1 Introduction

The Amundsen Scott station, located at the geographic South Pole, is arguably the most sensitive surface location on Earth for the detection of solar energetic particles because of the combination of low geomagnetic cutoff and high altitude. Three complementary instruments are now in operation there. IceCube is an array of 162 ice Cherenkov detectors each comprising approximately 2000 kg of clear ice. Each detector is viewed by photomultipliers feeding rate scalers set to different threshold levels, typically counting 1 kilohertz and above. The array of thresholds in principle allows IceTop to determine the energy spectrum of the solar energetic particles. The South Pole neutron monitor, with a long operating history at this location, is a standard 3NM64. Additionally there is an array of bare neutron detectors (without lead shielding) referred to as the Polar Bares. The monitor and bares respond to successively lower energy particles than the Cherenkov detectors, extending the spectral response. In this work we examine the Ground Level Enhancement (GLE) of May 17, 2012, related to an M5.1 solar flare, which was the first GLE in this solar cycle and the first one since December 2006. We estimate the energy spectrum of the solar particles and interpret the result in the context of observations from the global neutron monitor network.

2 GLE Observation from the Neutron Monitor Network

An overview of the GLE as seen in the neutron monitor network is shown in Figure[1]. Onset was around 1:50 UT at Apatity and Oulu, both of which had viewing directions close to the inferred sunward direction of the interplanetary magnetic field (IMF). Mawson, which actually views closer
to the inferred field direction also saw a fast rise however the peak was not clearly observed and intensity was about half of others (8%). It is not unusual to see an offset of the peak fluxes from the inferred field direction. Other stations with less favorable viewing directions saw smaller enhancements as is typical. The South Pole NM64 and Polar Bare increases started a few minutes after Apatity and Oulu and showed a clear pulse like enhancement (≥15%) with a peak just after 2:00 UT even though their viewing direction is more comparable to that of Peawanuck and Nain, which saw relatively small increases. All of those stations see broader enhancements (≥5%) behind the pulse. Other stations see only broad enhancements but with small (≤5%) amplitudes.

### 3 GLE Observation at South Pole

Figure 2 compares the GLE observed at South Pole with data from the GOES-13 spacecraft which had a similar asymptotic direction. IceTop rates are average counting rate of several discriminators. SPE1 and SPE2 are the average of the lower 62 and higher 100 SPE discriminator thresholds respectively, while MPE is the average of all 162 MPE discriminators. We can see that lower threshold discriminators have larger percentage increases. The Bare count discriminators. We can see that lower threshold discriminators have larger percentage increases. The Bare count discriminators have larger percentage increases. The Bare count discriminators with higher base count rates defined as an average count rate from 01:00 to 01:30 UT. Discriminators with higher base count rates have larger percentage increases. The Bare count discriminators with higher base count rates have larger percentage increases. The Bare count discriminators have larger percentage increases. The Bare count discriminators with higher base count rates have larger percentage increases. The Bare count discriminators have larger percentage increases. The Bare count discriminators have larger percentage increases. The Bare count discriminators have larger percentage increases. The Bare count discriminators have larger percentage increases. The Bare count discriminators have larger percentage increases. The Bare count discriminators have larger percentage increases. The Bare count discriminators have larger percentage increases. The Bare count discriminators have larger percentage increases. The Bare count discriminators have larger percentage increases. The Bare count discriminators have larger percentage increases. The Bare count discriminators have larger percentage increases. The Bare count discriminators have larger percentage increases. The Bare count discriminators have larger percentage increases. The Bare count discriminators have larger percentage increases. The Bare count discriminators have larger percentage increases. The Bare count discriminators have larger percentage increases. The Bare count discriminators have larger percentage increases.

### 3.1 NM and Polar Bare Analysis

If we assume that the galactic cosmic ray flux is constant during the baseline interval and throughout the enhancement, the neutron monitor counting rate increase at the location of geomagnetic cut-off rigidity $P_c$ is expressed as

$$\Delta N(P_c) = \int_{P_c}^{\infty} S(P) \cdot J_{sep}(P) dP$$

where $S(P)$ is the NM yield function and $J_{sep}(P)$ is the primary solar energetic particle (SEP) spectrum. By assuming a simple power law SEP spectrum as $J_{sep}(P) = J_0 P^{-\gamma}$, the ratio of rate increases of Bare to NM64 can be expressed as a function of $\gamma$

$$\frac{\Delta N_{\text{Bare}}}{\Delta N_{\text{NM64}}} = \frac{\int_{P_c}^{\infty} S_{\text{Bare}} \cdot P^{-\gamma} dP}{\int_{P_c}^{\infty} S_{\text{NM64}} \cdot P^{-\gamma} dP}$$

Response functions for Bare $S_{\text{Bare}}$ and NM64 $S_{\text{NM64}}$ are determined in [7] from Dorman functions $N(P) = N_0 (1 - \exp(-\alpha P^{-k}))$ which have parameters $N_0=157.68$, $\alpha=7.846$, and $k=0.940$ for Bare, and $N_0=151.67$, $\alpha=8.415$, and $k=0.894$ for NM64.

