Search for Prompt Neutrino Emission from Gamma Ray Bursts with IceCube

The IceCube Collaboration

Abstract: IceCube is the first neutrino telescope with TeV-PeV sensitivity sufficient to constrain the prompt neutrino flux from Gamma Ray Bursts (GRBs). Limits based on data from the 40- and 59-string partially completed detector configurations have been published previously. Much of the parameter space for the previous generation of neutrino fluence models was excluded, which has encouraged continued theoretical work on more precise GRB fireball particle physics calculations. With data from the first year of the completed 86-string detector, plus one year of the 79-string partial detector, our analysis is now more sensitive to prompt neutrino emission from GRBs by more than a factor of 2. We present results from analysis of the latest data set as well as combined results including data from the 40- and 59-string partial detector configurations.

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1 Introduction

Very energetic astrophysical events are required to accelerate cosmic rays to above $10^{18}$ eV. Gamma Ray Bursts (GRBs) have been proposed as source candidates because of the enormous energy these events release in very little time in gamma rays: $\sim 10^{51} - 10^{54}$ erg/Ω/4π, where Ω is the solid angle of a possible beamed emission. If neutrinos are present in the acceleration engine, and if they are accelerated with similar efficiency to electrons, then GRBs could account for the observed ultra high energy cosmic rays. It is very difficult to correlate cosmic rays directly to GRBs (or other sources). Because they are charged, and they therefore travel in curved paths through galactic and intergalactic magnetic fields, information about the source location and time is lost. However, if high energy protons are present in the acceleration engine, then interactions such as $p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+$ would take place. Cosmic rays could escape the acceleration region as neutrons or possibly protons, and high-energy muon and electron neutrinos would be produced by the decay of charged pions. An observation of neutrinos coincident with GRBs in time and direction would confirm the presence of high energy protons in the source, thereby lending support to the hypothesis that GRBs produce high energy cosmic rays.

IceCube has previously published limits which constrain models that normalize the GRB neutrino fluence with the assumption that the entire cosmic ray flux at the highest energies is due to neutrons accelerated in GRBs. IceCube has also published limits which constrain models that derive a neutrino fluence prediction from the observed gamma ray fluence, but using some approximations which break down at next-to-leading order. In this contribution, we update these limits using four years of IceCube data. For models based on the gamma ray fluence, we also update the model prediction, using numerical simulation of the GRB fireball particle physics to account for all relevant standard model processes.

2 IceCube

IceCube is a km$^3$-scale neutrino detector deployed deep in the South Polar ice cap. Construction of the detector was completed in December, 2010. IceCube detects Cherenkov light emitted by energetic charged particles produced in neutrino-nucleon interactions in the ice. The finished detector consists of 5160 optical modules (DOMs), with 60 optical modules placed on each of the 86 strings. Construction was performed during southern summers; each year during the construction process, a new set of strings was commissioned for data taking. The results presented here were obtained with three years of data with 40, 59, and 79 string partially completed detector configurations, as well as one year of data using the completed detector.

3 Event Reconstruction

IceCube’s astrophysical neutrino sensitivity varies with neutrino flavor, energy, and declination due to event topology and relevant backgrounds. For this analysis we focus on the promising upgoing νμ channel, which allows us to use both time and space correlation with GRBs. Product muons can travel long distances through the ice, providing high detection efficiency and good angular resolution which both improve with increasing neutrino energy. The energy of a muon neutrino may also be estimated, although resolution worsens with neutrino energy because an increasing fraction of product muon energy is deposited outside of the instrumented volume. A high purity sample (consisting of muons which really are produced by neutrinos interacting in the ice) may be obtained for upgoing events because an upgoing muon can only be produced by an upgoing neutrino interacting in the ice after passing through the Earth. For this analysis, we set the horizon at declination $-5^\circ$.

1. We define fluence as the number of events arriving from a source per detection area. Fluence is the time integral of flux.
between 0 and $-5^\circ$, the ice cap itself provides sufficient overburden to attenuate the cosmic ray muon background.

Muon events in IceCube are reconstructed by using a maximum likelihood method [5] to fit the spatial and temporal Cherenkov light detection pattern observed by the DOMs. IceCube is sensitive to muons with sufficiently high energy that the interaction frame is tightly boosted with respect to the detector frame, so that the muon is nearly collinear with the neutrino. The angular resolution is $1^\circ$ for neutrino energy of 3 TeV; for energies above 1 PeV, the resolution is $0.5^\circ$. Muon energy is reconstructed by measuring the charge collected by the DOMs as the muon traverses the detector. For an $E^{-2}$ spectrum, the median energy error is a factor of 4, with 90% of events having true energies between 800 GeV and 1.4 PeV. Much better resolution is possible for analyses requiring the interaction vertex to be within the instrumented volume. All resolution estimates are based on simulation.

