

# Relation of Forbush decrease with interplanetary magnetic fields.

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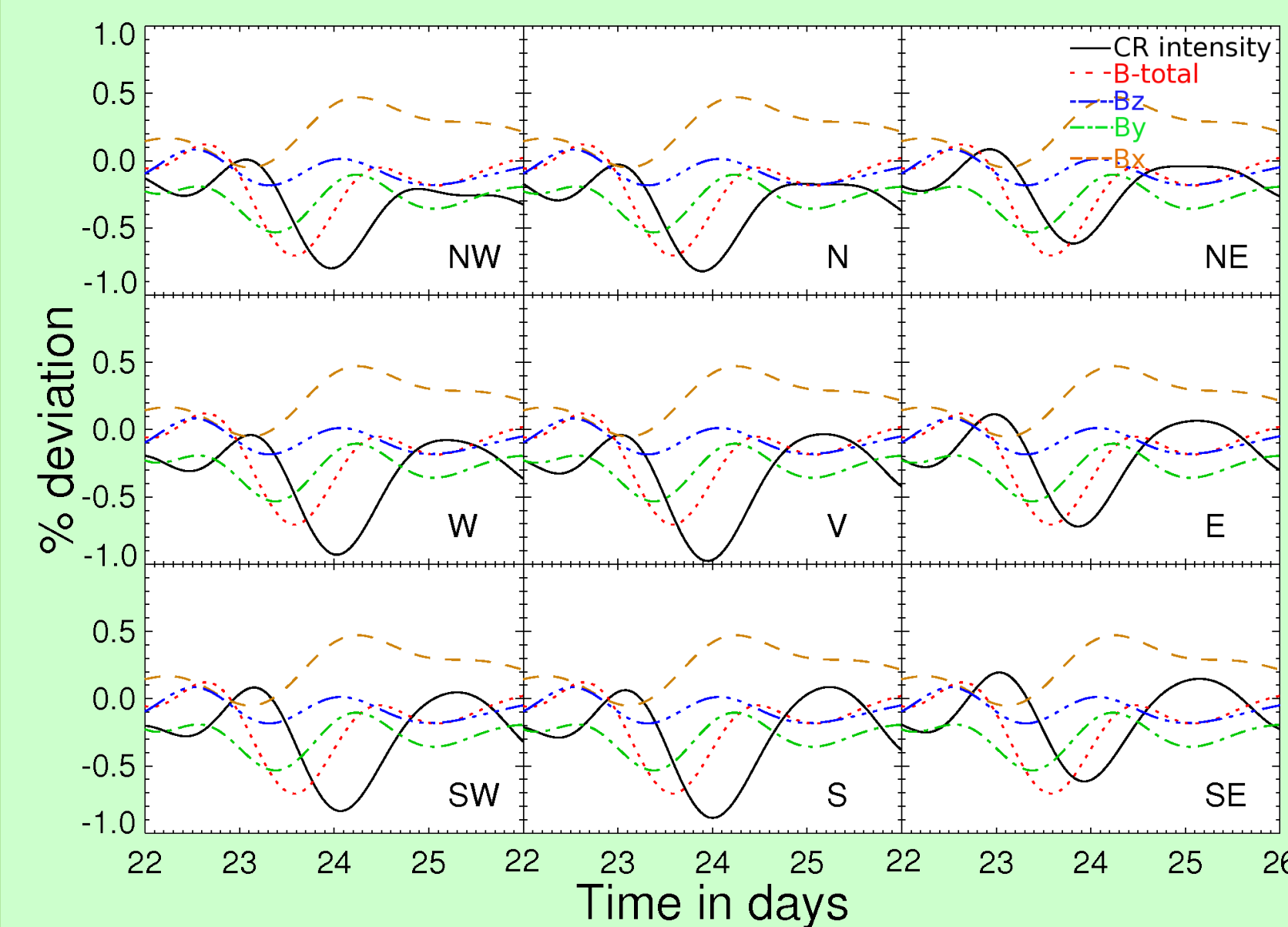
## Abstract

