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Heliospheric Physics with IceTop

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Abstract: IceTop is an air shower array now under construction at the South Pole. It is the surface component of IceCube, an observatory primarily focused on cosmic neutrinos. When completed, IceTop will have approximately 500 square meters of collecting area in the form of 160 separate ice Cherenkov detectors. These detectors are sensitive to electrons, photons, muons and neutrons. With the high altitude and low geomagnetic cutoff at the South Pole, IceTop promises to have unprecedented statistical precision, coupled with spectral sensitivity that can be used to observe solar energetic particles and transient phenomena in the flux of galactic cosmic rays. We discuss the potential of IceCube to contribute to heliospheric physics in general, and present a preliminary analysis of a complex interplanetary disturbance that occurred in August of 2006.

Introduction

IceTop is an air shower array now under construction at the South Pole as the surface component of the IceCube neutrino telescope. When completed, IceTop will have approximately 500 square meters of ice Cherenkov collecting area arranged in an array of 80 stations on a 125 m triangular grid. Each station consists of two, two meter diameter tanks filled with ice to a depth of 90 cm. Tanks are instrumented with two Digital Optical Modules (DOM) operated at different gain settings to provide appropriate dynamic range to cover both large and small air showers. Each DOM contains a 10 inch photomultiplier and an advanced readout system capable of returning the full waveform of more complex events. For the present analysis we use two discriminator counting rates recorded in each DOM. For historical reasons, the two discriminators are termed SPE (Single Photo Electron), and MPE (Multi Photo Electron). As used in IceTop the SPE threshold corresponds typically to 10 photoelectrons, and the MPE threshold to 20 photoelectrons.

Due to the high altitude (2835m) and the nearly zero geomagnetic cutoff at the South Pole, secondary particle spectra at "ground" level retain a significant amount of information on the spectra of the primary particles. This is illustrated in Figure 1, which summarizes the result of a FLUKA [4] calculation of the secondary spectra due to galactic cosmic rays at solar maximum (left panel) and a typical solar flare particle event (right panel). Of course the solar spectrum would be superimposed

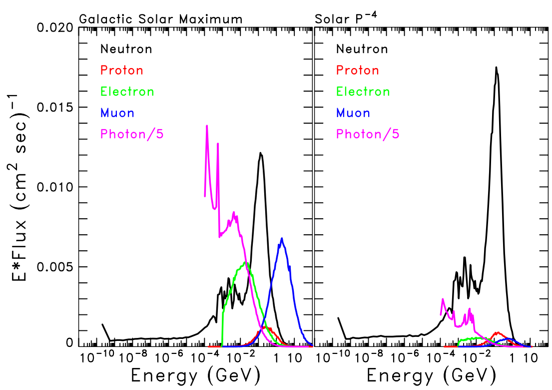

Figure 1: Calculated secondary particle spectra at the South Pole. Left: Galactic solar maximum. Right: Solar flare particle event normalized to produce a doubling of the count rate of a standard (NM64) neutron monitor.

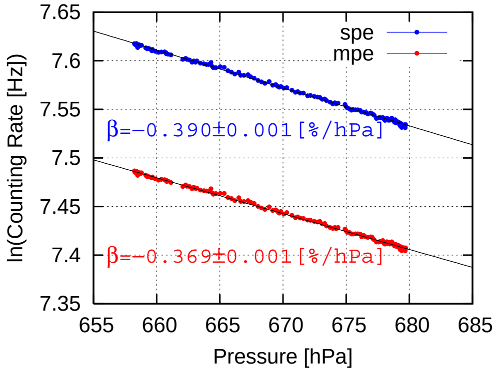

Figure 2: Correlation of scaler rate with pressure for one DOM on October 8-9, 2006.

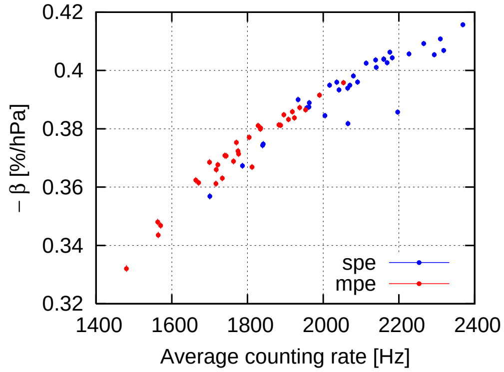

Figure 3: Pressure correction coefficient for all DOM as a function of scaler rate.

on the galactic background. It is beyond the scope of this brief paper to show this in detail, but because the IceTop tanks are thick enough to totally absorb many of the incident particles the signal distribution in the tank contains information on the primary spectrum. More details are provided in a companion paper [2].