## 4 Event Selection

In this analysis, the primary background consists of down-going cosmic ray muons, which trigger the detector at a rate of 2 kHz. A large fraction of these events are correctly reconstructed as down-going, and they are easily excluded from this analysis. The primary remaining backgrounds are (1) muons passing near the boundary of the instrumented volume and emitting light upwards, and (2) independent muons traversing the detector at the same time. These backgrounds may be separated from true upgoing muon events based on fit quality, fit stability and event topology parameters. The remaining sample consists primarily of atmospheric neutrino events from the northern hemisphere. For this analysis, atmospheric neutrinos constitute an irreducible background which can only be separated from astrophysical neutrinos probabilistically based on reconstructed energy and correlation with a GRB.

The results presented here were obtained by combining different event selections optimized separately for multiple detector configurations as the detector was constructed. For the 40 string configuration, a simple set of cuts was used to select events which performed well on several quality criteria. For the 59, 79 and 86 string configurations, Boosted Decision Tree forests (BDTs) were trained using well-reconstructed simulated neutrino events as signal and off-time data (not within ±2 hours of a GRB) as background. For well-reconstructed events, the $E^{-2}$ efficiency is >80% with respect to trigger level, with a data rate of <4 mHz.

## 5 GRB Selection

Between 2008-04-05 and 2012-05-15, 543 GRBs were observed at declinations greater than $-5^\circ$ and reported via the GRB Coordinates Network (GCN) [6] and the Fermi GBM catalogs [7, 8]. 492 bursts which occurred during stable IceCube data taking are included in this analysis. The search window is determined by the time of gamma emission and the location in the sky for each burst. When multiple satellites observed a given burst, the time window is defined by the most inclusive start and end times reported by any satellite. The angular window is determined by the direction and angular error reported by whichever satellite reports the smallest angular error. For modeling neutrino fluence predictions, the gamma ray fluence and spectral parameters are taken preferentially from Fermi GBM [7], Konus Wind [9], Suzaku [10], Swift/BAT [11], and INTEGRAL [12] in this order. When a parameter is unreported, average parameters are used. The average parameters are calculated separately for short bursts (shorter than 2 s) and long bursts (longer than 2 s). Burst information is cataloged in an online database called GRB-web [13].

## 6 Analysis

While alternative GRB neutrino models are possible, the analysis presented here is designed to be sensitive to neutrinos arriving from the direction of GRBs at the same time as the observed gamma rays. We use an unbinned likelihood analysis [14] in which the likelihood that a given event is a signal event is quantified based on separately normalized time, direction, and energy probability distribution functions (PDFs): $S/B = (S/B)_{\text{time}} \times (S/B)_{\text{direction}} \times (S/B)_{\text{energy}}$.

For a given burst, the signal time PDF is flat during gamma emission, with Gaussian tails with a width equal to the duration of the burst but no less than 2 s and no more than 30 s. The burst time window is truncated at $4\sigma$, and the background time PDF is flat throughout the time window.

The signal direction PDF is a two-dimensional circular Gaussian: $S_{\text{direction}}(v, GRB) = 1/(2\pi\sigma^2) \exp[-\delta\theta^2/(2\sigma^2)]$, where $\sigma^2 = \sigma_{\text{GRB}}^2 + \sigma_{\text{sys}}^2$ and $\delta\theta$ is the opening angle between the burst and the reconstructed neutrino direction. For most satellites [15, 16, 17] the GRB localization error ($\sigma_{\text{GRB}}$) is much more tightly constrained than the per-event estimated neutrino reconstruction error ($\sigma_{\text{sys}}$). However, for Fermi GBM, there is a systematic error of 2.6' with 72% weight plus 10.4' with 28% weight [12]. To include GBM bursts in the analysis chain, we set $\sigma_{\text{GRB}}^2 = \sigma_{\text{stat}}^2 + \sigma_{\text{sys}}^2$, with the conservative setting that $\sigma_{\text{sys}} = 10.4'$. The background direction PDF is constructed from off-time data, taking into account the direction-dependent acceptance of the detector.

The signal energy PDF is computed from the reconstructed muon energy of simulated signal events with an $E^{-2}$ spectrum. The background energy PDF is taken from off-time data in the regime where we have good statistics; at higher energies, this PDF is extended using the tail of the reconstructed muon energy distribution of simulated atmospheric neutrinos.