The relation between the Forbush decreases (FDs) and near-Earth interplanetary magnetic field (IMF) enhancements associated with the solar coronal mass ejections (CMEs) is studied. We have used data from GRAPES-3 tracking muon telescope to identify the Forbush decrease events. We have chosen events that are having a reasonably clean profile, and magnitude  $>0.25\%$ . We have used IMF data from ACE/WIND spacecrafts to investigate how closely the FD profile follow the IMF enhancements. We found that the enhancement of magnetic field responsible for the FD takes place mainly in the sheath region and also the MHD turbulence level get enhanced in this region. We found that the FD profile looks remarkably similar to that of IMF enhancement, yielding good correlation with a time lag. The FD profile lags behind the IMF by few hours. This observed lag corresponds to the time taken by high energy protons to diffuse into the magnetic field enhancement through cross-field diffusion.

## Forbush decrease and IMFs

Forbush decreases are transient dips in the observed galactic cosmic ray intensity. They can be due to the magnetic field compression of a shock (which acts like an umbrella), or due to the low (cosmic ray) density CME behind it.(Subramanian et. al., 2009, Arunbabu et. al., 2013). We used the muon intensity data from muon telescope which is a part of GRAPES-3 apparatus located in Ooty. (Gupta et. al., 2005,Gupta et.al., 2009, Hayashi et. al., 2005, Nonaka et. al., 2006, Mohanty et. al., 2009, Mohanty et. al., 2012)

The FDs we study are associated with near-Earth coronal mass ejection (CME) counterparts, which contribute to significant increases in the interplanetary magnetic fields (IMFs). We intend to investigate the relation between these IMF enhancements and FDs. We used the IMF data observed by the ACE and WIND spacecraft. We used hourly resolution data of  $B_{total}$ ,  $B_x$ ,  $B_y$ ,  $B_z$  magnetic fields in the geocentric solar ecliptic (GSE) coordinate system.  $B_{total}$  is the scalar magnetic field,  $B_x$  is the magnetic field component along the Sun-Earth line in the ecliptic plane pointing towards Sun,  $B_z$  the component parallel to the ecliptic north pole and  $B_y$  the component in the ecliptic plane pointing towards dusk.



**Figure 1 :** The FD event of 23 May 2002 and the magnetic field for 9 directions in GRAPES-3 muon telescope. Black solid line is percentage deviation of cosmic ray intensity in each direction. The red-dotted, blue-dash-dot-dotted, green-dash-dotted and orange-dash lines are percentage deviation of IMFs  $B_{total}$ ,  $B_x$ ,  $B_y$  and  $B_z$  respectively, that are scaled down by a factor of 10 to fit in the frame.

## Correlation FD magnitude with peak IMF

We first studied the correlation of FD magnitude with the maximum magnetic field in the magnetic field compression. The FD magnitude is calculated as difference between the pre-event cosmic ray intensity to the intensity at the minimum of decrease. We examined the corresponding IMF during these events. Since for an ideal fluxrope CME approaching Earth, the  $B_x$  component of IMF will be the radial magnetic field of fluxrope and  $B_y$  and  $B_z$  will be perpendicular components as appear to a typical cosmic ray particle trying to diffuse in to the fluxrope CME. So in this study, we consider two derived IMF componets: the scalar magnetic field ( $B_{total} = (B_x^2 + B_y^2 + B_z^2)^{1/2}$ ) and the perpendicular magnetic field ( $B_p = (B_y^2 + B_z^2)^{1/2}$ ). The correlation coefficients of peak  $B_{total}$  and  $B_p$  are listed in the table below

