A Study of Project GRAND

and the Forbush Decrease of 16-17 July 2005

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Abstract

Project GRAND detected a small decrease in the muon counting rate below the average background level during the 16-17 July 2005 Forbush decrease (FD) as seen by the Oulu Neutron Monitor, which detects secondary particles at lower primary energies than GRAND. A Forbush decrease refers to a rapid decrease in cosmic ray intensity, where maximum depression is reached within a day, and then has a more gradual recovery time. These events typically follow coronal mass ejections (CME), which are ejections of magnetized plasma from active regions of the Sun. The magnetized plasma propagates through interplanetary space, taking several days to arrive at the Earth. When the magnetic field of the CME gets close enough to the Earth, it can deflect cosmic rays from outside the solar system away from the Earth, thus causing a small but noticeable decrease in rate. The mean angle of incoming muons was compared to GRAND's total counting rate. The mean angle of muons increased in the north and west directions and decreased in the south and east directions during the time of the FD.

Introduction

During 16-17 July 2005, two significant decreases were detected by neutron and muon detectors. This decrease in cosmic ray intensity is known as a Forbush decrease (FD) which typically follows a coronal mass ejection (CME). A CME is an ejection of plasma material from the Sun, consisting of moving particles. These moving charges of the coronal mass create a magnetic field. As the mass travels towards the Earth at a speed of 400-1000 km/s, its magnetic field shadows the Earth. An FD occurs when this magnetic field deflects cosmic rays away from the Earth, thus causing a decrease in the cosmic rays detected. An FD is usually observable by particle detectors on Earth within a few days after a CME. The counting rate typically drops over the course of a few hours and it takes several days for the solar cosmic ray intensity to return to normal.

Project GRAND is an extensive detector array which studies cosmic rays in two energy bands depending on the trigger selected: the primary band, from 30 to 300 GeV (giga or billion electron volts); and secondary band, from 100 to 100,000 TeV (teva or trillion eV) [1]. The geometrical arrangement of detectors allows GRAND to view a portion of the sky ± 63° from its local zenith; therefore, GRAND cannot always collect the data relevant to certain solar activity. A network of muon detectors spaced around the Earth can, however, cover all regions of the sky at any given time. The detectors are most sensitive to particles in the 10 to 500 GeV range, with peak detector sensitivity at 56 GeV. Neutron monitors, e.g. Oulu in Finland, detect particles at much lower energies, around 300 MeV [2].

A careful study of the variations of muon counting rate could help with the understanding of the effects of CMEs as they arrive at the Earth from the Sun. By utilizing the angular data of the incoming muons, it may be possible to obtain additional information regarding the effects of the CME's magnetic field.

Experiment: Project GRAND

Project GRAND (Gamma Ray Astrophysics at Notre Dame) now operates as the world's largest muon detector currently studying solar physics. It is an array of 64 proportional wire stations, aligned in an 8 x 8 grid on a 100m x 100m square field, located north of the University of Notre Dame campus at 86.2°W and 41.7°N, at an altitude of 220m above sea level. Each of the 64 stations contains four proportional wire chamber (PWC) plane pairs, yielding a total active area of 84 m^2 [3]. PWCs are tracking detectors used in cosmic ray research that have the advantage of providing superior angular resolution and instantaneous particle identification. The array runs as two experiments at the same time. One experiment tracks low energy single muon events, and the other experiment records high-energy air showers that occur when multiple tracks are registered in coincidence. These PWC tracking detectors are ideal for studying the highest-energy particles generated by the Sun.

Each PWC plane pair consists of a horizontal plane of signal wires running north-south and another horizontal plane of signal wires running east-west. This paired configuration is known as a chamber. Inside each chamber are 160 wires, 80 wires in each plane, held at 2600 V. Each hut contains four chambers and a 50 mm think steel plate between the third and fourth chambers, which helps to identify muons. This configuration allows the incidence angle of a particle in the north-up and east-up projected planes to be measured with an average precision of 0.26° [4]. Muons pass through the plate undeflected 96% of the time, and electrons are stopped, deflected, or shower 96% of the time. A gaseous mixture of 80% Argon and 20% Carbon Dioxide flows through the chambers of each hut. When a charged particle, like a muon, passes through a chamber, the gas is ionized, and it leaves a trail of ions. These ions are accelerated toward the closest signal wire during which they collide with more gas molecules and release more charge. This process is known as gas amplification. A small current is formed on the signal wire that is amplified and this electronic signal denotes the position of the charged particle that passed through the wire.