The signal and background PDFs provide a measure of the signal-to-noise of a single event. To calculate the signal-to-noise of an ensemble of events, we use the following test statistic:

$$T = -n_s + \sum_{i=1}^{N} \ln \left( \frac{n_s S_i}{(n_b)_{B_i}} + 1 \right),$$

which is the log of the ratio of the likelihood an ensemble consists of $n_s + (n_b)$ signal plus background events to the likelihood the ensemble consists of $(n_b)$ expected number of background events. Specifically, for a given ensemble, we take the value of $T$ corresponding to the value of $n_s$ which maximizes this likelihood ratio.

The significance of an observation is determined by calculating the probability $p$ of finding an equal or greater $T$ given background alone. To find this probability, pseudo-experiments are performed in which background-like events are generated by drawing from the energy, direction, and direction error distributions in off-time data. The resulting $T$ distribution sets the significance of any single observation.

Given a particular observed test statistic $T_{\text{obs}}$, we can calculate upper limits on models. We use a Feldman-Cousins
Table 1: While the 79 string configuration was running, a single neutrino was associated with GRB100718B. The table above summarizes the burst and neutrino properties. This observation is fully consistent with background.

The significance of this single coincident neutrino is further reduced when we analyze the four year data sample in combination. The test statistic in this case is 0, which gives a final post-trials $p = 1$.

In the absence of a significant observation, we produce limits on some contemporary models. Previous model-dependent limits have been based on the treatment by Guetta et al. [5], which derives an expected neutrino fluence from the measured gamma fluence and assumptions about the GRB fireball properties such as the ratio of energy in protons vs. electrons, the bulk Lorentz factor $\Gamma$ of the fireball, and the characteristic time scale $t_{\text{var}}$ of variability in the fireball due to magnetic shocks. This treatment neglected physics details such as the energy distribution of fireball particles and interaction channels other than the $\Delta^{+}$ resonance. Numerical simulation of these fireball details allows a next-to-leading order fluence prediction which is generally lower than the approximate result [4].

Here, we refer to this model generically as the fireball model. Zhang and Kumar [19] present an analytic model similar to Guetta et al. but with proton acceleration and neutrino production taking place at the photosphere, where the fireball transitions from optically thick to optically thin with respect to $\gamma\gamma$ interactions. This production hypothesis, too, can be simulated numerically. Here, we refer to this model as the photospheric model.

Figures 1 and 2 summarize the photospheric and generic fireball model predicted fluence for the bursts occurring during each detector configuration. Each total fluence prediction may be recast as a quasi-diffuse flux, assuming that the burst fluences are independent. This production hypothesis, too, can be simulated numerically. Here, we refer to this model as the photospheric model.

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Figure 1: Fireball model predicted neutrino fluence for bursts occurring during each detector configuration included in this analysis. IC## indicates the number of strings in operation; IC86-I refers specifically to the first year of 86 string operation.

Figure 2: Photospheric model predicted neutrino fluence for bursts occurring during each detector configuration included in this analysis, labeled as in Figure 1.
the models differ in spectral break energies and the method in which the normalization is fit to the observed cosmic ray fluence. For all realistic models, the fluence is low enough at the high-energy break that its presence has a negligible effect on the number of events observed by IceCube; therefore, it is sufficient for us to report, as a function of the first break energy $\varepsilon_b$, a limit on single-broken power law emission of the form $\Phi(\varepsilon) \propto (\varepsilon - \varepsilon_b)^{-2}$. The limit from four years of IceCube data is shown along with the most recently published limit and three model predictions in Figure 4.

8 Conclusion

Previous results from IceCube have excluded models in which the entire cosmic ray flux at the highest energies results from neutrons escaping from GRBs and decaying later to protons [2]. Our updated limits based on four years of data tighten this constraint further still. Our previous results have also excluded models which normalize the neutrino fluence to the per-burst gamma ray fluence without properly simulating the particle physics interactions in the fireball [2]. The theory community has responded by delivering more complete calculations [4]. Since the updated model predictions give a smaller neutrino flux, we are not yet able to constrain them, but within $\sim 3$ years we expect to have sufficient exposure to begin to do so or to observe the flux they predict. In addition, an updated analysis of southern hemisphere bursts and a new $\nu_e$ analysis are planned, and results from a search for a correlation between GRB and high energy starting events (in which the interaction vertex is contained within the instrumented volume) will be available soon [23].

References

[23] IceCube Coll., paper 367, these proceedings.