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Experimental data and analysis of the October 2003 Forbush decrease

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Abstract

On October 28, 2003 an Earthward-directed coronal mass ejection (CME) was observed from SOHO/LASCO imagery in conjunction with an X17 solar flare. The CME, traveling at nearly 2000 km/s, impacted the Earth on October 29, 2003 causing ground-based particle detectors to register a counting rate drop known as a Forbush decrease. The CME was not only responsible for affecting the rate of cosmic rays, but also caused anisotropies in their direction of incidence. Data from Project GRAND, an array of proportional wire chambers which detects secondary muons, are presented during the time of this Forbush decrease.

Keywords: Forbush decrease; Muons; Space weather

1. Introduction

In 1942, Scott Forbush first noticed strong short-term increases of the cosmic ray background in his ionization chambers. It was not until after the end of World War II that he was able to correlate his data with radio and solar flare data (Forbush, 1946) and became the first scientist to associate a ground level particle event with a solar flare (Shea and Smart, 1985). During his research, Forbush would also occasionally observe large, protracted decreases in the background cosmic ray rate. In time, these decreases were known to be related to coronal mass ejections and came to be called Forbush decreases in recognition of Forbush's work (Forbush, 1957). Today, a Forbush decrease refers to an event where the cosmic ray counting rate experiences a sudden decrease (typically around several percent for neutron monitors (Usoskin et al., 2008) depending on the cosmic ray cutoff rigidity at their geomagnetic location), reaches maximum depression within a day, and then has a more gradual recovery. The relationship between neutron monitor counting rates and solar ejecta has been known for some time (Cane, 1993; Cane et al., 1994, 1996).

In late October of 2003 the Earth experienced an extraordinary amount of solar and geomagnetic activity originating from solar region NOAA 10486, including an X17 flare which was one of the largest solar flares since 1976 (IPS, 2003). This flare was detected beginning at 9:51 UT on October 28, 2003 (day 301) and had an X-ray peak in the 1–8 Å band at 11:10 UT the same day. This flare had an associated CME with a transit time from the Sun to the Earth of only 19 h, making it one of the fastest on record. The shock from the CME impacted the Earth's magnetic field as a strong sudden impulse (an abrupt increase in the horizontal component of the geomagnetic field) at 6:13 UT on October 29, 2003 (day 302) (NOAA/SEC, 2003). This CME caused a drop in the counting rate of ground-based cosmic ray detectors. The counting rate for neutron monitor stations remained suppressed for roughly 12 days after the impact of the shock.

2. Project GRAND

Project GRAND (Poirier et al., 2003) is a secondary muon detection array of proportional wire chambers located at 41.7° N and 86.2° W at an elevation of 220 m above sea level. GRAND is maximally sensitive to vertically incident protons with a median energy of 52 GeV,

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higher than that for neutron monitors (see, for instance, Table 1 reported by Storini and Laurenza (2003)). This allows GRAND to complement neutron monitor data by studying higher energy effects. GRAND has an average angular resolution of 0.26° on each of two projected planes for incoming muon tracks. The angular resolution, primary energy sensitivity, and large detector area of this experiment ($82\ m^2$) make it an excellent instrument to study Forbush decreases. Secondary muon data obtained by GRAND during the time of the October 29 Forbush decrease are discussed.

Project GRAND consists of 64 proportional wire chamber stations arrayed in an 8×8 grid over a 100×100 m field. Each station is housed in a wooden enclosure 2.4 m long × 2.4 m wide × 1.5 m high with a thin, homogeneous roof and is separated from adjacent stations by a distance of 14 m.

Each station is comprised of four pairs of proportional wire chamber (PWC) planes. The chambers in the array require a slow flow rate of a gas mixture of 80% argon and 20% CO_2. Each pair of planes is an x and a y plane with the top (x) plane oriented with wires in the north–south direction and the bottom (y) plane oriented with wires in the east–west direction to an accuracy of ±0.05°. Each plane contains an active area of $1.29\ m^2$. The center of each pair of planes is situated 200 mm above the next pair's center. A 50 mm steel plate is placed above the bottom pair of planes which allows the identification of muons. Electrons and hadrons are stopped, scattered, or showered due to the steel. Muon tracks, on the other hand, are able to penetrate the steel plate ($40\ g/cm^2 = 2.9$ radiation length) without scattering or stopping 96% of the time. For vertical muons, the energy required to traverse the steel is 0.1 GeV and increases by $1/\cos\theta$, where θ is the angle from vertical (for the maximum detection $\theta = 62°$, this increases to ~0.2). Electrons are stopped 85% of the time and scatter 11% of the time which leaves 4% of the time where electrons will be misidentified as muons. Muon-electron scattering in the steel causes muons to be misidentified as electron 4% of the time.