Direction	Cut-off Rigidity (GV)	Correlation coeff.	
		$B_{total}$	$B_p$
NW	15.5	0.702	0.712
N	18.7	0.707	0.714
NE	24.0	0.720	0.724
W	14.3	0.684	0.691
V	17.2	0.688	0.692
E	22.4	0.681	0.685
SW	14.4	0.669	0.676
S	17.6	0.660	0.666
SE	22.4	0.636	0.642

**Table 1 :** Correlation of the FD magnitude with the peak  $B_{total}$  &  $B_p$

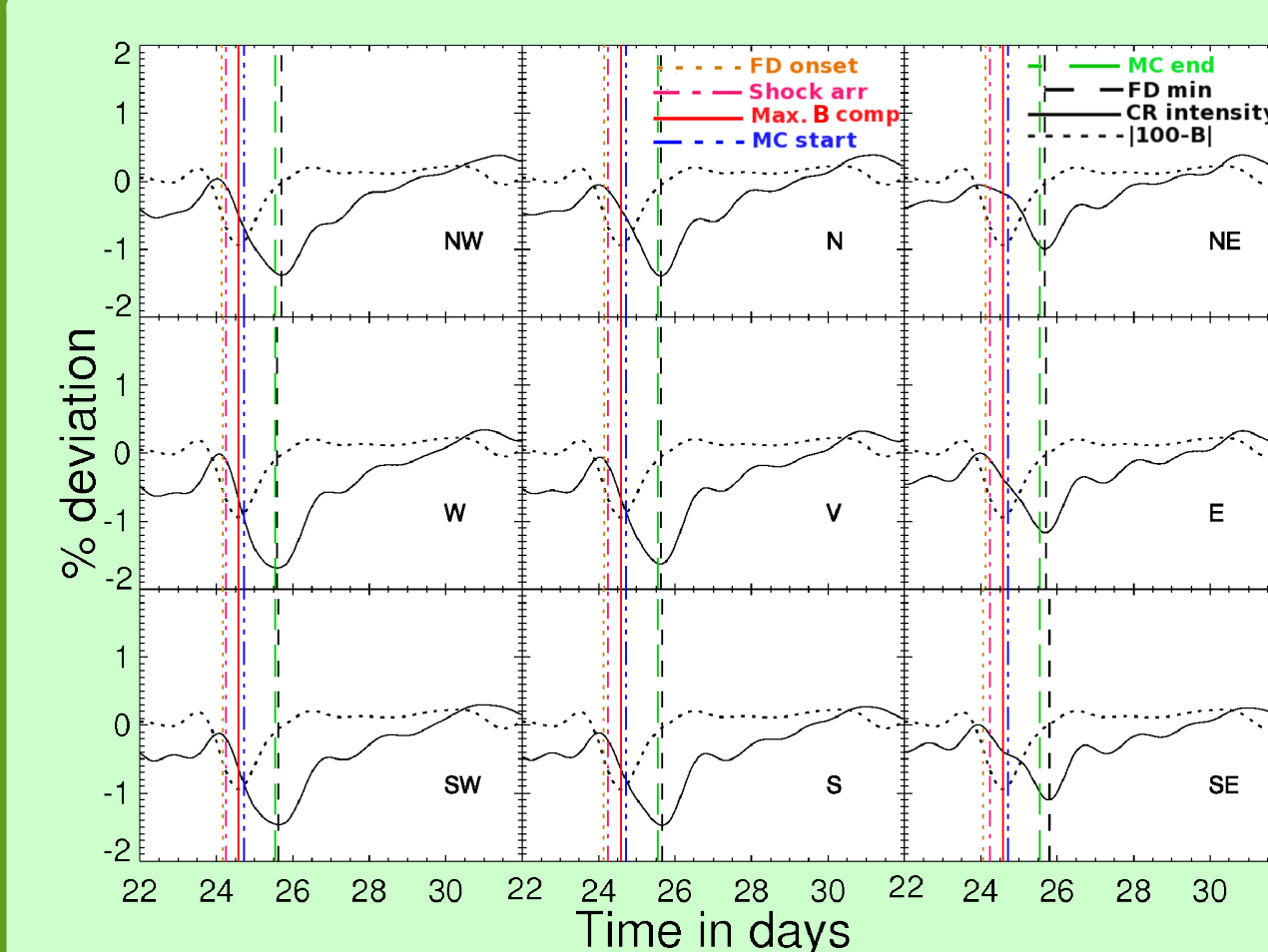
## Data analysis

We identify the Forbush decreases from the cosmic ray intensity data obtained from the GRAPES-3 muon telescope, which is located at Ooty (11.4°N latitude, 76.7°E longitude, and 2200m altitude) in India. This telescope provides muon flux data with high statistics so that a small change of  $\lesssim 0.1\%$  in the muon flux to be measured accurately over a time scale of  $\sim 5$  min, after appropriate corrections are applied for the time dependent variation in the atmospheric pressure (Mohanty et. al 2013).

