A Study of Project GRAND and the GLE of 20 January 2005

Brian Knorr

2008 NSF/REU Program
Physics Department, University of Notre Dame

Partner:
Freddy Martinez

Advisor:
Professor John Poirier

Abstract

Project GRAND detected a short spike (of duration ~6 minutes) in the muon counting rate above the background level during the 20 January 2005 ground level enhancement (GLE). A ground level enhancement is an event in which energetic particles from the sun interact with the earth's atmosphere and create secondary particles which have enough energy to penetrate the atmosphere and be detected at ground level. The statistical significance of this particular event is 19.2σ when muon angles are selected from an elliptical angular region offset slightly from zenith. This angular region is contrasted with that stated in [1] and the data are presented in finer time detail in an effort to make connections to the theory proposed by the authors of [2] and [3].

Introduction

On 20 January 2005, one of the largest GLEs ever recorded was detected by both neutron and muon detectors around the world. The event has since become the subject of intense study. Specifically, the event has been attributed to an X7.1 (7.1 × 10^{-4} W/m^2 of X-Ray flux at the earth [1]) X-Ray flare reported by [4] and a coronal mass ejection (CME) detected by [5]. The former peaked at 7:01 UT after beginning at 6:36 UT while the latter was determined to have originated at 6:54 UT and peaked at 7:10 UT (for protons with energy >100MeV) and 8:10 UT (for protons with energy >10MeV) [1].

Reference [1] reported a 9.9σ signal during the period from 6:51 – 6:57 UT for all angles of the sky and reported that the signal increased to 17.7σ when only muons from a rectangular portion of the sky 28° wide on the E-W axis and 23° long on the N-S axis and centered on 4°E, 1.5°S (measured from zenith) were accepted. These results were determined using data from the 28 detector huts that were left after excluding the contributions of huts with a ratio of $(rms/\sqrt{average})$ greater than 1.10 (for 10-minute bins). However, clearly a method designed to eliminate detectors for which the data varies too quickly will be problematic when the goal of such an experiment is to look for counting rates which change quickly. With this in mind, the present data was achieved by increasing the acceptable ratio of to 2.50. These cuts are less severe than those made by [1] because at the time of its writing, the authors wanted to be absolutely sure that the detector was seeing a real signal and were extremely conservative to that end. Therefore, having confirmed that GRAND indeed saw a real signal, this ratio was increased with the hopes of picking up more statistics and physics, and gaining a more complete view of the event. This provided data from 45 huts to analyze and increased the amount of available data by a factor of 10%.

It has been proposed by [2] and [3] that the GLE of 20 January 2005 is a "defining example" of a flare-induced GLE. Their model, illustrated in Figure 1, suggests that such a GLE will appear as two peaks, the first of which is short-lived and highly anisotropic, meaning that the particles are primarily incident along a particular axis or direction and do not approach from all angles homogenously. They postulate that particles in this first pulse originate from interactions between relativistic protons forced into areas of higher coronal matter density found at lower coronal altitudes. Once in this region, these particles experience extreme, changing magnetic fields which give them enough energy to escape the magnetic loop-structure of a sunspot into the nearby open Parker field lines that constitute the Heliospheric Magnetic Field (HMF), by which they travel to earth largely unscattered. Their early injection into the HMF, gives them a small pitch angle (the angle between the direction that the particle is traveling and the direction of the field), which, along with the lack of scattering, allow them to arrive at Earth anisotropically and with a small spread in velocities. Particles responsible for the second peak are believed to have been accelerated in the regions from 1.2 – 2.9 sun-radii (R_s = 695,500 km) and >6.0R_s by a super-critical shock associated with a coronal mass ejection. Shock acceleration, or Fermi acceleration, is achieved when individual charged particles encounter a moving magnetized plasma and, through "collisionless scattering" of the particle in the magnetic field, the particle absorbs some of the macroscopic kinetic energy of the plasma [6]. These particles enter the HMF much more isotropically at a greater distance from the sun than those responsible for the first peak. This gives them a greater pitch angle and they are therefore more susceptible to scattering and arrive at Earth with less energy.