We then follow [8] to derive the spectrum of the solar particles. Spectral parameters shown in the bottom two panels of Figure 2 are determined every 10 min from 2:00 to 4:30 (points), along with a 15 min average from 02:05 to 02:20 UT for the pulse and a 60 min average from 02:35 to 03:35 UT for the broad enhancement (bars). These averages and time intervals are used in the subsequent comparison with IceTop. We derive a somewhat harder spectrum for the pulse ($J_{sep}(P) = 1.14 \cdot P^{-1.3} (\text{cm}^2 \cdot \text{s} \cdot \text{sr} \cdot \text{GV})^{-1}$, P in GV) than for the broad enhancement ($J_{sep}(P) = 0.673 \cdot P^{-4.9} (\text{cm}^2 \cdot \text{s} \cdot \text{sr} \cdot \text{GV})^{-1}$, P in GV).

### 3.2 Spectrum from IceTop

Figure 3 shows the increase in counting rate of individual IceTop discriminators averaged over 15 min from 02:05 to 02:20 UT. These increases are plotted as a function of the base count rates defined as an average count rate from 01:00 to 01:30 UT. Discriminators with higher base count rates (lower threshold settings) have larger increases. In
Figure 2: GLE observation at South Pole and GOES. From top panel, GOES-13 proton channel, IceTop rates, South Pole neutron monitor rates, ratio of Bare/NM64 monitor, estimated parameters of primary spectrum from “Polar Bare” analysis as amplitude J0 and exponent \( \gamma \) of a power law in momentum.

order to derive a spectrum from the counting rates we must determine a separate yield function for each discriminator. The yield functions must minimally take into account the discriminator setting, characteristics of the tank, barometric pressure and snow cover, all on an individual basis.

Determining a complete set of yield functions is a work in progress. We are presently engaged in adapting the extensive simulation apparatus developed to analyze air showers with IceTop [10]. Significant modification is required because the minimum signal accepted in the air shower analysis corresponds to the MPE threshold, approximately 20 photoelectrons, whereas most of the information on solar events comes from signals with amplitudes below this. Simulation of signals above 20 photoelectrons is well developed on an integrated charge basis, whereas at lower levels the shape of the waveform becomes more irregular and the treatment must be on a voltage amplitude basis. In Figure 3, note the rather regular behavior of the increases for base rates below 4 kHz and the markedly different behavior to the right of this. The threshold producing a base rate of 4 kHz is predicted by the integrated charge calibration to correspond to 3 photoelectrons which defined as the half of the maximum value of the charge distribution [10]. Observationally however, 4 kHz is clearly the true single photoelectron threshold. Lower thresholds produce increasing base rates as they go deeper into the electronic noise but the enhancements during the event do not get larger as one photoelectron is the minimum signal that can be generated physically.

Until the more tailored calculations of yield functions are available we must be content to make phenomenological corrections to the data. One such correction is already implicit in Figure 3 where we have corrected all of the data for barometric pressure using multiplicative factors derived for the base rates. We can also easily derive a phenomenological correction of the snow effect to the base counting rate, this time an additive correction. When applied, as in Figure 4, this results in a much more aesthetic ordering of the data. However clear trends remain in the increases related to snow depth, as one might expect. The dashed line in Figure 4 is a calculation of the counting rate enhancements expected in IceTop based on the particle spectrum derived from the neutron monitor data.

At this point we return to the technique employed in our analysis of the 2006 December 13 event [11] where we used generic yield functions (in the sense that they were calculated for nominal tank properties, no snow overburden, and a single barometric pressure) for various discriminator settings from FLUKA simulations [12]. We derive the yield function \( S_i \) for each discriminator \( i \) from its snow corrected base count rate \( N_{i,\text{base}} \) and an assumed galactic cosmic ray spectrum \( J_{\text{gcr}} \) as

\[
N_{i,\text{base}} = \int S_i(P)J_{\text{gcr}}(P)\,dP.
\]

We can then determine the simple power law SEP spectrum \( J_{\text{sep}} \) by using a least squares fitting technique to minimize,

\[
\chi^2 = \sum_i \frac{1}{\sigma_{\Delta N_i}} \left[ \Delta N_i - \int S_i(P)J_{\text{sep}}(P)\,dP \right]^2,
\]

where \( \Delta N_i \) is the rate changes in \( i \)-th discriminator. From the FLUKA simulation 3.6 kHz is the rate at the single photoelectron setting, so we apply the fitting to the discriminators for which the base count rate is lower than that. The solid line in Figure 4 shows the calculated enhancements.

Figure 3: Increase of individual IceTop discriminator counting rates during the pulse above the base count rates (defined as the average count from 01:00 to 01:30 UT). Different colors correspond to different snow overburden.
The basic consistency of the two measurements is similar to the neutron monitor analysis in that it lies below the solid line, from IceTop analysis, is not consistent with the neutron monitor spectrum. This confirms the visual impression from Figure 4, in which the prediction of the IceTop response from the neutron monitor spectrum lies significantly above all of the actual data points. The most probable explanation is that the true spectrum exhibits a major steepening but at a significantly higher energy than might be indicated by the lines in Figure 5, and therefore cannot be adequately represented by a power law in rigidity in either detector. Further progress from this point must await improved calculations of the IceTop yield functions and calculations of the neutron monitor and bare yield functions within the same framework.

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References

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