In this study we analysed FD events during year 2001 to 2004, out of which which we chose events having a clean FD profile i.e., sudden decrease and gradual recovery in cosmic ray flux, magnitude  $>0.25\%$ , and associated with a near-Earth enhancement in the IMF. Although 0.25 % might seem like a small number, considering the high sensitivity of this instrument these are fairly significant events (Arunbabu et. al., 2013). We used GRAPES-3 data summed over a time interval of one hour, for each direction, which improved the signal-to-noise ratio. We used a low pass filter to remove the diurnal anisotropy and all other frequencies  $\geq \text{day}^{-1}$  (Subramanian et. al 2009).

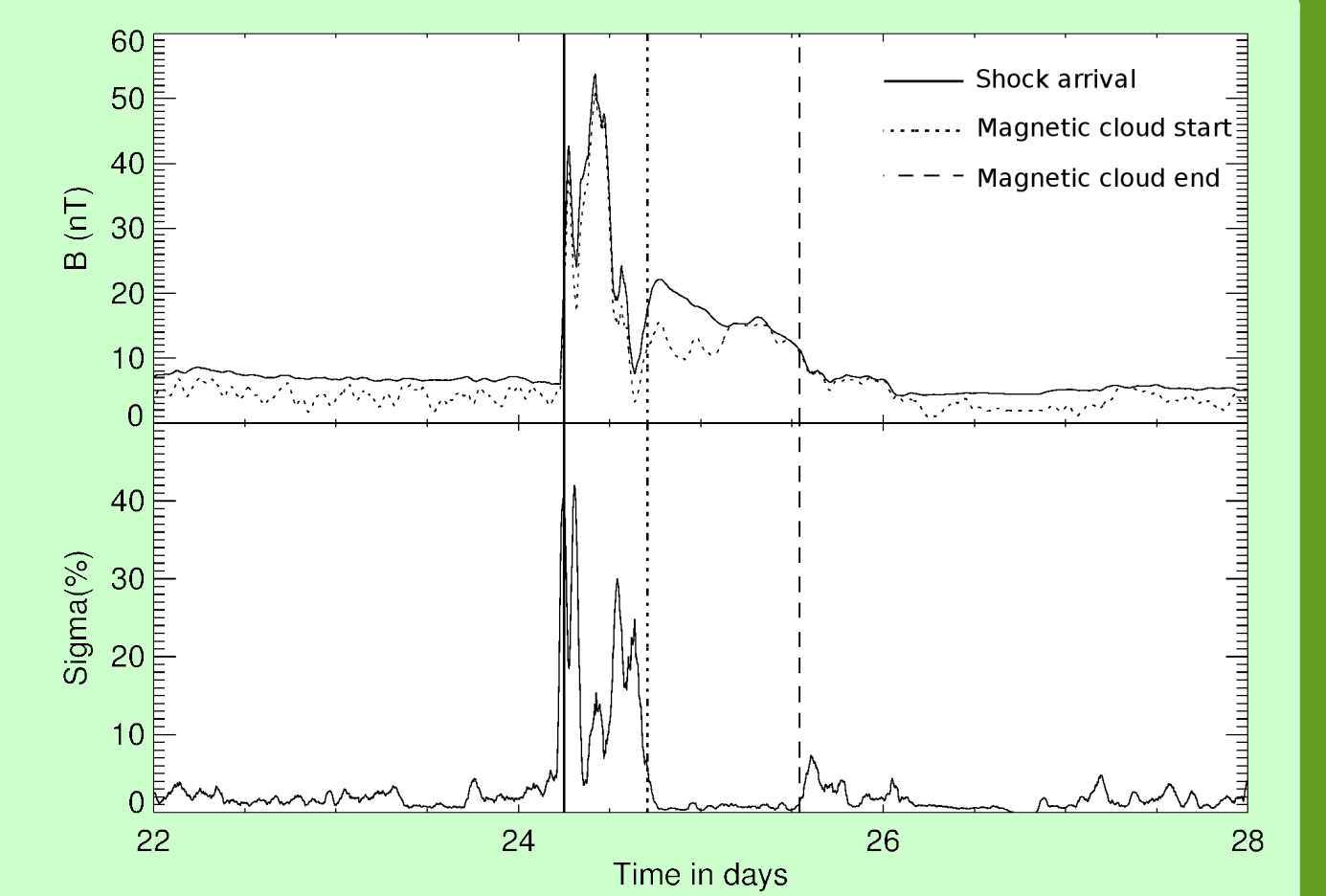
To studied FDs associated with IMF compressions due to near-Earth CMEs, we used the IMF data from the in-situ observations from ACE/WIND spacecrafts. We used hourly resolution magnetic field data of  $B_{total}$ ,  $B_x$ ,  $B_y$ ,  $B_z$  in the geocentric solar ecliptic (GSE) coordinate system. Since enhancement in IMF are associated with FDs, we used the quantity  $100 - |B|$  and calculate the average value and the percent deviation of this quantity over the same data interval as the FDs. This effectively flips IMF and make the enhancement appears like a decrease, enabling easy comparison with the FD profile. For consistent data analysis we used the same low pass filter which effectively remove all the frequencies  $\geq \text{day}^{-1}$ .

