Search for Short Transient Neutrino Emission with DeepCore-IceCube

IceCube Authors

Received ______________________; accepted ______________________

ABSTRACT

We present the results of a search for sources of brief transient neutrino emission using IceCube and DeepCore data acquired between May 15th 2012 and April 30th 2013. While the search methods employed in this analysis are similar to those used in previous IceCube point source searches, the data set being examined consists of a sample of predominantly sub-TeV muon neutrinos obtained through a novel event selection method. Thus, this search represents a first attempt at identifying astrophysical neutrino sources in this relatively unexplored energy range. The reconstructed direction and time of arrival of neutrino events is used to search for any significant self-correlation in the dataset; there is no comparison of the data set to a list of possible sources. This search encompasses the Northern sky ranging in declination from -5° to 90°. Examination of the data revealed no significant source of transient neutrino emission. This result has been used to construct limits on generic soft-spectra transients as well as a specific model of neutrino emission from soft jets in core-collapse supernovae.

Subject headings: neutrino astronomy, neutrinos, GRB, supernova, astroparticle physics

1. Introduction

The nascent field of neutrino astronomy exhibits great potential in its ability to answer several open questions in astrophysics. Specifically, the detection of astrophysical sources of neutrinos will help resolve one of the long-standing problems in astrophysics, the mechanisms behind the production and acceleration of cosmic rays. The hadronic nature of cosmic rays ensures that proton-proton collisions and photo-hadronic interactions are likely to occur at sites of cosmic ray acceleration therefore ensuring the production of pions and ultimately neutrinos. Unlike the charged nuclei that constitute cosmic rays, neutrinos lack charge and very rarely interact with intervening matter allowing these particles to provide directional information about their source. The detection of neutrino sources will therefore provide unequivocal identification of sources of cosmic rays.

The detection of these neutrino sources is a chief goal of the IceCube Neutrino Observatory (IceCube Collaboration et al. 2006). Located at the geographic South Pole, IceCube utilizes the clear glacial ice of the Antarctic ice cap as a detection medium for the secondary products of neutrino interactions. The detector consists of 5,160 Digital Optical Modules (DOMs) distributed among 86 cables to form a km^3 instrumented volume. These DOMs house photomultiplier tubes for the capture of Cherenkov photons as well as digitizing electronics for initial processing of the PMT data. A centrally located region of denser instrumentation featuring DOMs with more sensitive PMTs comprises the sub-array DeepCore (Abbasi et al. 2012). This extension to IceCube array augments the detector's response to lower energy neutrino events.

IceCube analyses attempting to resolve astrophysical neutrino sources typically make use of a high-energy muon neutrino sample ($E_\nu \gtrsim 1$ TeV) of high-purity to look for both steady (Aartsen et al. 2014) and transient sources (Aartsen et al. 2015). As of yet, these searches have not found any significant self-correlations within the data sample nor correlations between the neutrino data and known astrophysical objects of interest. These analyses have largely eschewed low energy neutrino events collected by DeepCore due to poor resolution of these events as well as an increasingly strong irreducible background at lower energies given by the soft spectrum of atmospheric neutrinos. However, application of these predefined search techniques to a sample of low energy (30 GeV $\leq E_\nu <$ 1 TeV) muon neutrino events from DeepCore can enhance IceCube's sensitivity to short transient neutrino sources with softer spectra.

Because of the strong atmospheric neutrino background in this energy range, searches using a data set composed of these low energy events will only be sensitive to time-dependent emission. Some potential sources include flaring from active galactic nuclei (AGN) due to brief periods of enhanced accretion **?**, 100-GeV scale sub-photospheric neutrino emission from gamma-ray bursts **?**, and neutrino emission from mildly relativistic jets in core-collapse supernovae. If the emission spectra for these sources are sufficiently soft or feature an energy cutoff below the optimum energy for IceCube, they may not be visible to the traditional IceCube point source searches.

