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GeV Solar Energetic Particle Observation and Search by IceTop from 2011 to 2016

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Only three Ground Level Enhancements (GLEs) produced by GeV-range solar energetic particles have been confirmed in the present solar cycle, and those have been quite small by historical standards. At the same time direct observations of high energy solar particles from spacecraft have become available. The combination of instruments at the Amundsen - Scott Station at the geographic South Pole offers an opportunity to span the two disparate sets of measurements. Operating at high altitude and low geomagnetic cutoff the neutron monitor at Pole has nevertheless traditionally been accepted as making a "ground level" observation. An enhanced array of bare neutron detectors and IceTop (surface ice Cherenkov detectors in the IceCube Neutrino Observatory) in principle allow spectral information to be extracted from events that previously were too small to use geomagnetic techniques to obtain spectra. We report our spectral measurements for the three confirmed GLE and compare them to other available data on these events. We also present preliminary results of an ongoing study of 34 particle events selected to have significant enhancements in the > 100 MeV channel in GOES data in terms of possible detections and sensitivity limits.

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1. Introduction

The only Solar Energetic Particle (SEP) events of relevance to radiation hazards at aircraft altitude are so called Ground Level Enhancements (GLE). GLE can also provide advance warning of lower energy SEP that are primarily responsible for damage to spacecraft [8]. With precision transport modeling [10] it is possible to infer the time profile of acceleration to GeV energies and investigate mean free paths and unusual transport conditions (such as magnetic bottlenecks and loops) in the interplanetary medium [2].

Spaceborne detectors [3, 1] now approach the energy range of ground based detectors. In fact AMS-02 has approximately the same collecting power as the South Pole neutron monitor. It has much better energy and composition sensitivity, but only "looks" in one constantly changing direction at a time. The duration of one orbit is much longer than the timescale of the evolution of anisotropy in a typical solar event. Therefore the network of ground based detectors will remain a vital partner for the life of AMS-02, and will continue observations beyond the planned end of the AMS-02 mission. It is important that systematic investigation of GeV solar particle events remain firmly rooted in this ground based network. Detectors such as IceTop, enhanced neutron detectors at the South Pole [4], and the new neutron monitor at Dome C [9] are important recent additions to this network.

Unfortunately just as these new tools have become available, the number of GLEs during the past solar maximum has been extremely low compared to that in previous solar cycles. Only three GLE have been reported; two are commonly accepted [7, 12] and one is considered problematic [9] because it was not detected by sea level instruments. A question of fundamental importance is whether the paucity of GLEs in the present solar cycle is due to the overall SEP flux of the events, or instead is a spectral effect. To investigate this question we have undertaken to use data from IceTop and from the neutron detectors at the South Pole to understand event systematics. In this paper we discuss our initial event selection and preliminary results. Characterization of the energy spectra and quantitative detection limits are a work in progress.

1.1 IceTop Tanks

IceCube is a cubic-kilometer scale neutrino detector completed in 2010 installed at the geographic South Pole [6]. Reconstruction of the direction, energy and flavor of the neutrinos relies on the optical detection of Cherenkov radiation emitted by charged particles produced in the interactions of neutrinos in the surrounding ice or the nearby bedrock. The Cherenkov light is measured by Digital Optical Modules (DOMs) containing photomultipliers deployed in the ice between depths of 1450 m and 2450 m. IceTop, the surface component of IceCube, is an air shower array with 81 stations. Each station consists of two Cherenkov detector "tanks" which are 2600 kg blocks of clear ice containg standard IceCube DOMs. One DOM in each tank is operated at high gain and the other at low gain in order to extend the dynamic range of the tank. To measure GeV cosmic ray fluxes we use count rates from two discriminators in each high gain DOM, termed SPE (Single Photo Electron) and MPE (Multi Photo Electron). The SPEs are set at selected thresholds ranging between 1 and 20 photoelectrons, while the MPEs are all set near 20 photoelectrons. Changing the discriminator level on a DOM "tunes" the response function of the DOM as illustrated in Figure