## IMF compression



**Figure 2 :** FD event on 24 November 2001. The black solid line denotes percentage deviation of the cosmic ray intensity and black dotted line is that of  $|100 - B|$ . The vertical lines are timing of parameters shown in legends.

We considered a subset of events which are having a well-defined shock and ICME/magnetic cloud associated with the corresponding magnetic field compression. We have observed that the **magnetic field compression responsible for Forbush decrease lies in the sheath regions, i.e., the regions between shock and CME** (figure 2). The cross field diffusion of cosmic rays through turbulent magnetic field depends on rigidity of proton and the turbulence level in magnetic field ' $\sigma^2 \equiv (B_{turb}^2/B_0^2)$ ' (candia & Roulet, 2004), hence it is important to study the turbulence level in this magnetic field compressions. We have calculated the turbulence level using one-minute averaged data from the ACE/WIND spacecraft. We observed that the **turbulence level ' $\sigma$ ' also get enhanced in this sheath region** (figure 3).



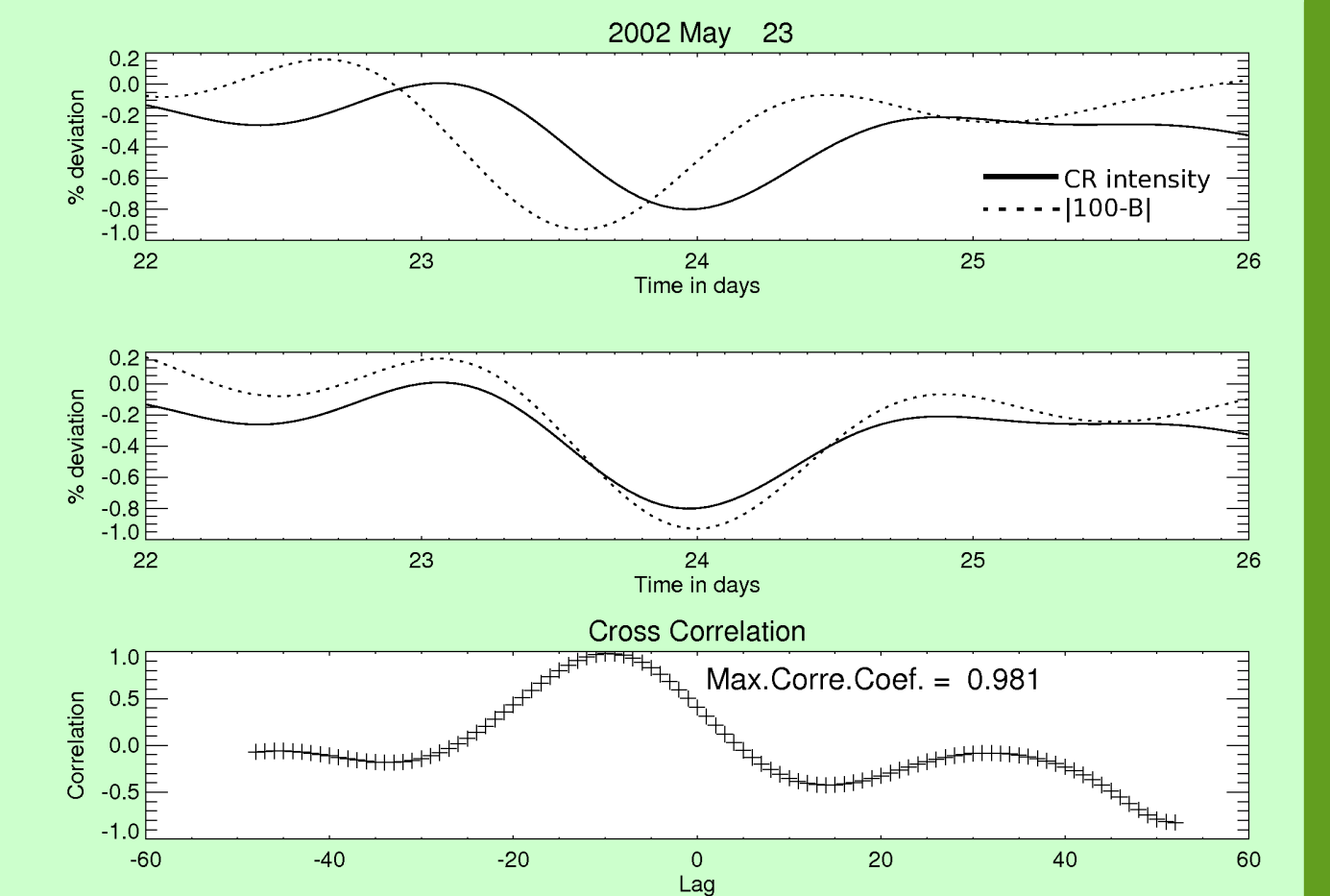
**Figure 3 :** IMF compression associated with the FD event on 24 November 2001. In the first panel the continuous line denotes  $B_{total}$  and the dotted line denotes  $B_p$ . The continuous line in the second panel shows the turbulence level for  $B_{total}$ .

