# Estimation of 3D structures of cosmic-ray low density region behind shock waves associated with solar flares

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**Abstract:** Using the data obtained by GRAPES-3 tracking muon telescope at Ooty, we are going to estimate the 3D structure of low density cosmic ray region caused by large solar flares. Since the GRAPES-3 muon telescope has a large acceptance ($\sim 3\,\mathrm{sr}$) with fine segmentation ($13 \times 13$), hourly 2D maps of multi-directional cosmic-ray intensity variations are easily obtained by this telescope. By comparing the time sequence of these 2D maps with the results of computer simulations in which some models of structure of the low density cosmic-ray region behind shock waves are assumed, we will try to extract their 3D structure of the region. In this paper, we examine the time profiles of the Forbush decreases so far observed and compare them with the time profiles of the solar wind velocity. Then, we present a simple 3D shock wave propagation model and draw a sample contour map of cosmic ray intensity for getting the idea about what we will be able to deduce from 2D maps of GRAPES-3 by comparison.

**Keywords:** Solar flare, Cosmic-ray low density region, 3D structure, GRAPES-3 tracking muon telescope

## 1 Introduction

It is thought that the transient phenomena of cosmic-ray intensity variations such as Forbush decreases and/or the cosmic-ray local (small scale) anisotropies are caused by shock waves (*i.e.* some unusual or special structures of the interplanetary magnetic field) associated with Solar flares, coronal mass ejections or high speed flows of the solar wind, because cosmic rays near the area may be brown away by such shock waves and some low density region might be made. So it is expected that the observation and analysis of cosmic-ray intensity variations will provide important information about the 3D structure of such low density region caused by the shock wave.

So far, this kind of phenomena have been mainly investigated by using muon or neutron monitors those have relatively less angular resolutions [1] [2]. In order to observe the more fine structure of the low density region caused by the shock wave, the more angular resolution with multidirectional field of view is required. The GRAPES-3 tracking muon telescope is the one of such detectors suitable to study transient phenomena or local anisotropies of the cosmic rays [3] [4] [5] [6] [7] [8]. The field of view of the telescope is schematically shown in Fig.1.

The GRAPES-3 tracking muon telescope is located at Ooty, India (11.4° N, 76.7° E). It consists of 16 modules of $35\,\mathrm{m}^2$ muon detectors, and the acceptance is about $\sim 3\,\mathrm{sr}$. This telescope can record the hourly 2D map of the arrival direction of muons above $1\,\mathrm{GeV}$ with $13 \times 13$ fine segmentation. The detailed explanation of the detector can be found elsewhere [3] [4] [5] [6] [7].

## 2 Time profile of the Forbush decrease

Before showing an example 2D map of the Forbush decrease viewed by the GRAPES-3 tracking muon telescope, we present several examples of the time profiles of Forbush decreases comparing with the time profiles of the solar wind velocity, here.

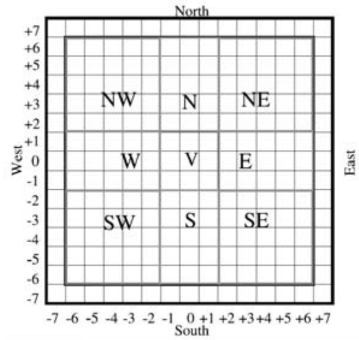


Figure 1: The field of view of the GRAPES-3 tracking muon telescope.

In all Figs.2 – 6, the daily averaged solar wind velocity and the daily averaged cosmic ray intensities of NW, N, NE, W, V, E, SW, S, SE components, which are corresponding directions to the letters indicated in Fig.1, are shown. For all the figures, the abscissa indicates the day of the observation, the left ordinate indicates the variation of cosmic ray intensities in $\%$, and the right ordinate indicates the variation of solar wind velocity in $\mathrm{km/s}$.

In case of Figs.2 and 3, peaks of the solar wind velocity precede valleys of the cosmic ray intensity, on the other hand, in case of Figs.4 and 5, the order is reversed. There are other examples in which a peak of the solar wind velocity and a valley of the cosmic ray intensity observed simultaneously at the Earth, as shown in Fig.6. Of course, there also exist more complicated events. The relation between the time profile of the variation of cosmic ray intensities and that of solar wind velocities is differ from one event to another.

## 3 Simple model calculation

From the data of only one dimensional time sequences, it is not easy to deduce the complicated relations as seen in the examples of the previous section. So, we are going to use hourly 2D maps of multi-directional cosmic-ray intensity variations provided by GRAPES-3 tracking muon telescope.

