Search for neutrinos from GRBs with IceCube

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***Abstract*. Gamma-ray bursts (GRBs) are one of the few potential sources for the highest energy cosmic rays and one of the most puzzling phenomena in the universe. In their ultra relativistic jets, GRBs are thought to produce neutrinos with energies well in excess of 100 TeV. IceCube, a neutrino telescope currently under construction at the South Pole, will have improved sensitivity to these yet unobserved neutrinos. This contribution describes the methods used for all IceCube neutrino searches from GRBs triggered by satellites. We also present the status of three searches for neutrinos in coincidence with GRBs. The first search seeks to extend existing IceCube 22-string ν_μ searches to the high background southern hemisphere bursts. A second search looks for neutrino-induced cascades with the 22-string configuration of IceCube. Another ν_μ search is planned for the 40-string configuration of IceCube, and its status is presented here. This paper is a companion of another ICRC IceCube contribution that summarizes the IceCube 22-string northern hemisphere ν_μ GRB search results and the expected capabilities of the completed 86-string detector.**

***Keywords*: Gamma-Ray Bursts, Neutrinos, IceCube**

I. INTRODUCTION

Gamma-ray Bursts (GRBs) have been proposed as one of the most plausible sources of the highest energy cosmic rays [1] and high energy neutrinos [2]. The prevalent belief is that the progenitors of so called *long-soft* GRBs are very massive stars that undergo core collapse leading to the formation of a black hole. *Short-hard* GRBs are believed to be the product of the merger of binary compact objects such as neutrons stars and black holes leading to the creation of a single black hole. Material is ejected from the progenitor in ultra-relativistic jets which then produce the observed burst of γ-rays and accelerate particles, including baryons, to high energy. Neutrinos are predicted to be produced in multiple scenarios: while the jet burrows through the envelope of the progenitor of a long-soft burst [3] (TeV precursor), in coincidence with the observed γ-ray signal [2] (prompt) and as the jet collides with interstellar material or the progenitor wind in the early afterglow phase [4] (EeV early afterglow.)

We use the Waxman-Bahcall model as a benchmark for neutrino production in GRBs. The original calculation with this model used average GRB parameters as measured by BATSE [2]. It was refined by including specific details for individual GRBs [5]. Our neutrino calculations follow this latter prescription. For many GRBs the available information is incomplete. In that case we use average parameters in the modeling of the neutrino flux.

IceCube is a high energy ($E \gtrsim 1\,\mathrm{TeV}$) neutrino telescope currently under construction at the South Pole [6]. The total instrumented volume of IceCube will be $\sim 1\,\mathrm{km}^3$. IceCube indirectly detects neutrinos by measuring the Cherenkov light from secondary charged particles produced in neutrino-nucleon interactions. A total of 5160 Digital Optical Modules (DOMs) arranged in 86 strings frozen in the ice are planned. The results presented here correspond to the 22- and 40-string configurations. AMANDA-II [7], IceCube's predecessor array, had an instrumented volume ≈ 60 times smaller than that of the full IceCube. Searches of neutrinos in coincidence with GRBs by AMANDA have been reported with negative results [8], [9].

The two main channels for detecting neutrinos with IceCube are the muon and the cascade channels. Charged current interactions of ν_μ produce muons that, at TeV energies, travel for several kilometers in ice. For the muon channel the detectors are mainly sensitive to up-going muons as the Earth can be used to shield against the much larger flux of down-going atmospheric muons. Because the neutrino-induced muon spectrum from GRBs is expected to be much harder than cosmic-ray induced muons GRB neutrino searches can be extended to the southern hemisphere are shown in section III. Searches for neutrinos from GRBs in the muon channel benefit from good angular resolution ($\sim 1^\circ$ for $E_\nu > 1\,\mathrm{TeV}$) and from the long range of high energy muons. In the cascade channel the detectors are sensitive to all neutrino flavors through various interaction channels. In this case almost all of the neutrino energy is deposited in a narrow cylinder of O(10 m) in length; point-like compared to IceCube dimensions. The cascade channel analyses benefit from good energy resolution (~ 0.1 in $\log_{10} E$) and from 4π sr sensitivity. Complex event topologies can also arise from ν_τ-induced events for energies above $\gtrsim$ 1 PeV [10].