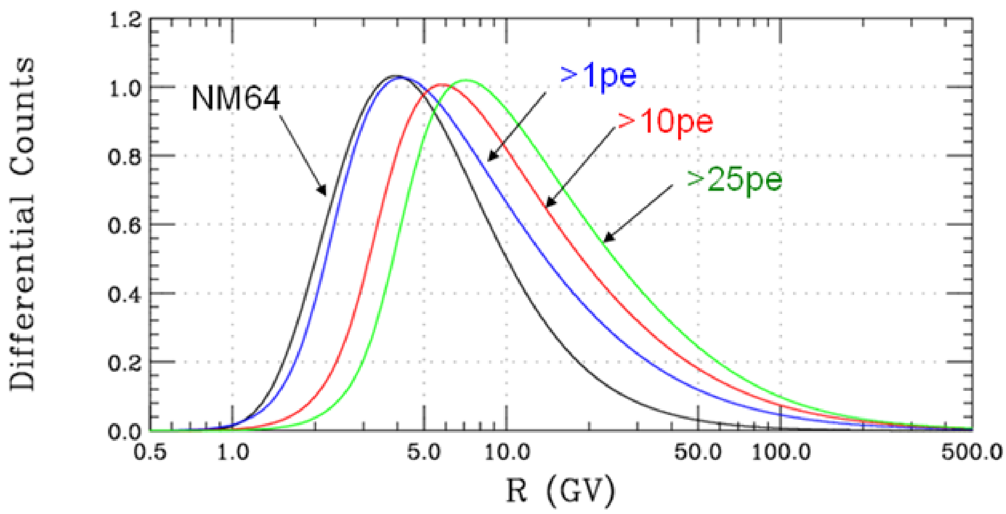

Figure 1: Illustration of response functions of neutron monitor and IceTop tanks for zero GV geomagnetic cutoff and the typical pressure altitude at the South Pole. Calculations were done using FLUKA and GEANT for galactic cosmic ray spectra and composition appropriate to solar minimum modulation conditions.

1. Comparing the counting rates of the various discriminators allows determination of the energy spectrum of the incident particles [7].

1.2 South Pole Neutron Monitor and Polar Bare

There is also a 3NM64 neutron monitor [5] at the South Pole with response (also shown in Figure 1) peaking at lower energy than any of the IceTop thresholds. Lead free neutron detectors at Pole, that we refer to as the "Polar Bares" although a more common name is "Moderated Neutron Detectors" respond to still lower energy [11]. The Bare to Monitor Ratio and the increase in the count rate of either have traditionally been used to identify small GLE [8].

2. Methodology

2.1 GOES Event Selection

In this analysis, we search for GLEs using five years of IceTop and South Pole neutron monitor data. High energy (above 1 GeV) particles responsible for GLEs are almost always part of a steeply falling but continuous spectrum extending to much lower energy. We therefore base our event selection on observations of lower energy protons by the GOES geostationary satellites. We use 5-minute averaged integral proton fluxes for energy thresholds of 10 MeV, 50 MeV, and 100 MeV. We chose events where the peak of GOES >100 MeV proton flux was 0.14 pfu (particle flux unit; 1 particle cm^{-2} $sr^{-1}s^{-1}$) because this selection produced cleanly defined onset times. A total of 34 events were found during 2011 to 2016, as listed in Table 2.1. The three known GLE are highlighted in the table. After the events were chosen based on the peak flux, the onset time was taken as the first measurement clearly above the background. These onset times, as listed in Table 2.1, were used to search for further GLEs that may have escaped independent detection.

YYYY/MM/DD	HH:MM	YYYY/MM/DD	HH:MM	YYYY/MM/DD	HH:MM	YYYY/MM/DD	HH:MM
2011/03/21	03:45	2012/01/27	18:30	2012/09/28	01:15	2014/01/07	19:20
2011/06/07	06:50	2012/03/07	01:30	2013/04/11	07:55	2014/02/20	08:00
2011/08/04	04:20	2012/03/13	17:35	2013/04/24	23:45	2014/02/25	03:30
2011/08/09	08:10	** 2012/05/17 **	01:50	2013/05/22	13:20	2014/04/18	13:20
2011/09/06	03:00	2012/07/07	00:00	2013/09/30	02:30	2014/09/01	21:55
2011/09/06	23:05	2012/07/08	18:00	2013/10/28	18:30	2014/09/10	21:25
2011/09/23	03:20	2012/07/12	17:05	2013/11/02	08:35	** 2015/10/29 **	02:55
2011/11/04	00:05	2012/07/19	06:40	2013/12/28	18:50		
2012/01/23	04:10	2012/07/23	08:30	** 2014/01/06 **	08:00		

