrease in cosmic ray. We noted that the correlation coefficient involving velocity parameters is nearer of the unit for stations with minor rigidity cutoff. Any correlation was found among density parameters and reduction in cosmic ray intensity through the forward shocks.

Introduction

The correlation of reduction in cosmic ray (CR) intensity and interplanetary magnetic field (IMF) was clearly demonstrated by Barouch and Burlaga, 1975. CR decreases and shock structure have been studied in several works, e.g. Cane, 1994, Da Silva, 2005 and Singh, 2007. Besides IMF, in this work we investigate the correlation between CR decreases and others plasma parameters. We start with comments related to the interplanetary shocks and CR decreases.

Interplanetary Shocks

Fast solar wind structures erupted from the Sun, such as the remnants of Coronal Mass Ejections (CMEs) and Corotating Interaction Regions (CIRs), often propagate with a speed exceeding the magnetossonic speed, and thus, drive interplanetary shocks (adapted from Sheeley et al, 1983, 1985 and Echer, 2005). It is usual that spacecrafts near Earth's orbit measure only the shocks effects because of their great spatial extension which are larger than its correspondent solar wind structures. They are seen in the interplanetary data as an abrupt increase in plasma and magnetic field parameters (Echer, 2005). A shock moving away from the Sun relative to the solar wind is called a "forward shock". A "reverse shock" moves toward the Sun relatively to the solar wind. However, because solar wind is moving away from the Sun, both types of shocks are moving away from the Sun itself and any satellite can measures its parameters (Burlaga, 1995). A shock is fast when its relative speed to the solar wind is higher than the fast magnetossonic wave speed; a shock is slow when its relative speed is higher than the slow magnetossonic wave speed (Echer, 2003).

The typical forward shocks profiles of temperature (Tp), density (Np), magnetic field strength (|B|) and solar wind proton speed (Vp) are presented in Figure 1. Fast forward shocks show positive jumps in all the variables, Tp, Np, |B| and Vp. Slow forward shocks show positive jumps in Vp, Tp and Np, but negative in |B|, because slow magnetossonic waves have plasma and magnetic field variations anticorrelated (Sagdeev, 1991). The profiles for the reverse shocks can be seen in Echer, 2003.

Cosmic Ray Decreases

Short-term decreases in the secondary cosmic ray count rate, which last typically for about one week, were first observed by Forbush (1937) using ionization chambers. It was at the early 1950s, using neutron monitors (Simpson, 1954) which showed that the origin of these decreases was in the interplanetary medium.

The Earth being reached by some solar wind structure from the Sun, e.g. CME, is illustrated in Figure 2. The arrows indicate the deviation caused in the galactic cosmic ray (GCR) trajectory by its interactions with the solar wind structure. Thus, during the passage of this structure through the Earth, usually is measured a reduction in muon and neutron ground-based detectors count rate. There are two basic types. Non-recurrent decreases are caused by transient interplanetary events which are related to CMEs from the Sun. They have a sudden onset, reach maximum depression within about a day and have a more gradual recovery. Recurrent decreases (Lockwood, 1971) have a more gradual onset, are more symmetric in profile, and are well associated with corotating high speed solar wind streams.

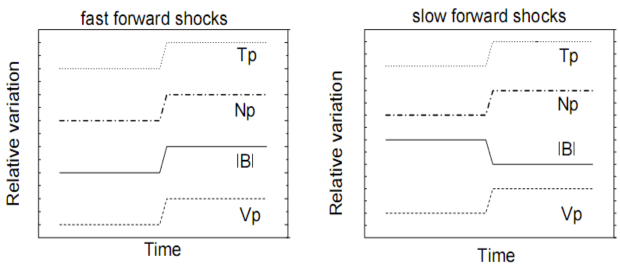

Figure 1 – Forward shocks profiles of Tp, Np, |B| and Vp (from Echer, 2003).

Historically, all short-term decreases have been called Forbush decreases (Fd). However, some researchers use the name more selectively to apply to only the non-recurrent events (Cane, 2000). In this work we analyze both types, without care about its discriminations.

