Detecting Neutrinos from Choked Gamma Ray Bursts with IceCube's DeepCore

THE ICECUBE COLLABORATION[1]
[1]*See special section in these proceedings*

Abstract: The detection of astrophysical point sources of neutrinos is a prime goal of the IceCube neutrino telescope. Probable high-energy neutrino sources of interest include transient events such as core-collapse supernovae and gamma ray bursts (GRBs). It has been proposed that jets are present not only in supernovae that lead to long GRBs but also more frequently in so called choked GRBs that lack a high-energy electromagnetic signature. Choked GRBs may be detectable by IceCube's DeepCore subdetector. The transient nature of these events coupled with the angular direction and current filtering algorithms should allow strong background rejection. We will present simulations of choked GRB signal at trigger level and with preliminary data selection cuts applied.

Corresponding authors: Jacob Daughhetee [2] (*daughjd@gatech.edu*), IgnacioTaboada[2] (*ignacio.taboada@gatech.edu*)
[2] *School of Physics. Georgia Institute of Technology, Atlanta, USA*
DOI: 10.7529/ICRC2011/V08/0288

Keywords: IceCube, DeepCore, GRB, neutrino

1 Introduction

Long duration gamma-ray bursts (GRBs) have shown a strong association with core collapse supernovae [1]. The leading model of GRBs attributes the production of gamma rays to Fermi-accelerated electrons in internal shocks of relativistic jets driven by the core collapse of the progenitor [2]. These GRBs require heavy progenitors ($M \geq 25\ M_{\odot}$) and highly relativistic jets (Lorentz boost factor $\Gamma \geq 100$) that break through the surrounding stellar envelope. Although long duration GRBs appear correlated with supernovae, very few ($\leq 10^{-3}$) observed supernovae themselves are associated with GRBs [3].

It is conceivable that a large fraction of core collapse SNe produce mildly relativistic jets. Unlike GRBs, these jets never breach the stellar envelope and are essentially 'choked' within the progenitor. The inability of the jet to break through the envelope could arise from either the envelope itself being more massive than that of a GRB event or simply due to a lack of sufficient energy. These choked GRBs could be part of a continuum class of astronomical objects with long duration GRBs (having highly relativistic jets) representing the far end of the spectrum. Recently, evidence for mildly relativistic jets has been observed in supernovae 2007gr [4] and 2009bb [5], as well as in the observed asymmetry in the explosions of core collapse supernovae [6, 7]. This lends credence to the notion that central engines with less relativistic jets might occur more frequently than observable, fully developed GRBs.

Both hidden and visible jets can accelerate protons in shocks, resulting in the production of neutrinos. Despite lacking an elecromagnetic signature like typical GRBs, these choked GRB events would still have an associated burst of neutrinos that could provide information about hidden jets. One model for this type of event has been proposed by Razzaque, Mészáros and Waxman [8], and it has been extended upon by Ando and Beacom to include kaon production [9]. This model will hereafter be referred to as RMW/AB. The neutrino spectrum predicted by RMW/AB is fairly soft but high in fluence, and should be within reach of the IceCube detector ($\geq$ 100 GeV sensitivity) and the DeepCore subdetector ($\geq$ 10 GeV sensitivity). Due to the soft nature of the RMW/AB spectrum, DeepCore will be better suited to detecting choked GRBs.

IceCube is a neutrino detector located at the South Pole optimized for neutrino energies on the TeV scale. Finished in December of 2010, it detects Cherenkov light emitted by secondary charged particles produced in a neutrino nucleon interaction. The completed detector is made up of 5160 optical modules, with 60 optical modules placed on each of the 86 strings. These optical modules contain PMTs with onboard digitizers and are more succintly referred to as DOMs (Digital Optical Modules). The DeepCore subarray includes 8 densely instrumented infill strings optimized for low energies plus 12 adjacent standard IceCube strings.

Complete PMT waveforms are recorded by the DOMs that meet the Hard Local Coincidence (HLC) condition. HLC requires hits in a DOM and its nearest or next to nearest neighbor in a time window of $\pm$ 1 μ sec. IceCube also records compact information for Soft Local Coincidence, or SLC, hits that do not meet HLC. DeepCore's trigger requires 3 HLC hits in a time window of 2.5 μ sec.