Table 1: List of events where greater than 100 MeV protons were clearly detected by the GOES spacecraft. Events previously identified as GLE are indicated with yellow shading and "**". The times given are the onset times used in the analysis.

2.2 IceTop Analysis

Figure 2 shows GLE 71, which occurred on 2012 May 17, as observed by IceTop and the neutron detectors. In the left panel the top traces shows the summed counting rate of the 12 bare neutron detectors and the 3NM64 (kHz). Then there are traces the IceTop DOMs grouped in order of increasing threshold (i.e. decreasing count rate): SPEa, SPEb, SPEc, SPEd, and MPE. These are expressed as the average counting rate per DOM in kHz. The lower panel shows the GOES proton fluxes above three energy thresholds. The steep energy spectrum of the GLE is evident from the pattern of the increases which are quite pronounced at the low thresholds and nearly invisible at the high thresholds.

We use counting rate as a proxy for discriminator setting and also as a simple correction for snow accumulation on the tank. In other words we assume that the reduction in counting rate due to snow accumulation changes the response in the same way as a similar reduction in count rate due to increasing the threshold. This approximation is discussed in more detail by [7] where we also present a preliminary energy spectrum for this event.

In order to conduct a systematic and quantitative search for high energy particles we compare an interval where they might be expected with an immediately preceding interval assumed to contain only background. The dividing line between the two intervals and the length of the intervals were chosen to maximize the visibility of the three established GLE, and then were applied uniformly to the remaining 31 events to conduct the search. The dividing line is always 10 minutes prior to the GOES onset.

Figure 2 shows "base" and "pulse" intervals as well as the GOES onset indicated by the dashed line. We define two statistics, the first is the fractional change of a count rate ratio. For this, both the pulse and base intervals are taken to be 60 minutes. The rate ratio itself, defined by $R_S = (SPEa + SPEb)/(SPEc + SPEd)$, is computed for each minute as shown in the top right panel of Figure 2. For the survey, R_S is averaged over both pulse (R_{SP}) and base (R_{SB}) intervals. The fractional change in the ratio is then $(R_{SP} - R_{SB})/R_{SB}$.

The second statistic is formed from a plot of the fractional change in counting rate of each DOM as a function of the average counting rate of the DOM. This is illustrated in the lower right panel of Figure 2. In this case the averages were taken over 50 minutes. The statistic is the slope of a straight line fit to the distribution, also shown in the figure. (The linear fit appears as a curve on the linear vs. log axes of the figure) Although seemingly closely related, these two statistics are not tightly correlated for background events, as discussed below.