Project GRAND

Project GRAND (GRAND stands for Gamma Ray Astrophysics at Notre Dame, an outdated acronym as GRAND presently operates as a muon detector) identifies both single muon hits (single tracks) and large air showers (which occur when multiple tracks are registered in coincidence). This paper deals solely with single muon tracks. Muons are produced through interactions between galactic cosmic rays, or energetic particles such as protons or other heavier nuclei from the sun, and earth's atmosphere. These interactions result in the creation of pions, π^+, π^0, and π^-, which decay into muons. Muons are identical to electrons in charge and spin, but have roughly 200 times the mass of an electron, and a lifetime of only 2μs. Because of this extremely short lifetime, muons need to be traveling at relativistic speeds in order to live long enough to reach the ground. This, along with other factors such as air temperature and pressure, and the local geomagnetic field strength, all cost energy, meaning that secondary muons usually need to originate in the atmosphere with energies of ~2.5 GeV in order to reach the ground and be detected by Project GRAND at 220m above sea level. The median energy value of primary particles for which secondary muons are detected is 56 GeV.

The detector itself has an effective area of 84 m^2 and is comprised of an array of proportional wire chambers. Inside each chamber are 80 wires at 2600V. A mixture of 80% Argon and 20% Carbon Dioxide flows through the chambers. When a muon passes through a chamber, the gas is ionized. The charge is then collected by a wire and the computer records the location of the wire. Each of 64 huts, aligned in an 8 x 8 grid on a 100m x 100m square field located at 86.2ºW and 41.7ºN, contains 4 chambers. Inside each chamber is a pair of planes. Each pair has 80 wires in one plane running perpendicular to another 80 wires in the other plane. Between the third and fourth pairs is a 50mm thick steel plate which differentiates between muons, which pass through undeflected 96% of the time, and electrons, which are stopped, deflected, or shower 96% of the time. This configuration allows the incidence angle of a particle in the north-up and east-up projected planes to be calculated with good precision.

Analysis of the GLE of 20 January 2005

Ten-minute counting rates from all 64 huts were analyzed for the period from 5:00:00 UT to 10:00:00 UT excluding the signal region on 20 January 2005. The average counting rate and rms deviation for each hut was calculated. Huts with an average greater than 7000 counts per 10 minutes and a ratio of $(rms/\sqrt{average})$ less than 2.50 were used in this analysis. These cuts were made so that various equipment fluctuations within detectors (such as a loss of efficiency due to weather-related effects) cannot artificially produce a peak in the counting rate. This resulted in an additional 17 good huts over the previous paper, bringing the total to 45.

These additional huts increased the mean of the time-dependent background counting rate from 186000 to 204000 muons per three-minute interval with an rms deviation from the background of 573 counts. The statistical significance of the event increases from 9.9σ as stated in [1] to 10.2σ. Figure 2 shows this data fitted along with the cubic curve to which the background was fitted.

Furthermore, the incidence angles of the muons were studied in a more sophisticated manner. The previous paper [1] looked at a rectangular region of the sky; an approach that inevitably includes in the analysis areas, such as those near the corners, which may not contribute anything to the signal. To eliminate these areas, a circular or elliptical region might be used to fit the data better. After studying the incidence angles of muons during this event, the acceptance window of the sky which delivered the greatest increase in the muon counting rate was determined to be an elliptical region centered on 3°E, 3°N (measured from zenith) with its major axis along the NW-SE direction (rotated -45° with respect to the E-W axis). The major axis spans 40° and minor axis spans 26°.

Figure 3 displays GRAND's counting rate within the elliptical window in three-minute bins for the eight hours from 2:00:00 - 10:00:00 UT surrounding the GLE of 20 January 2005. In determining the background rate, the period from 6:48:00-7:09:00 UT was removed, and the background was fitted with a cubic curve. An rms deviation of 328 muons per bin from the fitted background curve is represented by the error bars shown. For the 6-minute period beginning at 6:51:00 an excess of 8920 ± 464 counts (a 19.2σ statistical significance) above the background curve were recorded. The highest three-minute bin is 7.2% above the background level with 76697 muons. Figure 4 shows the counting rate in one-minute bins for muons incident from the described angular region. Figures 5 and 6 display the same muons in finer time detail (30-second and 15-second bins, respectively). These last two figures hint at the existence of a slight plateau that lasts for ~2 minutes near the peak of the signal, but otherwise show no significant structure to the event.