II. Satellite Triggered Searches for Neutrinos in Coincidence with GRBs

There are several methods for searching for neutrinos from GRBs. The present contribution and its companion [11] are *satellite triggered searches*. A list of GRB times and sky localizations is obtained from satellites, such as Swift, Fermi and others. From the perspective of IceCube, the ideal GRB that is a source of neutrinos has a high photon fluence, a well measured spectrum, redshift and other electromagnetic properties and is localized with higher accuracy than the pointing resolution of IceCube ($\sim 1^{\circ}$ for the completed detector). Therefore wide field of view searches are preferable even at the expense of reduced sensitivity. In that respect, Fermi is the main source of GRBs expected to produce neutrinos. Fermi started operations in summer 2008, before this time, the main source of GRBs for study was Swift.

To avoid potential biases, all satellite triggered searches are conducted using *blind* analysis methods. The *on-time* window around each GRB is left unexamined, except for low level quantities that allow to establish the stability of the detector. The length of the on-time window depends on the analysis. The remainder of the data collected by IceCube, or *off-time* window, are used to measure the background experimentally. The on-time window is studied (*unblinded*) only once the analysis procedure has been fully established.

Searches for GRB neutrinos are performed if the detector is determined to have been in a period of stable operation according to general data requirements developed and shared by the IceCube collaboration. In addition the time difference between consecutive events is calculated. At trigger level and for initial event selection criteria the event rate in IceCube is dominated by atmospheric muons produced in cosmic ray showers. Given uncorrelated cosmic rays the time difference between consecutive events is expected to fall exponentially with time and the time constant should correspond to the inverse of the detector event rate. Finally a histogram of the frequency of number of events in 10 s bins is fitted with a Gaussian distribution. Deviations from a normal distribution, measured by a reduced χ^2, indicate periods of high or low detector event rate. Only GRBs corresponding to stable detector periods are considered.

Neutrinos are simulated using an implementation of the ANIS code [12] and atmospheric muons using the CORSIKA air shower simulation package [13]. Propagation of neutrinos and muons through the Earth and ice are performed with ANIS and MMC [14]. The photon signal in the DOMs is determined from a detailed simulation [15] of the propagation of Cherenkov light from muons and showers through the ice. This is followed by a simulation of the DOM electronics and the trigger. The DOM signals are then processed in the same way as the data. The theoretical models tested have been corrected to take into account neutrino oscillations.

III. IceCube 22-string Southern Hemisphere Muon Search

In this analysis we search for muon neutrinos emitted in the prompt phase from GRBs in the southern hemisphere (negative declination). We use filtered data collected with the IceCube detector in its 22-string configuration between May 2007 and April 2008 for bursts with declination $> -40^{\circ}$. Very low level data taken within two hours of a burst trigger is used for those with declination $< -40^{\circ}$. In both cases, the data taken ± 20 minutes from the burst trigger is considered to be the on-time window. Following the stability procedure described in section II we find that two of the 42 southern hemisphere bursts do not pass the data quality criteria or have missing data during the prompt emission windows. For the remaining 40 GRBs, these tests show no indications of abnormal behavior of the detector.

Tracks are reconstructed using a log-likelihood reconstruction method [16]. A fit of a paraboloid to the region around the minimum in the log-likelihood function yields an estimate of the uncertainty on the reconstructed direction. Various quality parameters and energy related parameters are derived from the results of some other reconstructions discussed in [16] and [17].

The track quality and energy related variables are combined using a machine learning algorithm. The algorithm used was a Support Vector Machine (SVM) [18] with a radial basis function kernel. One SVM was trained for the filtered dataset after a loose preselection of events and another was trained on the low level dataset. In both cases, off-time background data is taken as the background and all-sky neutrino simulation is used as the signal. The result is an SVM classification between -1 (background-like) and 1 (signal-like) for all events.

An unbinned likelihood method like the one described in [19] was used to search each on-time window. This method avoids using restrictive selection criterion to throw away events but instead uses probability density functions (PDFs) to evaluate whether events are more likely to be signal or background. The signal, $S(\vec{x}_i)$, and background, $B(\vec{x}_i)$, PDFs are each the product of a time, a space, and an SVM PDF.

The space signal PDF is a two-dimensional Gaussian determined from the paraboloid fit. The time PDF is flat over the respective time window and falls off on both sides with a Gaussian distribution with width equal to the time window length. The SVM PDF is determined from the SVM classifier distribution for simulated signal events.

For the space background PDF the detector asymmetries in zenith and azimuth are taken into account by evaluating the off-time data in the detector coordinate system. The time distribution of the background during a GRB is flat over the entire on-time window. The SVM PDF is again determined from the SVM classifier distribution of off-time background data.