Barometer Correction

As with a neutron monitor, the counting rate of an IceTop detector shows a strong dependence on barometric pressure. From simulation and observation, it has been shown that barometric correction coefficients vary with the threshold energy of secondary cosmic rays [7] [3]. The energy sensitivity of IceTop detectors is nicely illustrated by the barometric coefficients we derive for them. By considering time periods in which there appears to be little variation in the primary particle intensity, it is possible to make a phenomenological estimate of the appropriate pressure correction by means of a simple correlation between detector counting rate and barometric pressure. Figure 2 shows this correlation for the two thresholds of an individual DOM. Note in particular the small but significant difference in the slope of the correlation, and hence the derived barometric correction.

In 2006 a total of 32 tanks were operational. Figure 3 shows the derived correction for each DOM (red symbols for the MPE discriminators and blue for the SPE discriminators) plotted as a function of the counting rate of the discriminator. At that time the tanks were all operating at the same nominal setting, but they had not been calibrated, so in fact the discriminators were triggering over a range of physical light levels. The correlation of correction with light level is nearly perfect. Those discriminators with lower counting rates, corresponding to higher light thresholds, have markedly lower barometric corrections. This is just what is expected since these signals should result preferentially from higher energy primaries. We are in the process of trying to use this information, plus simulations and calculations, to establish an energy response function for the tanks. For the remainder of this paper we rely on the approximate response functions derived from the FLUKA calculation that produced the plots shown in Figure 1.

Heliospheric Event

In Figure 4 we show several data sets characterizing a heliospheric event in August 2006. The IceTop measurements are shown in the second panel. We have averaged the SPE (blue) and MPE (red) counting rates for all 32 DOM, after individually applying the barometric corrections described in the previous section. Ten minute averages are shown, all expressed as percent changes relative to the normalization interval on August 17 prior to the first decrease. For comparison the top panel shows the similarly treated counting rate of the McMurdo neutron monitor. While the event is gen-

