Journal of Atmospheric and Solar-Terrestrial Physics 123 (2015) 124–136

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

An analysis of large Forbush decrease events using phase diagrams of view channels of the Nagoya multidirectional muon telescope

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ARTICLE INFO

Article history:
Received 23 July 2014
Received in revised form
24 December 2014
Accepted 30 December 2014
Available online 1 January 2015

Keywords:
Cosmic rays
Forbush decrease
Multi-directional muon telescope
Power-law model

ABSTRACT

Large Forbush decrease (FD) events are analysed using data recorded by the ground-based Nagoya multidirectional muon telescope in Japan. As a part of the analysis we introduce a phase diagram for the channels of telescope, which provides more robust information about characteristics of events. Specifically, the slope of the regression line in the phase diagram represents the FD amplitude which can be computed for different channels. This allows us to analyze the dependence of the FD amplitude on the rigidity of CR particles. Two models for this dependence are considered, a power law and exponential and the former is found to be more suitable for the considered events. In terms of the power-law index and the FD amplitude the events are split into two groups. It is shown that the larger events are characterized by smaller power-law index than the smaller ones.

1. Introduction

Cosmic Rays (CRs) are high-energy charged particles originating from a variety of galactic and intergalactic sources (e.g., Dorman, 1974). As they propagate through the solar system they interact with the interplanetary magnetic field (IMF) and their flux is modulated by its intensity, direction and turbulence. The ability of CR particles to penetrate magnetic fields and reach the surface of Earth is largely determined by their rigidity that is defined as the particle's momentum multiplied by the speed of light per unit charge. Rigidity of CR particles is usually measured in GV. Low rigidity particles may be deflected by the IMF or the terrestrial magnetic field while high rigidity particles are not. Thus, the interplanetary and geomagnetic fields serve as a giant magnetic spectrometer (e.g., Pomerantz, 1971). To reach a location on Earth a CR particle is required to have a minimum rigidity called cutoff rigidity (Smart et al., 2000). A value of cutoff rigidity is determined by the location on Earth and the viewing direction. Typically, the cutoff values depend primarily on the geomagnetic latitude and range from less than 1 GV near the geomagnetic poles to about 16 GV near the equator (Smart and Shea, 2005).

Cosmic ray particles which reach the Earth interact with the terrestrial atmosphere producing cascades of secondary particles (e.g., Simpson et al., 1953). Of these, neutrons and muons are usually detected by ground-based neutron monitors and muon detectors. These instruments have their highest sensitivity in different energy ranges, typically ~10 GeV for a neutron monitor and ~50 GeV for a muon telescope (Leerungnavarat et al., 2003) and therefore they represent complementary tools for a study of CRs properties. However, muon telescopes have some advantages. A muon telescope typically enables simultaneous records of CRs intensities in different directions of viewing, while a neutron monitor is an omnidirectional detector. In addition, muons with energy of a few GeV and higher have a low rate of interaction with matter, which helps to identify their arrival direction (Sharma, 2012).

In the heliosphere CRs interact with solar disturbances such as interplanetary coronal mass ejections (ICMEs) which often produce a rapid (half a day or less) decrease in the cosmic ray intensity called Forbush decrease (FD) (e.g., Cane, 2000; Kahler and Simnett, 2009). These decreases are usually followed by a slow recovery taking place over several days (Lockwood, 1971; Musalem-Ramirez et al., 2013). Since ICME often cause geomagnetic storms, FDs have space weather applications and may potentially play a role in storm forecasting (Kudela and Storini, 2006; Munakata et al., 2000, Leerungnavarat et al., 2003).

A FD effect is a rather complicated phenomenon which results from both long-term and short term solar modulations of CRs. For observation of FD events with ground-based detectors, perturbations of geomagnetic field are also important (Dorman, 2009). Various mechanisms and models have been offered to explain FD effects (Morrison, 1956; Parker, 1963; Quenby et al., 2008). A very good review of theoretical models for FD events can be found, for

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http://dx.doi.org/10.1016/j.jastp.2014.12.012
1364-6826/

example, in le Roux and Potgieter (1991). One of the common models of FD involves an ICME which creates a preceding shock. Then the turbulent "sheath" between the shock front and the leading edge of the ICME scatter CRs and thus sweep them out resulting in a rapid decrease in their intensity (Ifedili, 2004; Richardson and Cane, 2011). The scattering is often described as a diffusion process. Then diffusion–convection models (e.g., Sari and Ness, 1969) show that the FD magnitude is proportional to a product of a characteristic radial size of disturbance and a ratio of some averaged values of the solar wind speed and the diffusion coefficient along IMF, which is the largest component of the diffusion tensor describing transport of CR particles parallel and perpendicular to the IMF (Potgieter, 2013). Thus, the FD amplitude decreases with increase of the diffusion coefficient.

During FD events fluxes of CRs with different rigidities decrease differently since lower rigidity particles are more affected by the changes in the magnetic field. Modulation of CR particles with different rigidities has been extensively studied in the past. These studies often used and compared CR intensity data recorded by different ground-based and onboard spacecraft instruments. For example, Van Hollebeke et al., (1973) studied the ~6-year decrease in CR intensity for period 1966–1972. The authors plotted ~1-GV integrated proton counting rate, using measurements from the Goddard cosmic ray experiment on Interplanetary Monitoring Platforms (IMPs) IV and V, as a function of data from Deep River neutron monitor (~10 GV) to demonstrate a hysteresis effect due to a time lag between intensity changes for particles with different rigidities. This hysteresis effect was also explained by Chih and Lee (1986) who developed a diffusion–convection model using a perturbation approach. They showed that the effect is caused by the high-energy particles responding to the variation of the spatial diffusion coefficient before the low-energy particles.