Despite its smaller detector volume, DeepCore's enhanced sensitivity to lower energies greatly increases the observable flux. In addition, the location of DeepCore inside the IceCube detector should allow for significant background rejection through utilization of IceCube itself as a veto. For these reasons this analysis focuses on simulating the response of the DeepCore detector under its standard triggering and filtering, and we calculate the expected event count from a sample choked GRB for the fully completed DeepCore under the RMW/AB model.

2 Neutrino Production in Jets

The RMW/AB model assumes a mildly relativistic baryon-rich jet with a bulk Lorentz factor Γ_b = 3 and an opening angle $\theta_j \sim \Gamma_b^{-1}$ = 0.3. The kinetic energy of the jet is set to E_j = 3×10^{51} erg, a typical energy for GRBs. The variability timescale of the engine mirrors that of observed GRBs as well and is set as $t_v \sim$ 0.1 s. Shocks within the jet accelerate protons with a spectrum $\sim E_p^{-2}$ up to a maximum proton energy of 2×10^6 GeV determined by the acceleration timescale and radiative cooling. Neutrinos are the product of the kaons and pions produced in p-p interactions of the accelerated protons with the stellar envelope. Energies and densities involved are similar to those in neutrino production in the Earth's atmosphere. In the case of neutrinos from pion decay, the neutrino flavor flux ratio $\phi_{\nu_e} : \phi_{\nu_\mu} : \phi_{\nu_\tau}$ is 0:1:0. Secondary neutrinos from muon decays can be ignored here because the muons from pion decay are immediately subjected to radiative cooling. As for neutrinos from kaon decay, the small flux of ν_e from K_L^0 decay is neglected by RMW/AB. Thus, a flavor flux ratio of 0:1:0 is also assumed for neutrinos from kaon decay. After accounting for vacuum oscillations, the expected flavor flux ratio at Earth becomes ∼1:2:2 for both contributions. Neutrinos are emitted over a time window of O(∼10 s), set by the star's size (Δt ∼ $R_\star/c$).

The shape of the neutrino spectrum is dependent upon that of the mesons from the p-p interactions. Initially, these mesons have the same E^{-2} spectrum as the protons, but mesons undergo hadronic and radiative cooling before decay. The result is a meson spectrum with two break energies at which the spectrum becomes steeper. The neutrino spectrum will match the meson spectrum, and it can be modeled as a doubly broken power law. For a given supernova at 10 Mpc with Γ_b = 3, opening angle $\theta_j \sim \Gamma_b^{-1}$ = 0.3, and $E_j = 3 \times 10^{51}$ erg, the spectrum is of the form:

$$\frac{d\Phi_\nu}{dE} = F_\nu \begin{cases} E^{-2} & E > E_\nu^{(1)} \\ E_\nu^{(1)} E^{-3} & E_\nu^{(1)} < E < E_\nu^{(2)} \\ E_\nu^{(1)} E_\nu^{(2)} E^{-4} & E_\nu^{(2)} < E < E_{max} \end{cases} \quad (1)$$

F_ν is the all flavor flux normalization where $d\Phi_\nu/dE$ is 5×10^{-2} GeV^{-1}cm^{-2}(5×10^{-5} GeV^{-1}cm^{-2}) at $E_\nu^{(1)}$ for pions(kaons). The break energies $E_\nu^{(1)}$ and $E_\nu^{(2)}$ denote the onset of hadronic and radiative cooling respectively where $E_\nu^{(1)}$=30 GeV (200 GeV) and $E_\nu^{(2)}$=100 GeV (20 TeV) for pions(kaons). The neutrino flux from both pion and kaon contributions is shown as a function of energy in Fig. 1.