Reference [2] reported the times at which a signal was first detected and when the maximum(s) occurred for 12 different neutron monitors. Of those, three detectors saw only the first peak and five saw only the second. One detector saw neither peak while the Sanae, Nain, and Fort Smith detectors saw both peaks. Those detectors which saw the first peak show start times between 06:49:45 and 06:52:45 UT. The first peak reached maximum between 06:53:45 and 06:56:15. GRAND detected a signal which began at 06:51:00 ± 15", rose for ~2 minutes, and peaked at 06:53:30 ± 30". Following this peak, the counting rate declined for ~7 minutes, returning to the background level by 07:01:00. The beginning of the signal was determined by the first bin containing at least 10% of the maximum counting rate above the background. The rise time is the amount of time the signal took to increase from 10% to 90% of the maximum counting rate above the background level and the time of decline was calculated the same as the rise time in reverse. The width of the signal at half maximum is 3 minutes. Subsequently, the counting rate remained statistically near the background level and no second peak was detected by GRAND.

Conclusions

In the past, GRAND has proven that it can detect statistically significant GLEs [1], [7]. This allowed a broader definition for selecting reliable detectors, which brought the number of available detectors to 45 for the 20 January 2005 GLE. These additional detectors resulted in the availability of 10% more data for analysis and revealed a signal of 10.2σ statistical significance for the period 06:51-06:57 UT. When an elliptical portion of the sky was studied, the statistical significance of the event rose to 19.2σ. This event, as detected by GRAND, was found in close time association with the first short, anisotropic, harder (more particles per second toward the higher end of the energy spectrum than the average background rate), signal detected by various neutron monitors and summarized in references [2] and [3]. Studying this event in finer time detail revealed a slight plateau near the peak of the event, but overall did not show any particular structure for this GLE. Finally, GRAND did not detect a second peak, which indicates that the particles comprising the second peak seen by other detectors were not energetic enough to result in the interactions which lead to ground level muons detectable by GRAND.

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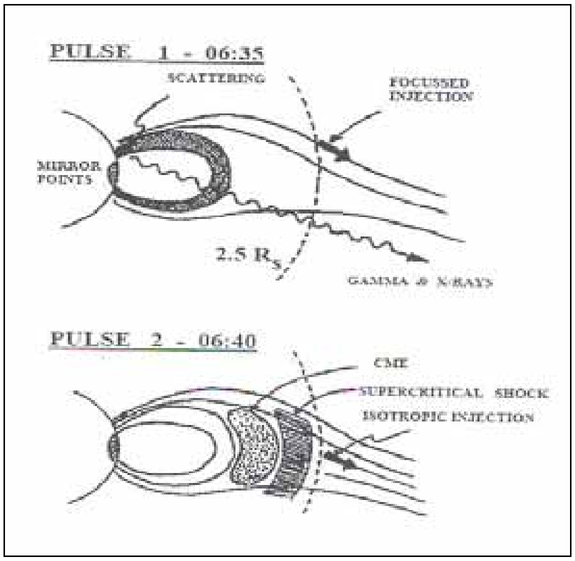

Figure 1: A drawing of the GLE acceleration model proposed by [2] and [3]. Image source: [3]

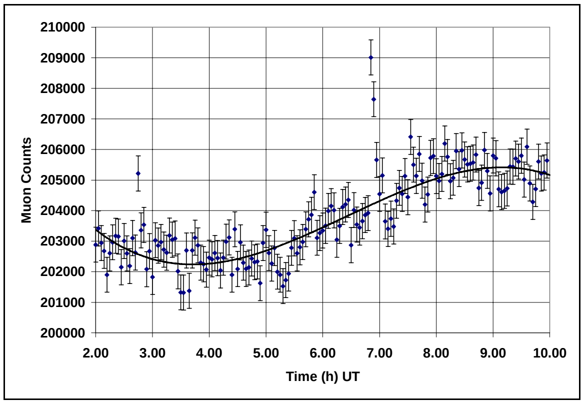

Figure 2: Data showing the counting rate for all angles of the sky in 3-minute intervals. The rms deviation is 573 counts from the background, which was fitted with a cubic curve. Note the single point of 4.6σ statistical significance at 2:45. This point is thought to be the result of a malfunctioning hut. Unfortunately, time did not allow us to further investigate this point. This should certainly be the subject of future work.