The atmosphere serves as a natural transducer and amplifier for muon detectors. Cosmic rays collide with air nuclei, creating many secondary particles, such as pions, π^+, π^0, π^-, that share the original energy. The charged pions (π) can decay into muons (μ), π^+ decay into μ^+, π^- decay into μ^-, or the pions can also collide with nuclei in the earth's atmosphere, creating a new generation of more particles that continue the process. Muons of negative or positive electric charge are identical to electrons or positrons, except for the higher mass of the muons, all with spins of ½. Muons have a mass of 105.7 MeV/c^2, a mass roughly 200 times that of an electron, and a mean lifetime of approximately 2.2 μs. Due to their greater mass, muons do not emit as much bremsstrahlung radiation; consequently, they are highly penetrating, much more so than electrons.

Analysis of the Forbush Decrease of 16-17 July 2005

GRAND data from 15 July 2005 at 05:00 UT through 18 July 2005 at 05:00 UT were considered for this study, focusing primarily on the period from 16 July 2005 at 18:00 UT to 17 July 2005 at 9:00 UT. This period is shown by Oulu's neutron monitor in Figure 1 [5]. In order to ensure experimental accuracy, the average counting rate and rms deviation for each hut was calculated. The above time interval was examined in 10-minute intervals for each hour and the muon count for this time interval was examined in one-hour bins. Any huts with a ratio of [*rms* / √(*average*)] greater than 3.40 were excluded in this analysis. These cuts ensured that a sudden drop in any one detector's efficiency could not cause a dip in the muon rate of the combined data. This cut resulted in 19 stations, which exhibited smooth operating conditions for the entire period and were selected for further analysis of the FD.

GRAND's muon data rate for 15-18 July 2005 (day 196-199 from the beginning of the year) is shown in Figure 2. This period in July for GRAND's history as a muon detector was at the start of the system copying data directly onto disk, resulting in some recording gaps in the data. Oulu detects two consecutive Forbush decreases and it takes approximately four days to recover to the original counting rate, as seen in Figure 3 [5]. The first 7% decrease was between 16 July 2005 at 18:00 UT and 17 July 2005 at 2:00 UT. The second 7.5% decrease, missed by GRAND because of a gap in recorded data, was from 12:00 to 22:00 UT on 17 July 2005. GRAND observes a 3% decrease in the count rate. Because Oulu measures secondary neutrons as opposed to muons, its primary energy sensitivity is influenced by different mechanisms producing neutrons rather than muons. In addition, Oulu has a lower geomagnetic cutoff rigidity (0.8 GV) compared to GRAND (1.9 GV). Because of these factors, Oulu is more sensitive to lower energy primaries than muon detectors and therefore can account for its larger drop in count rate [3]. GRAND detects the start of the first decrease at the same time as Oulu, but GRAND detects a longer decrease by seven hours. Additional data following these FDs show that it takes about four days to recover to its original counting rate.

Angular muon information was obtained from 15-17 July 2005. The average angle in the east-up direction and the north-up direction was calculated per one hour bins. The average angles toward the north direction were calculated and are shown in Figure 4 as a function of time during the decrease. The average angles toward the east direction are shown in Figure 5. Since an FD is caused by a large CME which deflects incoming particles when it impacts the Earth, it should be expected that this would cause a deficiency in particles from a particular direction, depending on the magnetic field of the CME. It is seen that there is an increase in the average angle of incoming muons in the north-up plane, and a decrease in the average angle of the east-up plane, giving information about the magnetic field of the CME.

The Naval Research Laboratory (NRL) detected a CME [6]. LASCO and EIT, instruments aboard the SOHO satellite that orbits the Sun, observed an asymmetric Full Halo Event on 14 July 2005. The event was first seen at 10:30 UT as a small brightening that develops as an extremely bright, big, and wide loop front by 10:54 UT. This event develops in the aftermath of a previous big and complex event associated with an M9.1 X-ray flare (peak at 07:25 UT) that was first seen at 6:30 UT. As the two events mentioned above get into close contact, the speed becomes ~ 1430 km/s, showing a marked deceleration of the original event. The Geostationary Satellite Server (GOES) also reported a long duration X1.2 X-ray flare on NOAA AR 10786 between 10:16 and 11:29 UT with peak emission at 10:55 UT [6]. The detection of this particular CME two days before the FD may be the cause of the decrease in counting rate of the ground based cosmic ray detector on 16 July 2005.