Method

We analyze plasma and magnetic field data observed by satellite Advanced Composition Explorer (ACE) together with particle counting rates (>60 MeV) in anti-coincidence guard of the GSFC medium energy experiment onboard IMP-8 spacecraft. We also analyze data from neutron monitors with different geomagnetic cutoff rigidities, namely, Thule - Greenland (~ 0 GV), Climax – Colorado, USA (2.97 GV), Beijing – China (~10 GV) and Haleakala – Hawaii (~13 GV). Another cosmic rays data source for our analyses is the prototype multidirectional muon telescope (MMT), which initiated its operation in March 2001. It had 4 m^2 detection area and it was installed at the Southern Space Observatory (SSO/CRS/INPE – MCT), (29.4°S, 53.8°W, 480 m a.s.l.), São Martinho da Serra, RS, in the South of Brazil. We choose the vertical direction because it can observe better than others directions the overall effects caused by some interplanetary structure, besides to have the major detection area and consequently minor errors (Da Silva, M. R. et al., 2004). The IMP 8 spacecraft finished its data transmission in October 25, 2001. Then, there are no data for the periods from January 01st to March 06th in MMT and from October 25th to December 31st in IMP 8 in 2001.

We select all forward interplanetary shocks that occurred in 2001 identify through the ACE Lists of Disturbances and Transients from the following web site: www.ssg.sr.unh.edu/mag/ace/ACElists/obs_list.html.

Examples

An example of non-recurrent (Fd) decrease in 2001 recorded by detectors before mentioned is shown in Figure 3. Counting rates from these sources have been normalized to 0% for the average values in 2001. In Figure 3 we chose an event on October 11th - equivalent to DOY (Day of Year) 284. Notice the sudden onset, fast decrease and gradual recovery. The percentage variations (∆ %) in this event are: ∆ %IMP 8 = 3, ∆ %Thule = 4.1, ∆ % Climax = 7.8, ∆ %Beij. = 4.8, ∆ %Hale. = 6.33 and ∆ %Vmuon = 2.5.

As well as Echer, 2003, in order to calculate the plasma and |B| variation through the shock, three time windows were defined, each one of about 10 minutes. The boundaries of these time windows are limited by dotes lines in Figure 4. The window central time corresponds to the shock itself. The lateral time windows correspond to the upstream, "U", and downstream, "D", sides of shock (according to Burlaga, 1995). Average parameters were calculated for the interval limited by upstream and downstream time windows, and the difference between these averages is quantified as the parameter variation through the shock. Slow shocks occur in smaller number than fast shocks. During 2001 a total of 9 slow forward and 52 fast forward shocks were identified.

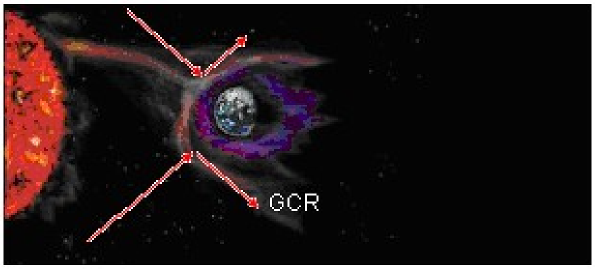

Figure 2 – GCRs being scattered by its interaction with the solar wind structure on the Earth (adapted from Augusto, 2006).