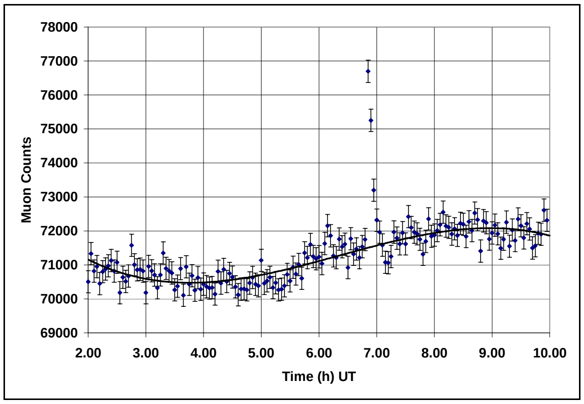

Figure 3: Data showing the counting rate in 3-minute intervals. The error bars represent an rms deviation of 328 counts from the background, which was fitted to a cubic curve and is shown by the solid black line. The elliptical angular cut described above has been applied.

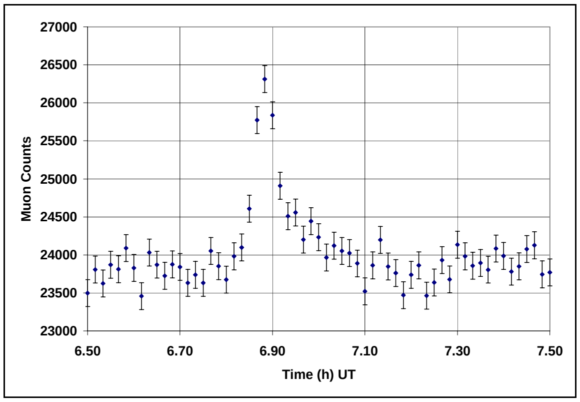

Figure 4: Data showing the counting rate in 1-minute intervals. The rms deviation is 177 counts. The elliptical angular cut described above has been applied.

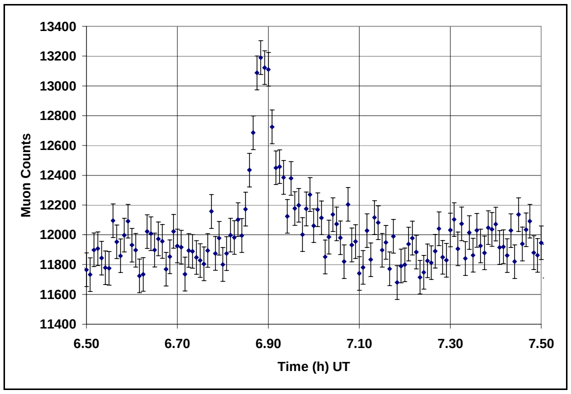

Figure 5: Data showing the counting rate in 30-second intervals. The rms deviation is 113 counts. The elliptical angular cut described above has been applied. Notice the slight plateau near the peak of the signal.

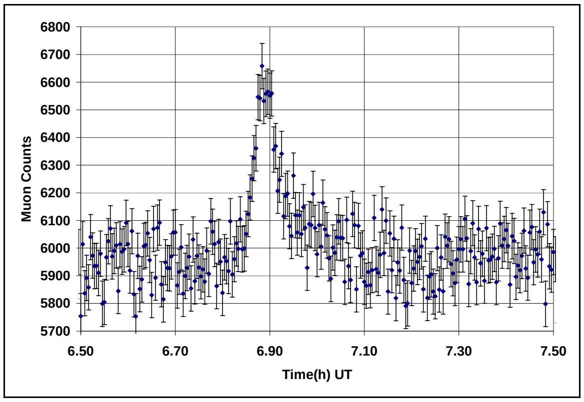

Figure 6: Data showing the muon counting rate in 15-second intervals. The rms deviation is 82 counts. The elliptical angular cut described above has been applied. Notice the slight plateau near the peak of the signal.