In another study of CR modulation, Evenson and Meyer (1981), correlated the daily averaged counts, measured with the University of Chicago instrument on board the ISEE-3 spacecraft (cutoff rigidity of 1.2–11 GV), to the particle fluxes obtained from Climax neutron monitor for period from August 15, 1978 to May 1, 1980. Using data from observations of a decrease stage during two FDs in September, 1978 and in August, 1979 as well as observations made before these decreases they obtained regression plots and rigidity dependence of a flux ratio for the short and long term modulations.

One more example relates to the Aragats Space Environmental Center (ASEC) monitors. Arakelyan et al. (2005) built a table of correlation coefficients between changing fluxes of charged particles registered by ASEC monitors including the Nor-Amberd multidirectional muon monitor during a FD event 2005/135. They found that values of the correlation coefficients lie between 0.83 and 1, which demonstrates coherent operation of ASEC monitors (see also Section 4 for a more detailed discussion).

All the studies mentioned above show that the FD amplitude depends on CR particle rigidity. This is explained by a mass-spectrometer like effect of the diffusion coefficient on CRs propagation, which in turn depends on the spectral density of IMF turbulence during a FD event (Alania and Wawrzynczak, 2008). Thus the rigidity dependence of FD amplitude is related to fundamental properties of the solar wind and IMF, which are important for space weather and astrophysical applications (Dorman, 2012).

In studies of a dependence of FD amplitude on particle rigidity, it is commonly approximated by a power function (e.g., Lockwood et al., 1991; Barbashina et al., 2009b). We briefly mention some particular results obtained under this assumption. Lockwood et al. (1991) used data from different particle detectors. They correlated the daily average count rates of the Tokyo neutron monitor and IMP 8 spacecraft channels to the Mt. Washington neutron monitor rate for three large FD events which occurred in 1980-s. The authors fitted a dependence of FD magnitude on rigidity by considering two types of dependence of the modulation function on rigidity, namely, as a power function and as a superposition of exponential and power functions (for details see Section 6). They found good agreement between these two models in the rigidity range $2.5\ \text{GV} < R < 10\ \text{GV}$. Cane (2000), describing general characteristic of FD events, pointed out a range for values of the power index as 0.4÷1.2. This range, particularly, is consistent with the results obtained by Sakakibara et al. (1985) who classified FD events into hard and soft groups according to a value of FD amplitude and found the values of the exponent in a power-like differential spectrum variation for these groups as 0.98 and 1.26 respectively. Similar results were also obtained by Kojima et al. (2013). Using data from neutron monitors and a muon telescope they found values of the power index as 0.65 and 1.26 corresponding to these two data sets. The authors made a plot of the rigidity dependence of FD amplitude which had a gap in the rigidities between the upper limit of the neutron monitors and the lower limit of the muon telescope. Also, Barbashina et al. (2009b) studied a dependence of FD amplitude on median energy of CR particles using measurements from muon hodoscopes for different zenith angle bands. They also assumed a power law for this dependence and found that larger FD events were characterized by smaller power indices.

In this paper we analyze large FD events using data from 17 viewing channels of the Nagoya muon telescope (MT). Different channels have different response functions and in fact may be considered as different instruments which record CR intensity. For analysis of these data we introduce in Section 3 an analysis technique based on a phase diagram for the different channels of telescope. Although this appears to be a new technique for muon telescope measurements, it has much similarity to the regression analysis used by Van Hollebeke et al. (1973), Evenson and Meyer (1981), and Lockwood et al. (1991). Phase diagrams show some new characteristics of FDs and make some of the data analysis less susceptible to the noise in the data. Section 2 describes a selection of the events. The rest of the paper is devoted to analysis of phase diagrams and modeling rigidity dependence of FD amplitude. Finally, our findings and results are summarized in the conclusions.

2. Selection of events

In this paper we consider data recorded by Nagoya MT from 1998 to 2005, which corresponds to the time period including the solar maximum in 2000. Nagoya MT is a part of Global Muon Detector Network (GMDN) providing real time data generation for space weather monitoring using ground-based muon detectors (Okazaki et al., 2008). Nagoya MT is located at 77 m above the sea level with geographical coordinates 35°09′N, 136°58′E (STEL, 2014 website) and has17 channels listed in Table A1 in Appendix. Particularly, for each channel the table lists the average counting rate N_0, statistical mean error of measurements σ and the cutoff, median and effective rigidities defined below. Symbol 'V' refers to the vertical component, 'N30' denotes the direction pointing toward the north with zenith angle 30° and so on. We note that $\sigma = 100\,\%{\cdot}N_0^{-1/2}$ (Dorman, 1974), and larger average counting rates for a channel correspond to more statistically significant measurements. Specifically, Table A1 clearly shows that channels with a larger zenith angle are less statistically significant so that the vertical channel is the most statistically significant.

Different channels of a muon telescope have different cutoff rigidities, therefore this instrument provides more detailed information about CR fluxes than an omnidirectional neutron monitor. In addition to the cut-off rigidity, two more