Each proportional wire chamber consists of 80 detection cells each 14 mm wide, 20 mm high, and 1250 mm long. The total width and length of the PWC planes together with the vertical separation between the top and the bottom planes produces a projected angle sensitivity cutoff at 63° from vertical. Since GRAND cannot be aimed or pointed, this is a hard limit on GRAND's viewing capabilities. In addition, GRAND has nonuniform sensitivity to the entire sky; it is more sensitive to cosmic rays arriving from near the zenith. A simplified expression for the GRAND's geometrical acceptance depends on the track angle and is given by

$$\text{Acceptance} = [1 - 0.537 \tan\theta_x][1 - 0.537 \tan\theta_y]\cos\theta \quad (1)$$

where the angle θ is the angle of the track from vertical. The angles θ_x and θ_y are the projections of θ on the xz and yz planes, respectively. The above equation combines two geometrical factors and a factor of $\cos\theta$ for the projection of the muons onto the horizontal direction. The geometrical factors arise from the arrangement of the proportional wire planes above one another and the requirement that a track pass through both the top and bottom planes in both projections.

The Monte-Carlo program FLUKA (Fassò et al., 2000a,b) was used to simulate primary protons in the atmosphere for energies of interest (1–3000 GeV). The results of these simulations were originally shown in Poirier and D'Andrea (2002) for primary protons and Poirier et al. (2002) for primary gamma rays. The results of the number of muons reaching ground level per incident proton of a given primary energy are shown in Fig. 1. Protons were used for this simulation because the majority of the primaries which generate ground level muon counting rates are protons.

The response of GRAND to background cosmic rays can be determined by using the results from the FLUKA simulation and folding it with the cosmic ray spectrum at those angles. A primary spectrum shape of

$$\frac{dN}{dE} \propto (E + 0.89)^{-2.75} \quad (2)$$

was used (Fujimoto et al., 1978) where E is the primary kinetic energy in GeV. The shape of the spectrum given by this equation is somewhat rough for energies below approximately 10–20 GeV, but is acceptable for the primary energies observed by GRAND. Folding the above galactic cosmic ray spectrum with GRAND's response function in Fig. 1 yields the response to galactic cosmic rays as a function of primary kinetic energy in GeV shown in Fig. 2 yielding a median response of 52 GeV kinetic energy for vertically incident protons; a somewhat harder galactic cosmic ray spectrum of primaries for this epoch would yield a slightly higher value. Further information

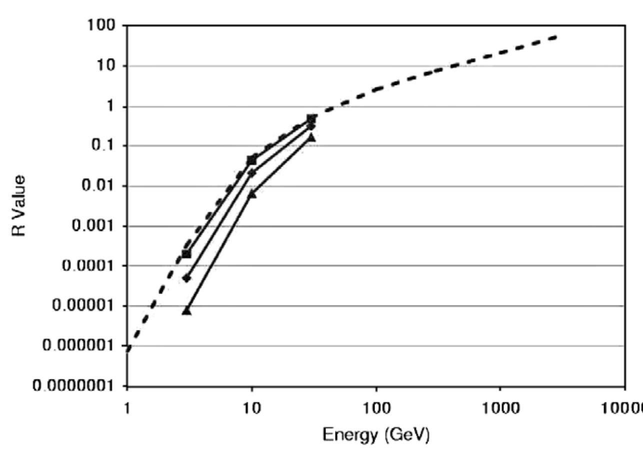

Fig. 1. Results from primary protons simulated by the FLUKA Monte-Carlo code. The R-value is the number of muons reaching ground level, on average, from a primary proton with the given energy. The dashed line represents vertically incident particles while the solid lines below the dashed represent (from top to bottom) 13°, 26°, and 39° inclination from vertical.