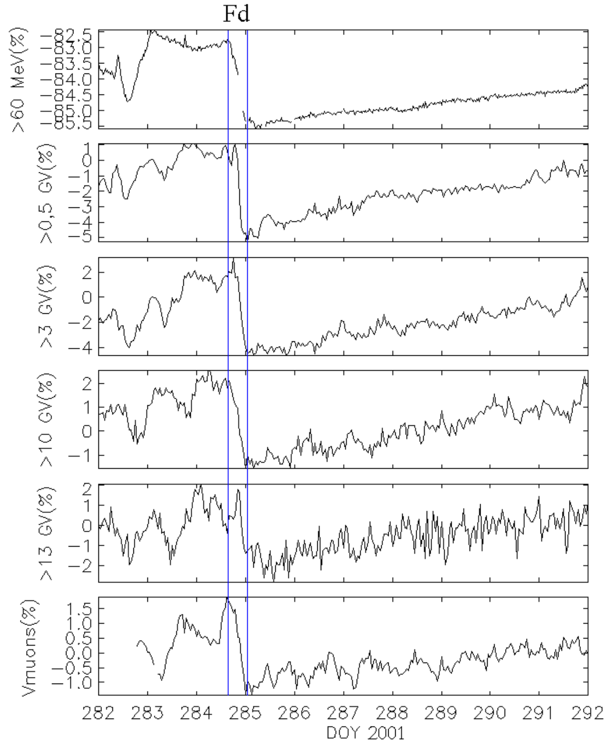

Figure 3 – A classical Forbush decrease. The panels are the percentage variations of GSFC IMP 8 instrument (>60 MeV), Thule (~ >0,5 GV), Climax (> 3 GV), Beijing (>10 GV) and Haleakala (>13 GV) neutron monitors and MMT vertical detector on October 11th, 2001.

As related by Cane, 1994, one difficulty in associating solar wind structures with cosmic ray decreases using neutron monitor (NM) data is that the Earth's rotation produces a diurnal modulation of the NM rate which is superimposed on variation resulting from solar wind structures. We also noted this diurnal modulation in muon data. An example of cosmic ray diurnal modulation due Earth's rotation is showed in Figure 5. Thus even using data from multiple NMs, it is difficult to relate changes in the cosmic ray intensity with solar wind structures. In studies by Cane et al (1993), it was shown that the integral rate of higher energy (> 60 MeV/amu) ions measured by the GSFC experiment on IMP 8 instrument can provide information about subtle intensity changes in decreases which are not evident in neutron monitor data because of diurnal variations.

On the other hand, because IMP 8 is in the space, it is more sensitive to solar particles (accelerated by solar flares and interplanetary CMEs) than ground based detectors. Consequently, often it recorded large increases in count rate instead of reductions. Thus, in 2001 only 15 decreases caused by interplanetary shock were observed.

An example of an enhancement in IMP 8 count rates, illustrated in Figure 6, probably is associated with the second solar flare ever recorded that occurred on April 2 2001 (DOY 92). The X-ray class emission was X20 (from: http://spaceweather.com/solarflares/topflares.html).

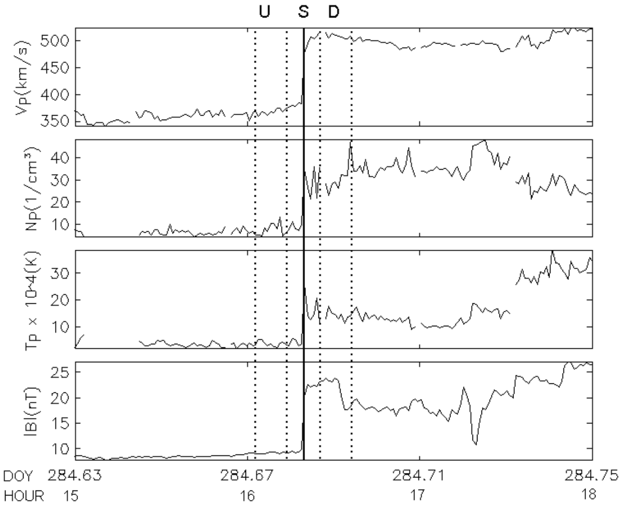

Figure 4 – Example of a fast forward shock observed on October 11th, 2001. Panels are speed, density and temperature proton and magnetic field strength. The continuous line indicates the shock (S) and the dashed lines indicate the upstream (U) and downstream (D) time windows.

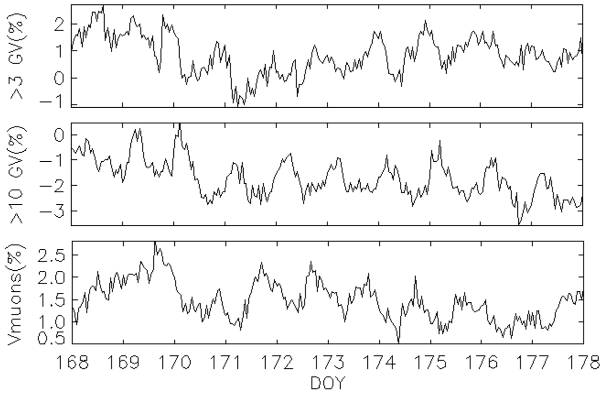

Figure 5 – Example of effect on CR count rate caused just by Earth's rotation. This may to complicate the recognition of a decrease caused by some solar wind structure.