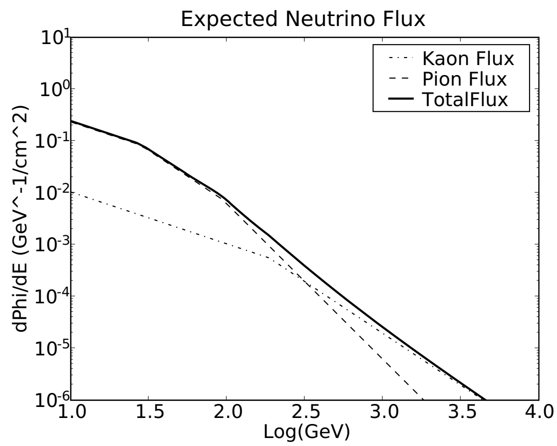

Figure 1: All flavor neutrino flux from pion, kaon and combined contributions.

3 Effective Area of DeepCore and Expected Events

We calculate the expected number of observed IceCube+DeepCore neutrino events N_{obs} given a flux $d\Phi_\nu/dE$ and detector effective area A_{eff} by

$$N_{obs} = \int dE A_{eff}(E) \frac{d\Phi_\nu}{dE} \quad (2)$$

In order to properly estimate the number of expected events from an astrophysical source, the neutrino effective area must be calculated through detailed simulation of a benchmark incident flux and the detector hardware. We briefly describe the calculation of the effective area.

The effective area of the detector has been calculated by simulating neutrinos in the nearby volume surrounding the detector, propagating them, and forcing them to interact (preventing the simulation of events that do not interact within the volume). These events are re-weighted to reflect the probability that the interaction would actually occur. All flavors of neutrinos used in this proceeding were simulated with NUGEN (a modified version of ANIS [10] that works with IceCube software). Simulation with NUGEN includes several effects including the ice/rock boundary below the detector, Earth neutrino absorption, neutral current regeneration, etc. The flavor flux ratio is taken from the ratio predicted by the RMW/AB jet model for neutrinos originating from both pions and kaons. Vacuum oscillations are included [11], and the ratio of neutrino to anti-neutrino is assumed equal for all flavors. The propagation of muons within the detector has been simulated with MMC [12]. Detection of events is determined by simulating the detector response to light produced by the daughter lepton (or cascade) of the interacting neutrino. Events are considered detected if they activate the standard DeepCore trigger. The calculated neutrino effective area under the standard DeepCore trigger is shown for all flavors in Fig. 2.

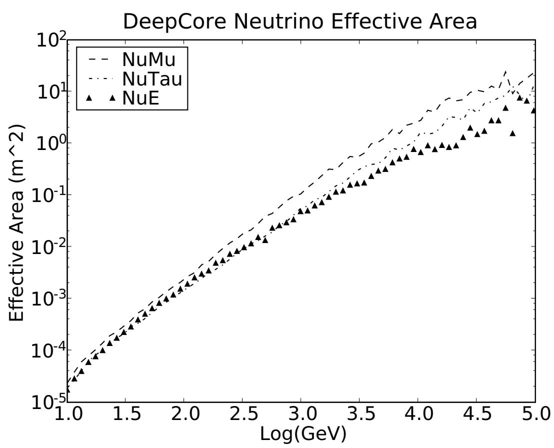

Figure 2: Effective area of the DeepCore detector given standard DeepCore SMT3 triggering for all flavor (ν_e-triangle symbols, ν_μ-dashed line, ν_τ-dashdot line). The effective area has been averaged over the entire sky.

As Fig. 2 shows, higher energy ν_μ events are significantly more visible than either ν_e or ν_τ. This can be attributed to muons produced outside of the physical DeepCore volume that then propagate near or through the ice occupied by DeepCore DOMs. At lower energies however, these muon tracks become shorter and more closely resemble cascade events.

It should be noted that there are some aspects of the simulation which are not accurate. Although NUGEN performs adequately at higher energies typical of IceCube analyses ($\geq$ 100 GeV), the cross-sections, and consequently interaction probabilites it predicts, lose accuracy at lower energies (between 10-100 GeV). This is particularly true for ν_τ as the simulation used does not properly take into account the kinematics of the τ lepton, and it is likely that the actual rate of ν_τ will be appreciably lower.

Combining the calculated effective areas with the flux predicted by the RMW/AB model via Eq. 1 yields an estimation on N_{obs} for the DeepCore detector. The number of expected events by flavor and the predicted background rate are listed in Table 1.