Here, we introduce a simple 3D shock wave propagation model as a tool to make correspondences between 3D structures of low density cosmic ray region and 2D maps of cosmic ray intensity. Schematic view of the model is shown in Fig.7. In this model, it is assumed that a shock front of the interplanetary magnetic field is a simple plane and propagate a given direction strait with a constant speed (*e.g.* $\sim 600\,\mathrm{km/s}$). For the calculation of cosmic ray intensities, at this time, we assumed that cosmic rays behind the shock front is totally swept out and the intensity of cosmic rays is proportional to the distance from the Earth to the boundary which is determined by the shock front and the spherical shell centered at the Earth with a given radius

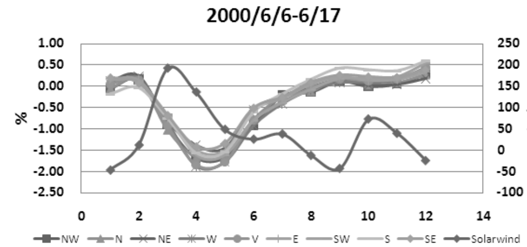


Figure 2: An example of Forbush Decrease observed behind the increase of the solar wind velocity.

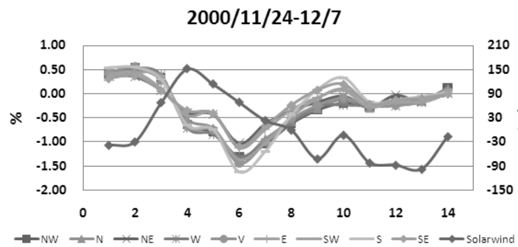


Figure 3: An example of Forbush Decrease observed behind the increase of the solar wind velocity.

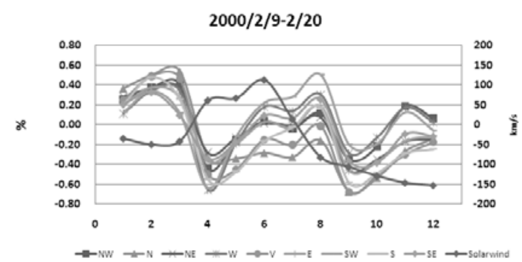


Figure 4: An example of Forbush Decrease precedes the increase of the solar wind velocity.

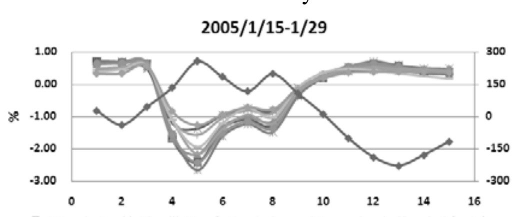


Figure 5: An example of Forbush Decrease precedes the increase of the solar wind velocity.

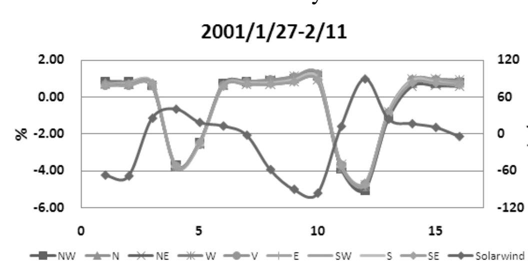


Figure 6: An example of Forbush Decrease observed simultaneously to the increase of the solar wind velocity.

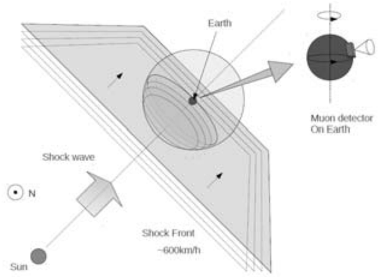


Figure 7: A simple 3D shock wave propagation model for an estimation of cosmic ray intensity 2D maps.

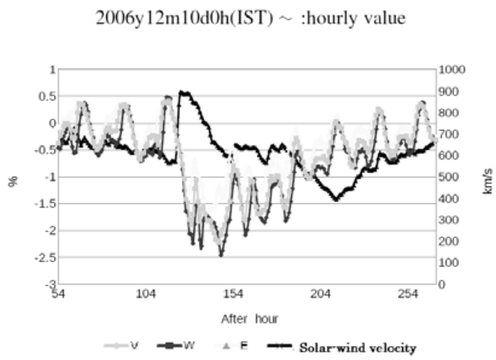


Figure 8: A Forbush decrease observed by the GRAPES-3 tracking muon telescope (V, W, E) and the time profile of solar wind velocity around 15 (from 12 to 21), Dec., 2006.

(*e.g.* $0.25\,\mathrm{AU}$). The orientation of the (multi-directional) telescope and the rotation of the Earth are, of course, also taken into account.

As a typical example, observed 2D maps of cosmic-ray intensity variations correspond to Forbush decrease observed around 15, Dec., 2006 (the hourly averaged solar wind velocity and that of cosmic ray intensities are shown in Fig.8) and the calculated contour maps are compared in Fig.9. From this figure, very clear qualitative correspondences are seen between the calculation and the observation.