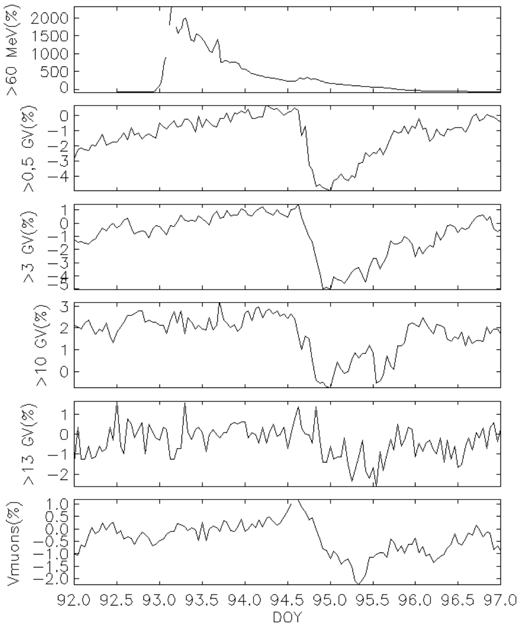

Figure 6 – Example of an increase in the IMP 8 count rate (top panel), while occur a decrease in the others cosmic ray detectors.

Results

The correlation coefficients among percentage variations in CR decreases and average variations of fast forward shock parameters are showed in Table 1. Δ |B|, Δ T, Δ N and Δ V are the difference between the average values of downstream and upstream regions. rN and rB represent the compression ratio between density and magnetic field strength in the downstream and upstream regions. Vs is the shock speed. According to Burlaga, 1995, supposing that the upstream and downstream are radials, so the shock speed can be calculated, relative to the Sun, through equation

$$Vs = \frac{N_2V_2 - N_1V_1}{N_2 - N_1} .$$

Where the subscripts 1 and 2 indicate the average values in the upstream and downstream sides, respectively.

We verified that cosmic ray flux is mainly modulated by fast forward shocks. As seen in Figures 1 and 4, in association with the passage of a fast forward shock, the intensity of the interplanetary magnetic field rapidly increases and its fluctuation also becomes larger. As a result, cosmic rays are prevented from diffusing across the shock waves. Thus, a cosmic ray intensity decrease is formed behind a shock because cosmic rays are unable to diffuse into this space by the action of this shock wave sweeping out them (Wada, M. and Murakami, K., 1988).

Table 1 – Correlation coefficients between percentage variations in different comic ray detectors and average variations of fast forward shock parameters.

	rN	rB	Δ |B|	Δ T	Δ N	Δ V	Vs
Δ % IMP 8		0.51	0.65	0.70	0.10	0.85	0.73
Δ % Thule	-0.03	0.43	0.60	0.62	-0.04	0.75	0.62
Δ % Climax	~0	0.50	0.55	0.56	-0.02	0.72	0.48
Δ % Beijing	0.08	0.55	0.60	0.55	-0.03	0.69	0.52
Δ % Hale	0.06	0.47	0.47	0.59	-0.06	0.64	0.42
Δ % Vmuon	-0.05	0.22	0.35	0.41	-0.16	0.48	0.34

There were 9 slow forward shocks in 2001 and in just 2 events we noted some decreases, whereas in the others 7 events the decreases were imperceptibles. This is reasonable because the magnetic field diminish through the slow forward shocks (see figures 1 and 4). Therefore, the mechanism that impedes the cosmic rays diffusion across the fast forward shock does not occurs with slow forward shock.

One can see in Table 1 that the variations in magnetic field strength, proton velocity and temperature are associated with cosmic ray decreases. Due to the B gradient, the higher compression ratio rB the stronger is the shock and the higher scattered are the cosmic rays. According to Wada, M. and Murakami, K., 1988, the motion of cosmic rays is directly influenced by the magnetic field in the solar wind, but the velocity of the solar wind is most important in the cosmic ray modulation, because this magnetic field is transported by, “frozen-in”, the solar wind.