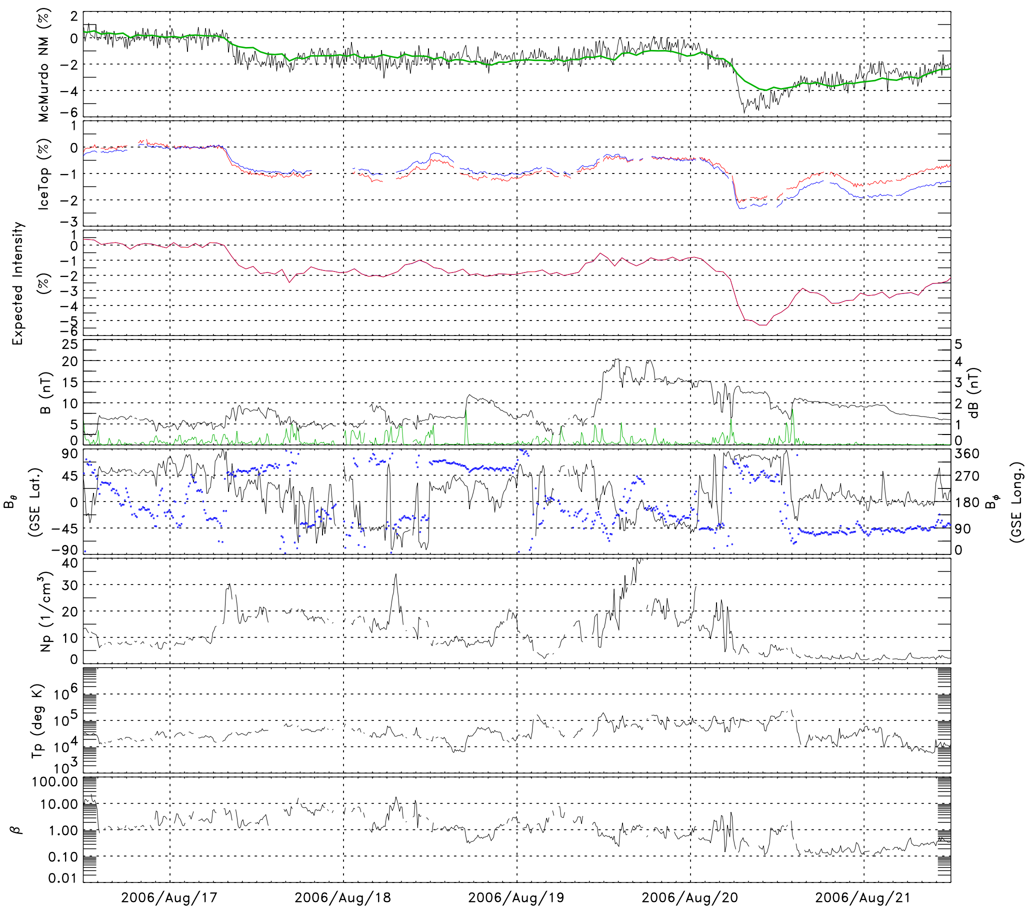

Figure 4: August 17-21, 2006. From top: (1) McMurdo monitor (black) and Spaceship Earth isotropic component (green). (2) IceTop SPE (blue) and MPE (red) scaler rate, 32 DOM average. (3) IceTop model prediction. (4) Interplanetary magnetic field magnitude (black) and derivative (green). (5) Field direction latitude (black) and longitude (blue). (6) Plasma density. (7) Plasma temperature. (8) Plasma β.

erally similar in the two detectors, the remarkably better counting statistics of IceTop stand out. In IceTop the total counting rate for the SPE channel is $\sim$64 kHz (2 kHz from each DOM), while the total counting rate of the 18NM64 McMurdo neutron monitor is $\sim$0.3 kHz [1].

From McMurdo alone, one might characterize this event as a double Forbush decrease [5]. Both decreases are associated with structures in what is evidently an interplanetary coronal mass ejection (ICME) containing at least one shock and multiple regions with different magnetic field and plasma parameters. However in IceTop the two decreases appear quite different. The second fits the conventional pattern in which the magnitude tends to scale inversely with primary rigidity [6]. Note that the decrease is consistently larger in low threshold SPE channel than high threshold MPE, and also that the higher rigidity particles tend to recover more rapidly.

In contrast, during the first decrease the higher energy channel shows a (slightly) larger deviation. There is also an intriguing feature in the IceTop data on August 18, near the time of a large change in the interplanetary magnetic field direction, that is not observed in the McMurdo neutron monitor. The *Spaceship Earth* neutron monitor network [1] measures a significant anisotropy during the event, which we can model as a dipole anisotropy with a time variable magnitude and direction superimposed on a time varying isotropic cosmic ray flux. The isotropic component of our model fit is shown as the green curve superimposed on the McMurdo data in Figure 4. The deviations of the McMurdo data from this line can only result from anisotropy since the Spaceship Earth stations have well matched energy response. Because IceTop has inherent spectral resolution it is possible for anisotropy to produce an apparent spectral feature. Even though the low and high rigidity channels of IceTop are derived from the same physical detector, the low and high rigidity particles will come from somewhat different asymptotic directions.

Using calculated response functions appropriate to the different discriminator levels, and asymptotic directions calculated as a function of rigidity, it is straightforward to convolute the two to make a specific prediction for IceTop. The third panel of Figure 4 gives the result of such a calculation under the simplest possible assumption, anisotropy independent of energy. We have used response functions that predict the observed counting rate corresponding to thresholds of ten photoelectrons (blue curve) and fifty photoelectrons (red curve). On the scale at which the figure is reproduced it is not possible to see the small difference in the curves. Our conclusion is that the observed splitting of the red and blue curves in the second panel results from spectral variation. We note that the overall time structure of IceTop data, and in particular the marked difference from McMurdo, is consistent with the dipole model derived from *Spaceship Earth*. The amplitude predicted for IceTop is understandably too large, particularly in the second decrease, because at these discriminator thresholds IceTop is observing at a higher average energy. Although IceTop is geographically further south than McMurdo, it is magnetically further north. Thus McMurdo looks nearly perpendicular to the ecliptic, whereas Pole has a mid latitude viewing direction.

The high statistical precision of IceTop may translate even small anisotropy into apparent spectral variation, and this must be taken into account in the analysis of interplanetary events. However there is no indication that the feature on August 18 results from such an effect. It is not clear at this time just what aspect of the complicated plasma and magnetic field structure at the time is responsible for the unusual spectral variation of the high energy cosmic rays. What is clear is that the high time resolution and energy resolution provided by IceTop will usher in a new era in the study of the propagation of GeV particles in the heliosphere.

Acknowledgements

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