A promising potential source for this study is a special class of core-collapse supernova referred to as a choked GRB. There is an observed correlation between long duration gamma-ray bursts (GRBs) and core-collapse supernovae (SNe) **?**. The standard GRB model assumes that relativistic jets are generated during accretion of material onto the compact object formed during core-collapse **?**. Fermi-acceleration of charged particles occurs within internal shocks of these jets leading to gamma ray emission once the jets breach the surrounding stellar envelope. The observed fraction of SNe resulting in the occurrence of a GRB is quite low, however, it may be that a larger fraction of core-collapse SNe still manage to produce mildly relativistic jets **?**. Due to insufficient energy, these jets fail to break through the stellar envelope and any gamma ray emission is effectively 'choked' off. If protons are accelerated in these jets, then neutrino production will occur in the shocks of the jet irrespective of whether or not the jet successfully escapes. A model of this neutrino emission proposed by Razzaque et al. (2004) and extended upon by Ando & Beacom (2005) suggests that these neutrinos may be detectable by IceCube-DeepCore for nearby supernovae (Taboada 2010).

We present the results of a search for transient neutrino emission on a set of low-energy neutrino event data collected from May 15th, 2012 to April 30th, 2013. The data selection methods used to acquire this unique event sample will be detailed in Sec. 2. Analysis methods and search techniques are discussed in Sec. 3. Lastly, the results of the search are given in Sec. 4 in addition to how these results may be interpreted within the context of generic neutrino flares as well as choked GRBs.

2. Event Selection

The IceCube detector is primarily designed for the detection of high-energy ($E_\nu \geq 1$ TeV) muon neutrinos originating from the Northern sky. However, the addition of the DeepCore sub-array in combination with veto techniques allow for significant lowering of the detection threshold energy.

2.1. Veto and Topology Cuts

The selection process begins with the output of the DeepCore filter, a data filter designed to isolate low-energy events interacting within a defined volume about the central DeepCore portion of IceCube.