The result for a reference supernova at 10 Mpc is an all-flavor expectation of $\sim$10.5 events in the IceCube+DeepCore detector under standard DeepCore triggering. This event expectation is subject to large variation due to uncertainties in the jet parameters of the RMW/AB model. After application of the DeepCore filter, which discards events that show causal relation to hits in the non-DeepCore IceCube strings (veto region), the all-flavor event expectation is about 9 events. This decrease in events is mostly due to the rejection of ν_μ and ν_τ interactions outside of DeepCore's fiducial volume. Events with the best possibility of reconstruction will be those neutrinos that interact within the DeepCore fiducial volume. Therefore, it is of interest to estimate the number of events that actually interact inside DeepCore. Examination of the simulated interaction vertices reveals the number of trigger level events originating in DeepCore to be 5.7 (1.1 due to ν_e, 2.4 due to ν_μ, and 2.2 due to ν_τ). The predicted event spectra for all flavors at trigger level is shown as a function of energy in Fig. 3.

Flavor	Trigger	Filter	Preliminary Data Cuts
ν_e	1.6	1.5	1.5
ν_μ	4.6	3.9	3.3
ν_τ	4.3	3.6	3.1
Corsika	250 Hz	7 Hz	1.2 Hz

Table 1: Event expectation in DeepCore by flavor for RMW/AB model choked GRB at 10Mpc. Background is simulated with CORSIKA, and rates are estimated by taking the product of the DeepCore trigger rate and the simulated rejection factor at each cut level. Event estimation for ν_τ may be overly optimistic due to issues in NUGEN simulation at lower energies.

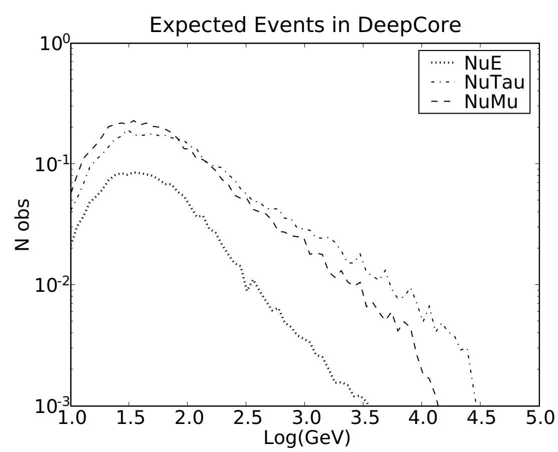

Figure 3: Expected trigger level signal in DeepCore as a function of energy for all flavors.

The plot shows a peak in event expectation at about 40 GeV for all flavors. This places most of the expected events below the typical IceCube threshold and well into the energy range of DeepCore.

4 Atmospheric Muon and Neutrino Background

A major goal of the DeepCore detector is to open up the southern sky to analysis to obtain a full 4π sr view. In order to do this, extensive steps towards reducing the large atmospheric muon background must be taken. The expected rate of atmospheric neutrinos in DeepCore is about 10^5 events per year over 2π while the atmospheric muon rate in DeepCore is a factor of $\sim 10^6$ larger. We are currently developing techniques to be used in conjunction with the IceCube veto that will allow for a rejection of atmospheric muons by a factor $\geq 10^6$ while maintaining high signal efficiency. For more information on DeepCore and its background rejection capabilities, see reference [13].

We have already begun investigating other background rejection methods. Some possible simple cuts include a modified version of the current filter, an algorithm using a reconstruction to search for correlated single detector hits (such hits are often cleaned in analysis), and a cut on the ratio of DOM hits inside and outside of the DeepCore detector. Taken in combination, these three additional data cuts can reduce background after standard filtering by an additional factor of six while maintaining a signal efficiency of $\sim$94%. The effect of these cuts on the number of expected events is shown in Table 1. Any future analyses will require a reduction in background to about the atmospheric neutrino level ($\sim$ 3 mHz).