All PDFs are combined in an extended log-likelihood function [20] where the sum runs over all reconstructed

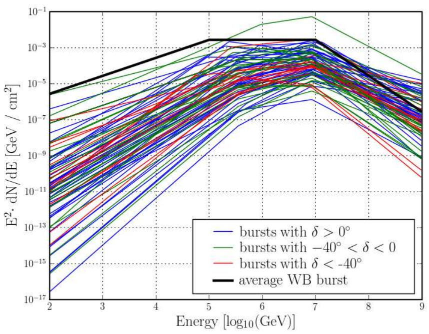

Fig. 1. The calculated neutrino fluxes for all burst triggers taken during IceCube's 22-string operations in different declination bands.

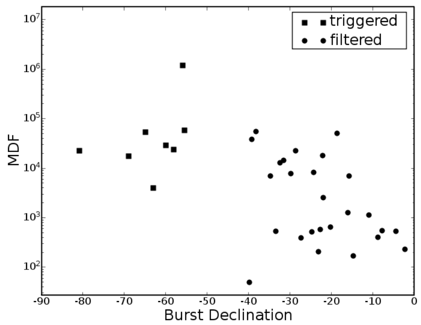

Fig. 2. The 5σ 50% MDF for each burst in the southern hemisphere muon neutrino search.

tracks in the final sample. The variable $\langle n_b \rangle$ is the expected mean number of background events, which is determined from the off-time data set. The mean number of signal events, $\langle n_s \rangle$, is a free parameter which is varied to maximize the expression

$$\ln\left(\mathcal{R}(\langle n_s \rangle)\right) = -\langle n_s \rangle + \sum_{i=1}^{N} \ln\left(\frac{\langle n_s \rangle\, S_{\mathrm{tot}}(\vec{x}_i)}{\langle n_b \rangle\, B_{\mathrm{tot}}(\vec{x}_i)} + 1\right) \quad (1)$$

in order to obtain the best estimate for the mean number of signal events, $\langle \hat{n}_s \rangle$.

To determine whether a given data set is compatible with the background-only hypothesis, 10^8 background data sets for the on-time windows are generated from off-time data by randomizing the track times while taking into account the downtime of the detector. For each of these data sets the $\ln(\mathcal{R})$ value is calculated. The probability for a data set to be compatible with background is given by the fraction of background data sets with an equal or larger $\ln(\mathcal{R})$ value. The sensitivity of each search is determined by injecting simulated signal events into these randomizations and observing the resultant $\ln(\mathcal{R})$ distribution. This allows for the calculation of the Model Detection Factor (MDF) for each analysis (figure 2). The MDF is the ratio of the lowest signal fluence required for a detection with the required significance and power to the predicted fluence [21].

IV. ICECUBE 22-STRING CASCADE SEARCH

We are currently conducting a search for neutrino-induced cascades in the prompt phase for 81 GRBs at all declinations in coincidence with data from stable detector periods (see section II for details) collected with IceCube in its 22-string configuration. The on-time period for this analysis is $\pm$ 1 hour. The off-time is the remainder of the data collected by IceCube with 22 strings between May 2007 and April 2008 with a livetime of $\sim$269 days.

The analysis proceeds in three steps. First, a preliminary selection of cascade-like events is performed online at the South Pole. Second, the South Pole filtered data are reconstructed by minimizing log-likelihood functions that take into account the propagation of photons through ice from the source to the digital optical modules [16]. The reconstructions are performed for both a muon hypothesis and a cascade hypothesis. The muon hypothesis reconstruction provides a position, a direction, time and several quality parameters that describe how appropriately the muon hypothesis fits the data. The cascade hypothesis reconstruction provides a candidate neutrino interaction vertex, time, cascade energy and quality parameters. After the reconstruction further selection criteria are applied:

- $L_\mu - L_{cascade} > -16.2$. The difference in the log-likelihood quality parameters for the muon and cascade reconstruction identifies events that are better described by the cascade hypothesis.
- $\theta_\mu > 73°$. Events that match a down-going muon are rejected. Here the $\theta_\mu = 0°$ represents a vertical down-going muon.
- $L_{cascade}/(Nhit - 5) < 8.0$. Cascade events that are low energy or too far from the detector are reconstructed poorly. We use the cascade hypothesis reduced log-likelihood quality parameter to select well reconstructed cascade events.
- $N_{1hit}/N_{hit} < 0.1$. This quantity is a simple cascade energy proxy because it is equivalent to the surface to volume ratio of a spherical pattern of light. N_{1hit} measures the number of DOMs in an event that have only one hit (typically one photo-electron), N_{hit} measures the total number of hits.