## 4 Conclusion

From the comparison of the time profiles of the Forbush decreases with those of solar wind velocities, we can conclude that the relation between them are differ from one event to another, and it is not easy to deduce the complicated relations from the data of only one dimensional time sequences, at first.

Next, introducing the simple 3D shock wave propagation model and drawing the sample contour map of cosmic ray intensity help us to examine the relation between physical (or plasma) and geometrical parameters of the solar wind (or the 3D structure of low density cosmic ray region) and the hourly 2D maps provided by GRAPES-3.

Though the result presented here is only limited to the qualitative comparison, this is the first trial and there is the potential to develop a useful tool to estimate the 3D structure of low density cosmic ray region caused by large solar flares.

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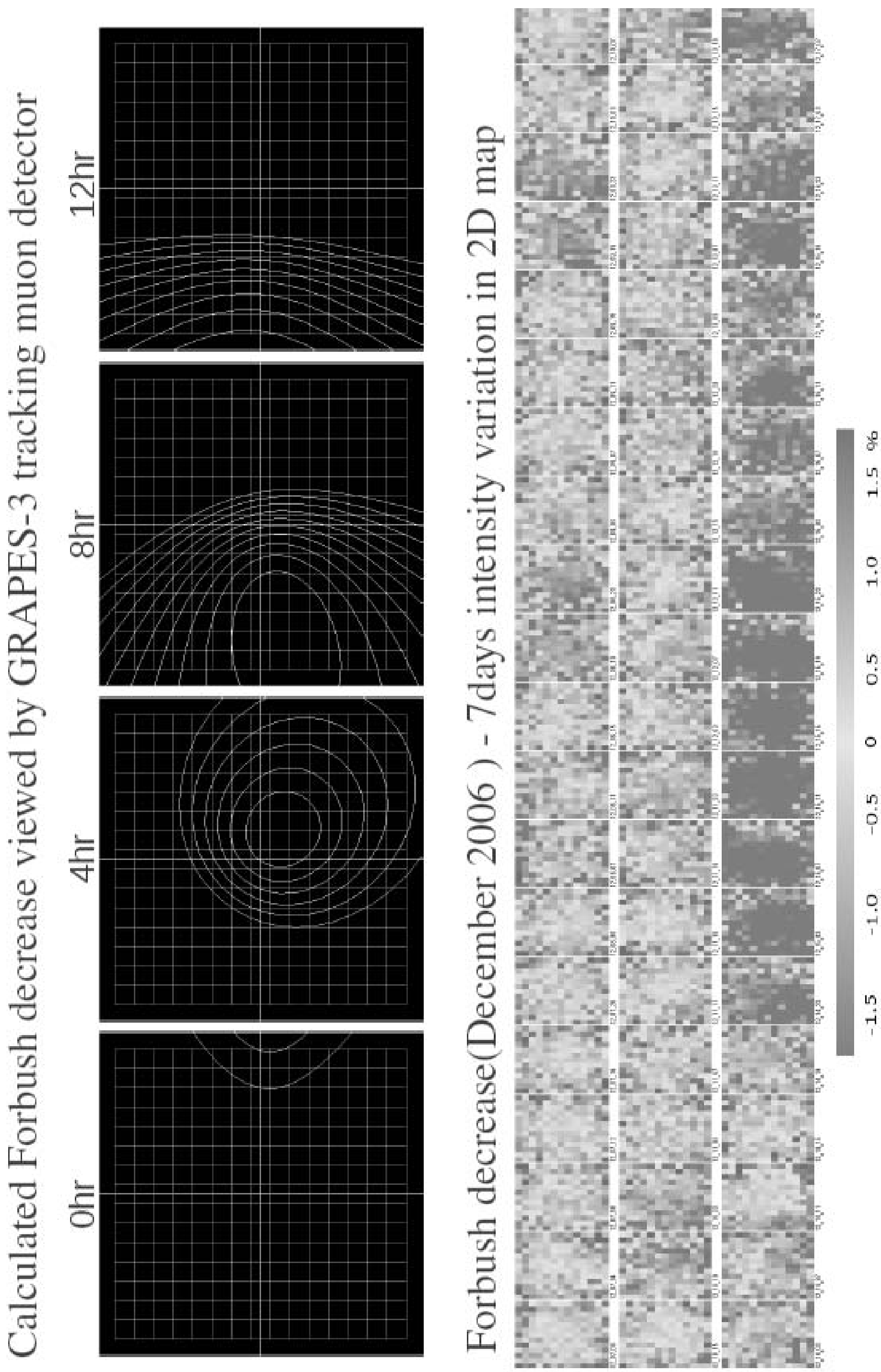


Figure 9: Calculated and observed Forbush decrease viewed by the GRAPES-3 tracking muon telescope around 15 (from 7 to 17), Dec., 2006.