Forbush decrease precursors observed in GRAPES-3

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Abstract

Earth-directed Coronal mass ejections (CMEs) emanating from the Sun and the shock associated with it are the primary drivers of space weather disturbances. Forbush decrease precursors are advance warning of these upcoming magnetic field disturbances. GRAPES-3 tracking muon telescope which is a part of GRAPES-3 experiment located in Ooty, India, provides high statistics measurement of the muon flux with good temporal resolution. In this study we are using data from GRAPES-3 muon telescope and making use of its multi-directional observations to study the Forbush decrease precursors in greater detail. We have identified few Forbush decrease precursor signatures in muon flux well before the arrival of the actual shock. We use these Forbush decrease precursors to study the characteristics of magnetic field compression associated with the upcoming CME shock-sheath system.

GRAPES-3 muon telescope

The GRAPES-3 muon telescope is part of GRAPES-3 experiment which is located at Ooty ($11.4°$N latitude, $76.7°$E longitude, and 2200 m altitude) in India (Gupta et. al., 2005,Gupta et.al., 2009, Mohanty et. al., 2009, Mohanty et. al., 2012). This large area tracking muon telescope is a unique instrument used to search for high energy protons emitted during the active phase of a solar flare or a CME, which provides a high statistics, directional measurement of the muon flux. It covers an area of 560 m^2, consisting of a total of 16 modules, each of them is 35 m^2 in area. The energy threshold of the telescope is sec (θ) GeV, for the muons arriving along a direction with zenith angle θ. The observed muon rate of $\sim 3000\,s^{-1}$ per module, yields a total muon rate $\sim 3 \times 10^6$ min^{-1} for the entire telescope (Hayashi et. al., 2005, Nonaka et. al., 2006). This large rate permits even a small change of $\lesssim 0.1\%$ in the muon flux to be measured accurately over a time scale of ~ 5 min. The design of the telescope help us to look in 169 solid angle directions (Nonaka et. al., 2006, Kojima et. al., 2015). Then these 169 directions were regrouped in a suitable manner to form nine different directions, named NW, N, NE, W, V, E, SW, S, and SE with uniform solid angle in field of view. The cutoff rigidity varies from 14 to 42 GV across its field of view of 2.2 sr.

Data analysis

We analyzed the 4-minute average muon flux data from the GRAPES-3 muon telescope. We applied efficiency correction and then pressure correction on this data for the 16 modules. The data after going through these correction will represent the actual cosmic ray intensity reaching our upper atmosphere. This data will have the signatures of interplanetary magnetic field (IMF) modulation on cosmic rays. Since we are interested in Forbush decrease events and its precursors we used a 'band-rejection-filter' to remove the periodic diurnal variations and its second harmonics in the frequency range of $\mathbf{1/day \leq f \leq 2/day}$.

We calculated the percent deviation of muon flux from average value obtained during a quite time period. Forbush decrease precursors shows significant change in the intensity, which is identified in 169 directions and as well as in nine directions. To confirm that the observed variations are connected with the up coming shock/CME we checked the pitch angle of our directions with the directions of IMF using the in-situ IMF data from ACE/WIND space crafts. Since precursors are caused due to the presence of Earth directed CME-shock system magnetically connected Sun-Earth line, we can see the precursors in lowest pitch angles only (Munakata et. al., 2000, Munakata et. al., 2005). One example of the FD precursor observed in 169 directions and the pitch angle of corresponding viewing directions at 9:12 local time or 3:42 UT is shown in figure 1. Figure 2 represents precursor event observed in SE direction along with the IMF.

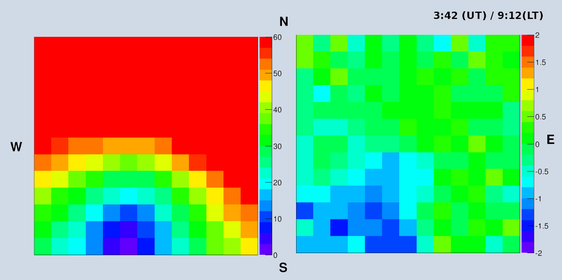

Figure 1 : Forbush decrease precursor observed in GRAPES-3 at 9:12 local time or 3:42 UT 14 December 2006. Left figure shows the pitch angle of the viewing directions of GRAPES-3 muon telescope, right figure shows the percentage deviation of observed muon flux

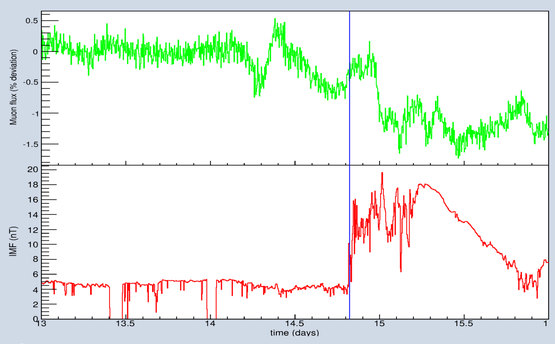

Figure 2 : FD precursor observed on 14 December 2006. Top panel shows the percentage deviation of muon flux observed in SE direction. Bottom pannel shows the scalar IMF. Vertical line corresponds to the shock arrival time. The time is given in Ooty local time (LT=UT+5:30 hrs).