## Comparing FD and IMF profiles

Event	$B_{total}$		$B_y$		$B_z$	
	Corr. (%)	Lag (hrs)	Corr. (%)	Lag (hrs)	Corr. (%)	Lag (hrs)
2001 Jan 13	97.2	-13	95.8	-14	96.6	-23
2001 Apr 11	90.7	-19	89.9	-17	91.3	-5
2001 May 27	66.5	0	65.0	-3	75.7	-21
2001 Sep 12	79.2	-25	26.7	-30	86.2	-1
2001 Nov 24	85.3	-21	41.0	-31	77.1	-14
2001 Dec 14	74.7	-35	69.7	-2	72.8	-17
2002 Sep 07	77.1	-18	49.6	-24	87.4	3
2002 Sep 30	81.1	-5	72.1	8	75.7	-12
2002 Dec 22	73.4	-15	43.4	0	84.7	-12
2003 Jan 23	70.9	-21	-	-	92.8	-28
2003 May 04	83.4	-8	84.7	-10	80.7	0
2003 Jul 25	95.3	-19	73.3	-2	41.6	2
2003 Dec 27	86.1	-35	21.7	5	87.2	-3
2004 Aug 30	-	-	-	-	92.4	1
2004 Dec 05	85.3	-12	89.4	8	58.4	-13
2004 Dec 12	81.1	-17	73.3	-25	78.9	-13

**Table 2 :** FD events correlates well only with the perpendicular component of the IMF enhancement.

Near-Earth CMEs cause a magnetic field compression in the IMF. We investigated the relation of this magnetic field compression to the FD profile for each individual events separately. For this study we took hourly resolution IMF data from ACE/WIND spacecrafts. **A visual comparison of FD profile with the IMF compression always shows a remarkable similarity. To quantify this we studied the cross-correlation of cosmic ray intensity profile with the IMF compression profile.** In order to do this we shift the magnetic field profile with respect to FD profile with a range from -36 to 12 hours with an interval of one hour. We identify the peak correlation value and the shift corresponding to this value as the lag between the IMF and FD profiles. Cross correlation of 23 May 2002 event is shown in figure 4 as an example, which shows a high correlation of **98%** with a lag of **13 hrs**. Few events which show good correlations with the perpendicular magnetic fields are listed in the table.



**Figure 4 :** Cross correlation of the cosmic ray flux with  $B_{total}$ . The top panel shows the percentage deviation of cosmic ray flux using solid black lines and the magnetic field using dotted black lines (scaled to fit in the frame). The middle panel shows the same with magnetic field shifted to the right corresponding to the time lag and the bottom panel shows the correlation coefficient for different lags.

## Diffusion through the magnetic field compression

The observed lag between the cosmic ray flux and IMF is poorly correlated with the FD magnitude and CME speed. This lag occurs because the high-energy protons are not responding to the IMF compression instantaneously. In this study we are concentrating on the cross-field diffusion of high energy particles through the turbulent sheath region. The perpendicular diffusion coefficient depends on the rigidity of the particle and the magnetic turbulence level  $\sigma$ . We interpret the observed time lag between the IMF and the FD profiles as the time taken by the high-energy protons to diffuse through the turbulent magnetic field compression. The time taken for a single diffusion random walk of a high-energy proton into the magnetic structure of CME is given by " $t_{diff} = \frac{D_{\perp}}{cV_{sw}}$ ", where  $D_{\perp}$  is the perpendicular diffusion coefficient (Candia & Roulet, 2004),  $c$  is the speed of light (which is the typical propagation speed for the highly relativistic galactic cosmic rays we are concerned with) and  $V_{sw}$  is the solar wind velocity upstream of the CME. We estimated the number of diffusion lengths required to account for the observed time lag between the IMF and FD profile using, " $\text{No. of Diffusions} = \frac{\text{Lag}}{t_{diff}}$ ". This number of diffusion is calculated using the peak value of IMF compression. **We found that the observed lag between the IMF compression and FD profile can be addressed by a few tens to a few hundred diffusion times.**

## Conclusions

- The magnetic field enhancement responsible for the Forbush decrease is in the shock sheath region.
- The magnetic field turbulence level also get enhanced in the shock sheath region.
- We find that FD profile displays excellent correlation with B-field compression, with a time-lag
- The observed time-lag between the cosmic ray flux and the IP magnetic field corresponds to few tens to few hundreds of diffusions.

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