For the optimization of the selection criteria we are currently using the Waxman-Bahcall spectrum [2] for the expected $\nu_e + \bar{\nu}_e$ signal. After applying the selection criteria described above, we expect 0.36 ($\nu_e + \bar{\nu}_e$) from 81 GRBs. Because Swift is the main source of GRBs for this analysis, we expect the typical GRB to be about one order of magnitude dimmer than what was assumed for the Waxman-Bahcall spectrum[1]. If a detailed per-burst simulation is performed we expect a significantly lower signal rate. After applying the selection criteria described above $\approx 1.5 \times 10^5$ events remain in the off-time data.

[1]The Waxman-Bahcall model assumed BATSE average GRB parameters, especially $z_{\mathrm{GRB}} = 1$, while Swift's mean observed redshift is significantly higher.

For the third and final part of the analysis we discriminate signal from background with a neural network that uses the parameters described above plus the reconstructed energy of the cascade hypothesis and a topological parameter that discriminates long (muon) from spherical (cascade) events. A cut on the neural network parameter provides the final discrimination between signal and background.

V. ICECUBE 40-STRING MUON SEARCH

IceCube began operating with 40 strings on April 5 2008 and continues to collect data in this configuration at the time of writing. During this time IceCube remained extremely stable and maintained a livetime of approximately 95%. These additional strings give IceCube a fiducial volume of approximately 0.5 km^3 making it the largest neutrino detector to date. This section will cover the analysis of the northern hemisphere bursts. An analysis of the southern hemisphere bursts will follow.

To date there have been 116 northern hemisphere GRBs reported via GCN circulars during 40-string operations. The launch of the Fermi Gamma-Ray Space Telescope with the Gamma-Ray Burst Monitor (GBM) has greatly increased the number of bursts available for analysis. However, the GBM bursts are usually poorly localized and have 1 sigma uncertainties spanning from 1 to 15 degrees. In addition there are several bursts detected by other satellites of the InterPlanetary Network (IPN), including the brightest burst in the sample, GRB080408B, which result in a total of 48 bursts with localization uncertainties of larger than one degree. In order to search regions of the sky larger than IceCube's angular resolution of approximately 1.5 degrees, new methods must be utilized. Expanding on the unbinned likelihood analysis presented in section III, an extended source hypothesis must be created that takes into account both the GRB's localization error and IceCube's angular uncertainty:

$$S_{\text{space}}(\vec{x}_i) = \frac{1}{N}\int_{4\pi} \mathrm{d}\Omega \cdot e^{\frac{(\vec{r}-\vec{r}_\gamma)^2}{2\sigma_\gamma}+\frac{(\vec{r}-\vec{r}_\nu)^2}{2\sigma_\nu}} \qquad (2)$$

where $\vec{r}_\gamma$ and σ_γ are the location and uncertainty of the GRB as reported in the GCN circular, $\vec{r}_\nu$ and σ_ν are the uncertainty of the IceCube neutrino candidate, and N is a normalization.

Sensitivity studies are currently being performed and will be available soon.

VI. CONCLUSIONS

Satellite triggered searches for neutrinos in coincidence with GRBs use many common techniques. The southern hemisphere ν_μ search is a first attempt to extend IceCube's sensitivity to GRBs into the higher background region above the horizon. The cascade search provides sensitivity to all neutrino flavors over 4π sr. The 40-string search provides greater sensitivity due to IceCube's growing effective area and greater number of burst triggers from Fermi.

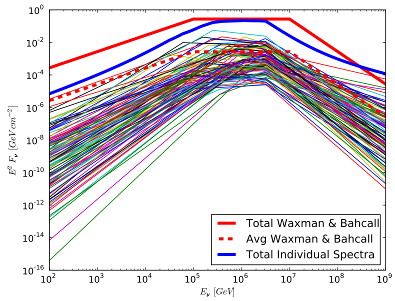

Fig. 3. The Calculated Neutrino Spectrum for 102 of the 116 northern hemisphere bursts for which spectral information was available. The Sum of the Neutrino spectrum is plotted along with the Average Waxman and Bahcall spectrum for a single burst and for 102 bursts.

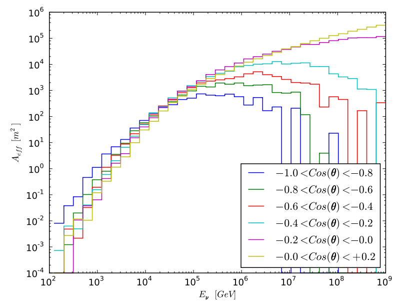

Fig. 4. Effective Area of 40 string IceCube.

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