FD precursor on 14 December 2006

This event was observed on 14 December 2006, followed by a large FD. This event was associated with a CME which was first observed in LASCO field of view on 13 December 2006 at 02:54 UT and was having a speed of $\sim$1774 $km\,s^{-1}$. The shock associated with this CME reached the Earth and identified by ACE/WIND spacecrafts on 14 December 2006 at 14:14 UT, which corresponds to 19:44 LT, the solar wind speed was $\sim$ 955 $km\,s^{-1}$. We started seeing the precursors more than 10 hrs before the arrival of the shock, which is represented by blue vertical line in figure 3. This event observed in nine different direction are shown in figure 3.

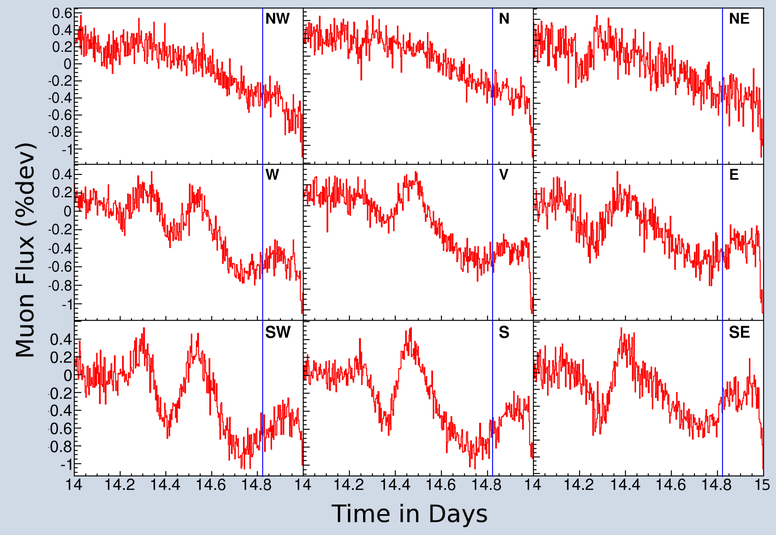

Figure 3 : FD precusrsor on 14 December 2006 observed in nine different directions using GRAPES-3 muon telescope. Each pannel shows the percentage deviation of muon flux and the vertical line shows the shock arrival time. The time is given in Ooty local time (LT=UT+5:30 hrs).

FD precursor on 29 October 2003

This event was observed on 29 October 2003 followed by the largest FD observed in 23rd Solar cycle. This event was associated with a CME that was observed first on 28 October 2003 at 11:30 UT with a speed $\sim$ 2459 $km\,s^{-1}$, which caused the famous halloween events. The shock associated with this event reached the Earth on 29 October at 06:11 UT, which correspond to 11:41 LT. The solar wind speed during the arrival of shock/CME system was $\sim$1900 $km\,s^{-1}$. We started seeing the precursors $\sim$ 7 hours before the arrival of the shock. This event observed in nine different direction are shown in figure 4.

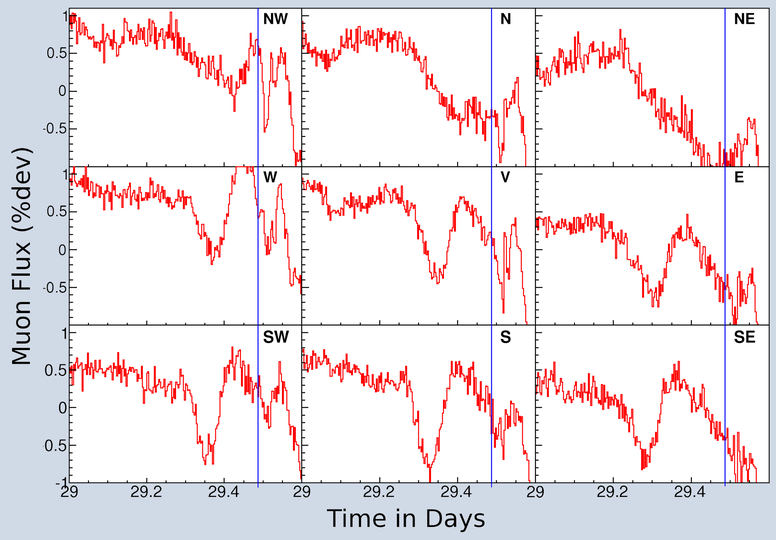

Figure 4 : FD precursor on 29 October 2003 observed in nine different directions using GRAPES-3 muon telescope. Each pannel shows the percentage deviation of muon flux and the vertical line shows the shock arrival time. The time is given in Ooty local time (LT=UT+5:30 hrs).