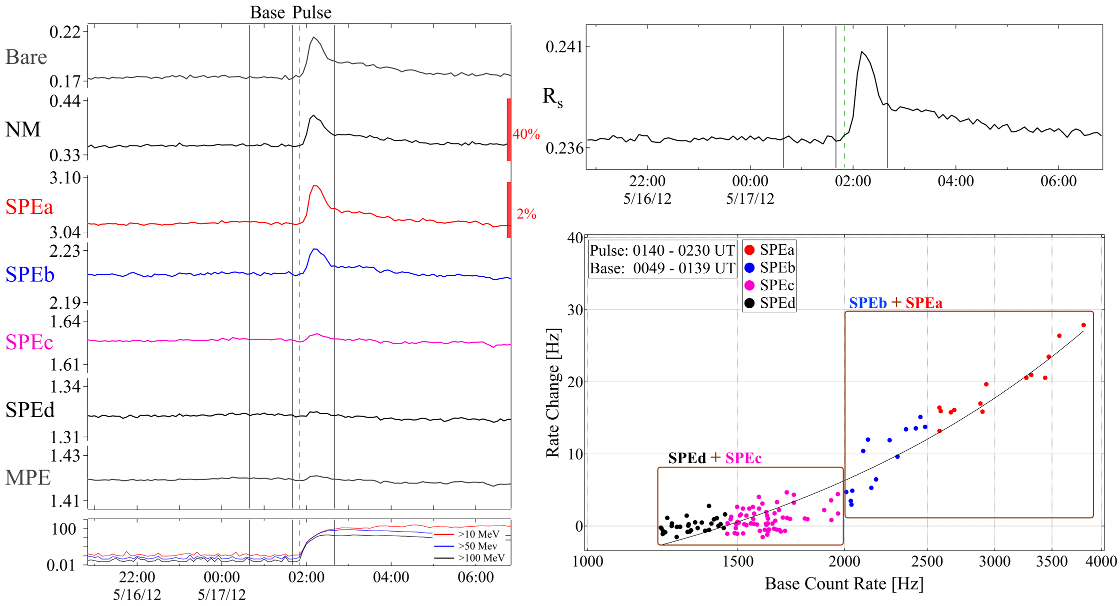

Figure 2: The ground level enhancement (GLE71) on 2012 May 17. Left: Observations at South Pole and GOES Spacecraft. Right Top: Analysis to produce ratio parameter. Right Bottom: Analysis to produce ratio parameter. (Horizontal axis on log scale and vertical axis on linear scale.) See text for details.

2.3 South Pole Neutron Monitor and Polar Bare Analysis

The Polar Bares respond to lower energy particles on average than the NM64. The fractional Bare to Monitor ratio and the fractional increase in the count rate of the monitors form a pair of parameters that have traditionally been used to search for small GLE. We use these two parameters, constructed for the same 60 minute intervals as the IceTop ratio statistic, as an alternate method of searching for small GLE, representative of the traditional approach.

3. Results

Figure 3 compares the IceTop analysis with the neutron monitor analysis as scatter plots of the two parameters defined for each. The May 2012 (GLE71) event stands out clearly. Both the January 2014 (GLE72) and October 2015 (GLE73) events lie outside the cluster near the origin if one considers the joint distribution of both parameters, although there are larger fluctuations in either parameter separately. As noted above, the two parameters are not tightly correlated in cases where there is no clear observation of energetic particles.

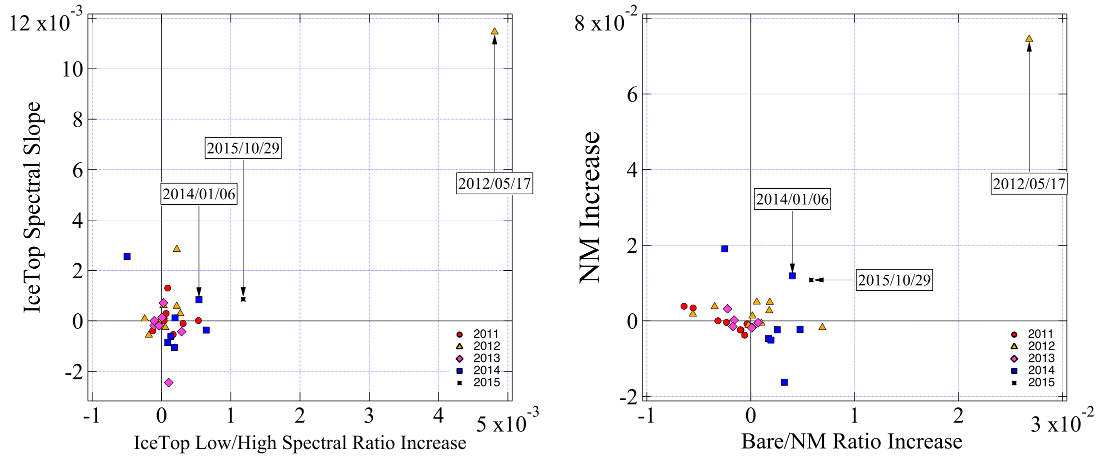

Figure 3: Left: IceTop spectral slope against IceTop spectral ratio. See text for details. Right: Neutron Monitor increase against Bare to Monitor Ratio.