Actually, the correlation with proton temperature occurs because T increases simultaneously with |B| and V, therefore, there is a non causal correlation among Δ T and CR decreases.

The correlation coefficients seem to be related to rigidity cutoff for Δ V and Vs. For these two shock parameters there is a clear tendency for its correlation coefficient to have higher values the lower is the rigidity cutoff.

The percentage variations from GSFC experiment on IMP 8 versus changes in proton velocity through forward shocks are presented in Figure 6. This relation has the higher correlation coefficient analyzed in this work.

Also it is possible to observe in Table 1 that the density parameters (rN and Δ N) are not related to cosmic ray decrease. Figure 8 displays an example of this with a graph of CR decreases in Climax neutron monitor and density compression ratio. One can see that this plot is largely scattered without any clear trend for a Δ % - rN relationship. A probably explanation for this different behavior may be related with the heliosphere particles transport equation suggests by Parker in 1965. This equation describes the modulation mechanisms of the cosmic rays intensity when entering the heliosphere (see Mursula and Usoskin, 2003). In the transport equation we noted that all terms are not directly related to the density, consequently, we have the observed weak correlation between density parameters and cosmic ray decreases.

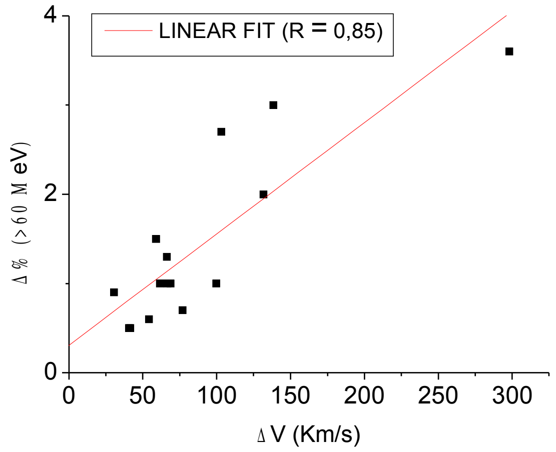

Figure 7 - Percentage variations from GSFC experiment on IMP 8 versus changes in proton velocity through forward shocks. This figure shows that the higher CR decrease is observed in regions of lower rigidity cutoff.

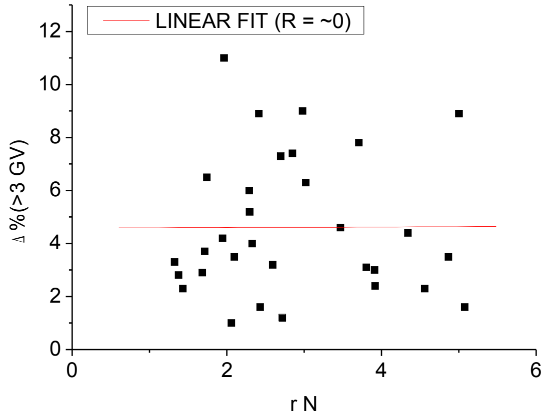

Figure 8 – Example of CR decreases versus density ratio. This figure does not show any association between those parameters, contrasting with what is shown in Figure 7.

Conclusions

The analyses of the correlation between cosmic ray decreases in 6 stations and fast forward shock parameters for several events occurred in 2001 are presented. It was verified that the modulation in cosmic ray flux caused by slow forward shocks is insignificant because the magnetic field diminish through the slow forward shocks. It was observed the presence of a relationship among $\Delta |B|$, ΔV, ΔT and cosmic ray decreases. The correlation coefficients seem to be related to rigidity cutoff for ΔV and Vs. For these two shock parameters there is a clear tendency for the its correlation coefficient to have higher values the lower is the rigidity cutoff. On the other hand, for density parameters there are any association with cosmic ray decreases. A possible justification for this can be related with the transport equation of the cosmic rays modulation in the heliosphere, since this equation is independent of the density. Thus, it is reasonable to observe that there are any correlation between density parameters and cosmic ray decrease intensity.

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