Conclusions

Project GRAND sees a Forbush decrease event when examining the secondary muon counting rate at ground level between 16 July 2005 at 18:00 UT and 17 July 2005 at 9:00 UT. The Oulu Neutron Monitor in Finland detects a similar decrease. The differences in the magnitude in the drop between the muon and neutron detectors come from the different mechanisms that produce muons and neutrons, as well as the differences in geomagnetic cutoff rigidity. After a cut was made based on a ratio of [$rms / \sqrt{(average)}$], 19 good huts were left to analyze. GRAND's muon counting rate was examined in one hour bins over a span of three days, from the start of day 196 to the start of day 199, and a decrease was seen during the same time Oulu detected a decrease in cosmic ray intensity. The mean angle of incoming muons in the north-up and east-up projected planes was studied and a deviation in angle was measured during the time of the FD. An increase in the angle measured in the north and west directions was seen as well as a decrease in the angle measured in the south and east directions. The decrease in counting rate is at least partially caused by the magnetic fields of the CME, which would be a natural explanation for this change in angle, as the cosmic rays are deflected as they pass through the magnetic field on their way to the detectors.

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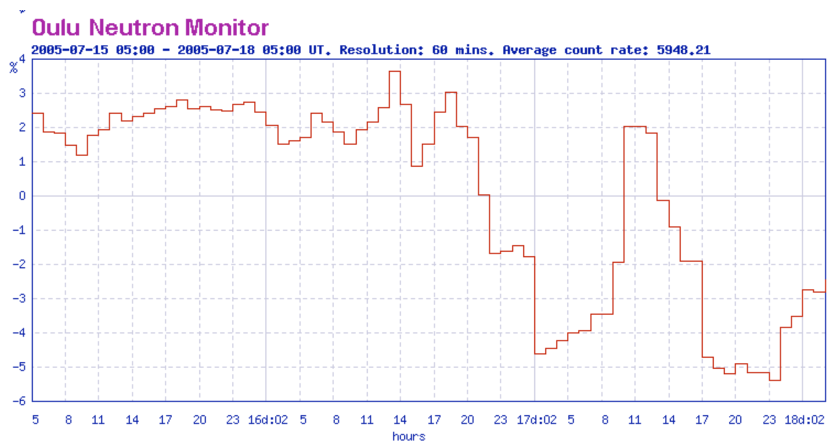

Figure 1: This figure shows Oulu's counting rate from 15 July 2005 at 05:00 UT through 18 July 2005 at 05:00 UT, in one hour bins. Oulu detected an 8% decrease.

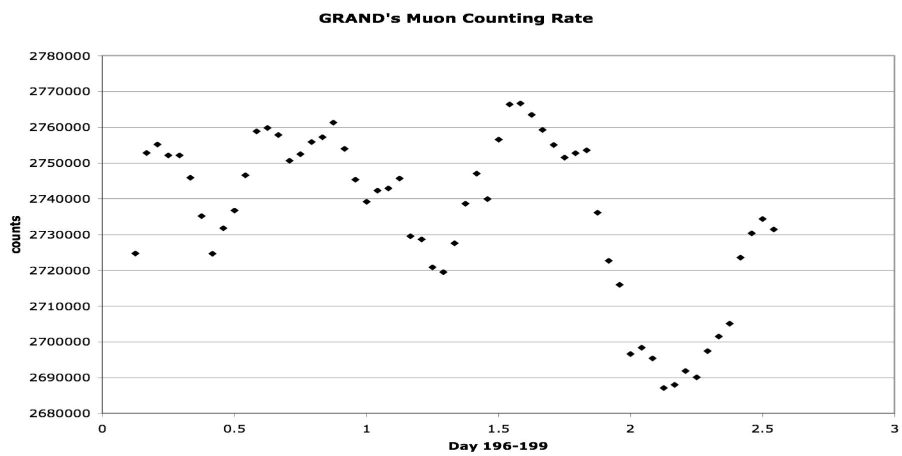

Figure 2: This figure shows GRAND's counting rate for three days from 15 July 2005 (0) at 05:00 UT through 18 July 2005 (3) at 05:00 UT, in one hour bins. GRAND detected a 3% decrease in particles. The suppressed zero emphasizes the structure. The one-sigma error is the height of the diamonds.