The October 2015 event is barely detected, as the full analysis presented in Figure 4 shows. The identification of this event as GLE73 is supported by the simultaneous detection by the neutron monitor at Dome C in Antarctica [9]. Recognition as GLE73 is in fact debated within the community since it was not detected by any sea level neutron monitors. This therefore probably represents the smallest event that can be detected as a GLE.

Although the two search parameters for IceTop are mostly uncorrelated in the "background" region it is curious that the IceTop spectral ratio parameter clearly has more positive values than negative. It is tempting to speculate that this might indicate the presence of low fluxes of high energy particles as a general feature but we rather think that it is due to some kind of structure in the background.

An example of such a structured background would be the well known Forbush decreases, which have the property that they produce rapid decreases in the counting rate followed by slow increases. The net result is that for intervals chosen at random the count rate is more likely to be increasing rather than decreasing. We would have to investigate whether such an effect might be present in the IceTop ratio before drawing any conclusions. Unfortunately such an investigation is itself not well defined since solar particle events are seldom isolated events. Large events in particular often come in clusters accompanied by major, correlated perturbations of the solar wind.

In this search the monitor data are essentially statistics limited, with the South Pole monitor counting at roughly 300 Hz. In contrast, an IceTop DOM at MPE threshold counts at approximately 1.2 kHz, giving the entire array of 162 tanks at least a factor of ten better statistical accuracy. Unfortunately for this work the increased statistical precision has revealed true fluctuations in the background approximately the same size as the statistical fluctuations in the neutron monitors. Figure 4 shows this clearly, particularly for the higher thresholds where the rates during the pulse interval are clearly *lower* than during the baseline interval. In this case, however, the change in the spectral ratio is still giving a rather clear indication that solar particles are present.

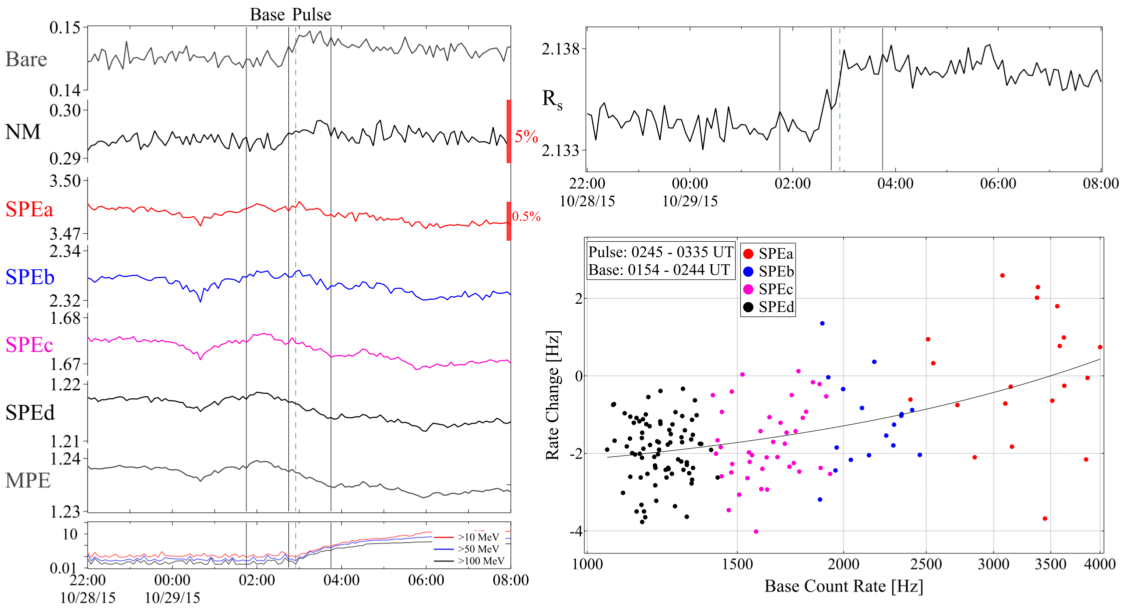

Figure 4: The small ground level enhancement (GLE73) on 2015 October 29.