FD precursor observed in 169 directions

We observed the FD precursor in 169 directions. An example of such an event is shown below, which is a precursor on 14 December 2006. The shock reached Earth at 14:14 UT on 14 December 2006, which corresponds to 19:44 Ooty local time. We started seeing the precursor signatures much before ($\sim$ from 6:00 hrs local time) the arrival of this shock.

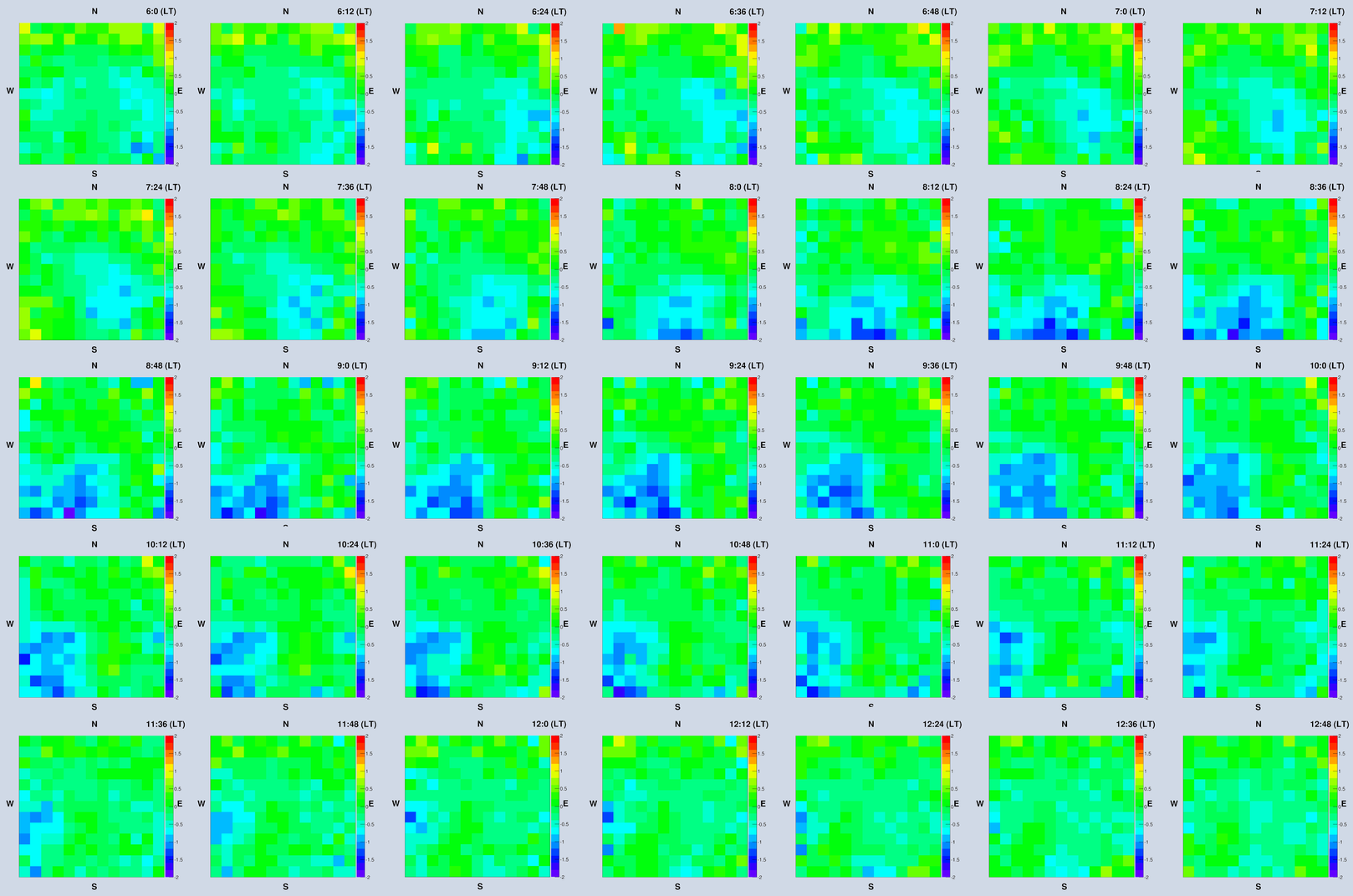

Figure 5 : Forbush decrease precursors observed in 169 directions on 14 December 2006. The time is given in Ooty local time (LT=UT+5:30 hrs).

Conclusions

- GRAPES-3 muon telescope provides muon flux data with high statistics and temporal resolution.
- We designed a band rejection filter which removes the fequencies in the range $\mathbf{1/day \leq f \leq 2/day}$, that helped us to removed the components of diurnal anisotropy and its second harmonics.
- The resultant data after applying the filter showed the Forbush decrease and precursor event clearly.
- We identified Forbush decrease precursors well before the arrival of actual shock.
- The evolution of precursor events in the 169 directiosn FOV can give us information about the upcoming CME and better understanding of these phenomena.

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