5 Discussion

By simulating a choked GRB in accordance with the RMW/AB model, we have predicted the expected neutrino event count in the IceCube+DeepCore detector. For a reference supernova at 10 Mpc with a bulk Lorentz boost factor Γ_b = 3, opening angle $\theta_j \sim \Gamma_b^{-1}$ = 0.3, jet energy $E_j = 3 \times 10^{51}$ erg, and time variability $t_v \sim 0.1$ s, we expect $\sim$10.5 trigger level neutrino events in DeepCore. This level of event expectation would make a search for neutrinos in coincidence with known supernova on a distance scale $\sim$ 10 Mpc possible.

One possibile sensitivity enhancement is the expansion of DeepCore to a 2-layer IceCube veto (roughly doubling the detector volume used). This option would be particularly useful in a search for correlated neutrinos from known sources. The higher rate of background acceptance brought on by expanding the detection volume should be mitigated by the increase in signal rate for an overall increase in detection capability.

We also expect the event rate predictions to be modified when a more accurate simulation of the detector response is implemented. Most of this improvement will come from the use of superior neutrino cross-section simulation provided by GENIE [14]. A version of GENIE compatible with IceCube software has recently been developed to simulate lower energy neutrinos with much greater accuracy than that of the NUGEN based simulation used presently. This will greatly improve the simulation of ν_τ events in particular, which, due to oscillations, constitute $\sim$ 40% of the incident flux.

One promising method for searching for neutrino bursts from choked GRBs is a rolling time window search [15]. In this type of search, a time window for bursts is set by the characteristic neutrino emission time (Δt $\sim$ $R_\star/c$). This fixed time window slides across the dataset looking for a statistical excess of events. For choked GRBs, the time window would be about 10-100 s. Only background events falling inside a time window seeing an excess would be kept, thus greatly reducing the amount of background accepted. An advantage of the rolling search is that it is not dependent on any optical observations, allowing it to look for photon-dark neutrino sources as expected for choked GRBs.

In addition to searching for choked GRBs, it may also be possible for DeepCore to detect neutrinos from high luminosity GRBs. A model using parameters inferred from observations by *Fermi* developed by P. Mészáros and M.J. Rees predicts a neutrino spectrum of luminosity comparable to the photon component [16]. The model predicts a muon neutrino energy spectrum centered around $\sim$ 12 GeV. We are curently investigating the event rate expected in DeepCore.

Observations of neutrinos in the DeepCore detector on the order of 10-100 GeV in coincidence with supernova would be strong evidence for the existence of choked jets from the central engine. Such an observation would help to uncover the relationship between long duration gamma ray bursts and core collapse supernovae, a relationship that is not currently fully understood.

References

[1] S. E. Woosley and J. S. Bloom, Ann. Rev. Astron. Astrophys., 2006, **44**: 507-556

[2] B. Zhang, P. Mészáros, Int. J. Mod. Phys. A, 2004, **19**: 2385.

[3] E. Berger et al., Astrophys. J., 2003, **599**: 408.

[4] Z. Paragi et al., Nature, 2010, **463**: 516.

[5] A.M. Soderberg et al., Nature, 2010, **463**: 513.

[6] J.R. Maund et al., Astrophys.J (to be published); arXiv:0909.2841.

[7] M. Tanaka et al., Astrophys.J, 2009, **700**: 1680

[8] S. Razzaque, P. Mészáros and E. Waxman, Phys. Rev. D, 2003, **68** (083001).

[9] S. Ando and J.F. Beacom, Phys. Rev. Lett., 2005, **95** (061103).

[10] A. Gazizov and M. Kowalski, Comput. Phys. Commun., 2005, **172**: 203.

[11] S. Razzaque, A. Yu. Smirnov, JHEP, 2010, **3**: 31.

[12] D. Chirkin and W. Rhode (unpublished). arXiv:hep-ph/0407075.

[13] C. Wiebusch et al., in *proceedings of the 31st Int. Cosmic Ray Conf., Lodz, Poland, 2009*; arXiv:0907.2263.

[14] C. Andreopoulos et al., Nucl.Instrum.Meth.A, 2010, **614**: 87-104.

[15] Achterberg A. et al., Astrophys. J., 2007, **664**: 397.

[16] P. Mészáros and M.J. Rees, ApJ, 2011, **733**: L40.