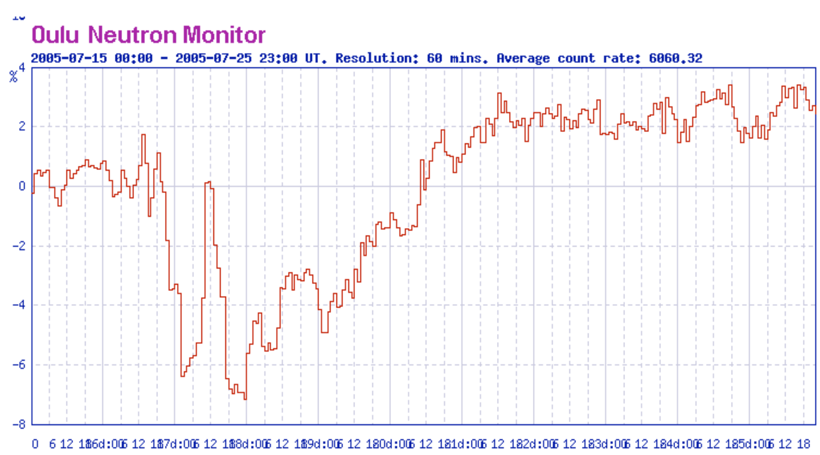

Figure 3: Ten days of Oulu neutron monitor data showing both Forbush decreases from 15 July 2005 at 00:00 UT through 25 July 2005 at 00:00 UT, in one hour bins. Each decrease takes between 8-10 hours and the recovery time takes about four days.

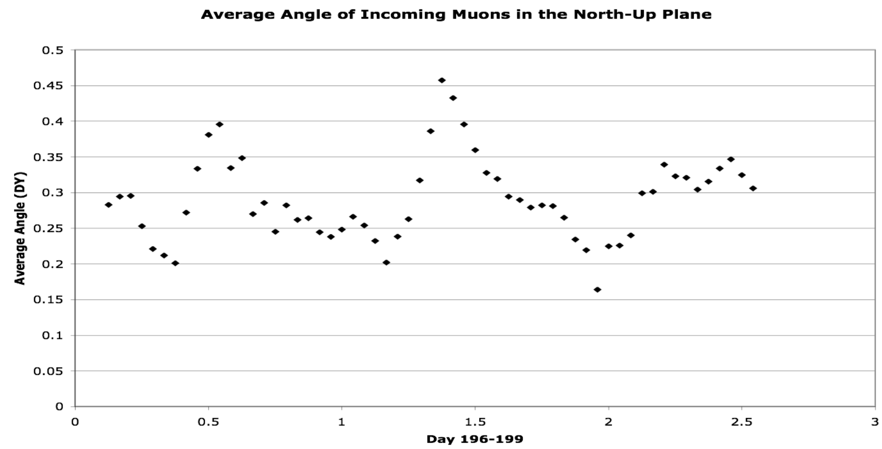

Figure 4: This figure shows the mean angle of incoming muons for three days from 15 July 2005 (0) at 05:00 UT through 18 July 2005 (3) at 05:00 UT in the north-up projected plane, in one hour bins. DY is the difference between the y-cell position in the top and bottom chambers. The vertical span of 0 to 0.5 in the figure corresponds to 0.012°. Note the deviation in average angle for those muons coming from a more northerly direction during the time of the first Forbush decrease.

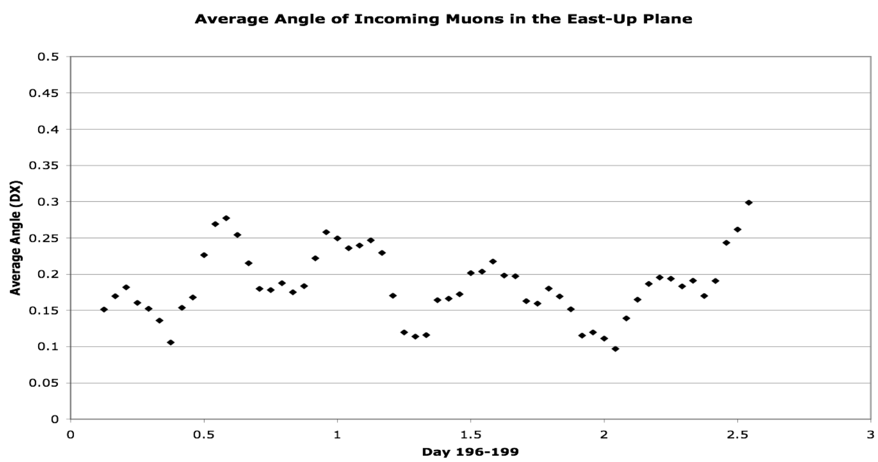

Figure 5: This figure shows the mean angle of incoming muons for three days from 15 July 2005 (0) at 05:00 UT through 18 July 2005 (3) at 05:00 UT in the east-up projected plane, in one hour bins. DX is the difference between the x-cell position in the top and bottom chambers. The vertical span of 0 to 0.5 in the figure corresponds to 0.012°. The mean angle decreases during the FD onset.