4. Summary and Conclusions

Our analysis of 34 solar particle events selected for the presence of greater than 100 MeV protons at a GOES spacecraft revealed no definitive GLE other than the ones already known. GLE73, on 2015 October 29 is probably the smallest GLE that could be detected with any degree of certainty. A truly quantitative statement in terms of absolute particle fluxes is not possible because the visibility of the increase depends on the time structure of the event and the asymptotic direction of the detector. IceTop and the Antarctic neutron monitors have similar sensitivity limits for GLE detection although for different reasons. The monitors are statistics limited, but the greater statistical precision of IceTop has revealed true fluctuations in the background approximately the same size as the statistical fluctuations in the neutron monitors. The silver lining to this is that the better statistical accuracy of IceTop will allow a more detailed study of cosmic ray fluctuations, sometimes called “scintillations”, than has previously been possible.

5. Acknowledgements

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References

[1] Adriani, O., G.C. Barbarino, G.A. Bazilevskaya *et al.*, Observations of the 2006 December 13 and 14 solar particle events in the 80 MeV/N Ű 3 GeV/N range from space with the PAMELA detector, *Astrophysical Journal* **742** (2011) 102-112, doi:10.1088/0004-637X/742/2/102.

[2] Bieber, John W., Wolfgang Droege, Paul A. Evenson, Roger Pyle, David Ruffolo, Udomsilp Pinsook, Paisan Tooprakai, Manit Rujiwarodom and Thiranee Khumlumlert, Energetic particle observations during the 2000 July 14 solar event, *Astrophysical Journal* **567** (2002) 622-634.

[3] Bindi, V., Solar energetic particles measured by AMS-02, *International Cosmic Ray Conference 34*, The Hague, Netherlands, (2015) PoS(ICRC2015)108.

[4] Evenson, Paul, John Bieber, John Clem and Roger Pyle, South pole neutron monitor lives again, *International Cosmic Ray Conference 32*, Beijing, (2011).

[5] Hatton, C. J., The Neutron Monitor, *Progress in Elementary Particle and Cosmic Ray Physics* **X** (1971), American Elsevier Publishing Company, New York.

[6] **IceCube** Collaboration, M. G. Aartsen et al., The IceCube Neutrino Observatory: Instrumentation and Online Systems, *JINST* **12** (2017) P03012.

[7] **IceCube** Collaboration, Ground level enhancement of May 17, 2012, observed at South Pole, Paper 0368, *International Cosmic Ray Conference 33*, Rio De Janeiro, (2013).

[8] Oh, S.Y., J.W. Bieber, J. Clem, P. Evenson, R. Pyle, Y. Yi, and Y.K. Kim, South Pole neutron monitor forecasting of solar proton radiation intensity, *Space Weather* **10** (2012), S05004, doi:10.1029/2012SW000795.

[9] Poluianov, Stepan, Ilya Usoskin, Alexander Mishev, Harm Moraal, Helena Krüger, Giampietro Casasanta, Rita Traversi, Roberto Udisti, Mini neutron monitors at concordia research station, Central Antarctica, *J. Astron. Space Sci.* **32(4)** (2015), 281-287 http://dx.doi.org/10.5140/JASS.2015.32.4.281.

[10] Sáiz, Alejandro, Paul Evenson, David Ruffolo, and John W. Bieber, On the estimation of solar energetic particle injection timing from onset times near earth, *Astrophysical Journal* **626** (2005) 1131-1137.

[11] Stoker, P.H., Spectra of solar proton ground level events using neutron monitor and neutron moderated detector recordings, *International Cosmic Ray Conference 19*, La Jolla **4** (1985) 114-117.

[12] Thakur, N., N. Gopalswamy, H. Xie, P. Makela, S. Yashiro1, S. Akiyama, and J. M. Davila, Ground level enhancement in the 2014 january 6 solar energetic particle event, *Astrophysical Journal Letters* **790** (2014) L13-17.