2.2. Boosted Decision Tree

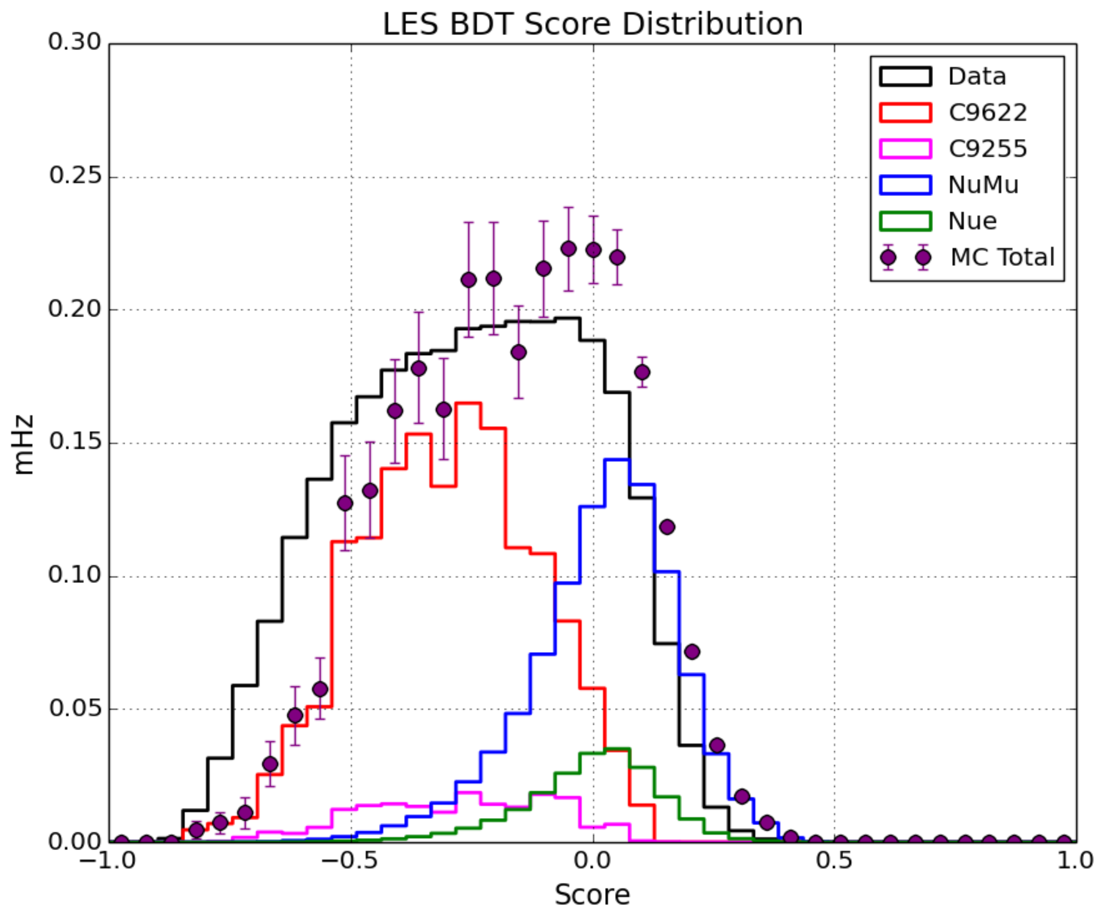

Fig. 1.— [add caption]

3. Analysis Method

The search methods employed in the analysis of this data are nearly identical to those used in previous time-dependent IceCube analyses (see Braun et al. (2008) and Aartsen et al. (2015)). The arrival times and directions of events within the dataset are fed to a likelihood function which is then used to compare a signal plus background hypothesis of the data to a background only hypothesis.

Construction of this likelihood function begins with the assignment of individual event probabilities that reflect the likelihood of seeing an event i arriving at t_i with reconstructed direction $\vec{x}_i$ given a hypothetical source located at $\vec{x}_s$ with strength n_s having a Gaussian time profile with mean time t_0 and width σ_w.

$$\mathcal{P}_i(\vec{x}_i, t_i, \sigma_i | \vec{x}_s, n_s, t_0, \sigma_w) = \frac{n_s}{n_{\text{tot}}} \mathcal{S}_i + \left(1 - \frac{n_s}{n_{\text{tot}}}\right) \mathcal{B}_i \tag{1}$$

The $\mathcal{S}_i$ and $\mathcal{B}_i$ terms listed in Eq. 1 are the signal and background probability density functions (p.d.f.) respectively. The p.d.f.s used in this search differ slightly from those in previously reported searches in that they use no reconstructed energy information. The signal p.d.f. has the following form

$$\mathcal{S}_i(|\mathbf{x}_i - \mathbf{x}_s|, t_i, t_o, \sigma_w, \sigma_i) = S_i(|\mathbf{x}_i - \mathbf{x}_s|, \sigma_i) \cdot T_i(t_i, t_o, \sigma_w) \tag{2}$$

where

$$S_i(|\mathbf{x}_i - \mathbf{x}_s|, \sigma_i) = \frac{\kappa}{4\pi \sinh \kappa} \exp\left(\kappa \cos |\mathbf{x}_i - \mathbf{x_s}|\right) \tag{3}$$

and

$$T_i(t_i, t_o, \sigma_w) = \frac{1}{\sqrt{2\pi}\sigma_w} \exp\left(-\frac{(t_i - t_o)^2}{2\sigma_w^2}\right) \tag{4}$$

where t_0 is the mean time of the source The spatial term, S_i, is the Kent-Fisher distribution, and it is analogous to the Gaussian distribution normalized to the 2-sphere (Kent 1982). This represents another deviation from previous methods which instead use a

$$\mathcal{L}(\mathbf{x}_s, n_s, t_o, \sigma_w) = \prod \mathcal{P}_i(|\mathbf{x}_i - \mathbf{x}_s|, n_s, t_i, t_o, \sigma_w, \sigma_i) \tag{5}$$

$$\hat{\lambda} = 2 \log \left[\frac{\sqrt{2\pi}\hat{\sigma}_w}{T} \frac{\mathcal{L}(\mathbf{x}_s, \hat{n}_s, \hat{t}_o, \hat{\sigma}_w)}{\mathcal{L}(n_s = 0)} \right] \tag{6}$$

[Sky scan]

4. Results and Interpretations

Applying the described analysis method on the unscrambled dataset yields a skymap of the pre-trials p-values derived from the maximized test statistic for each bin. This map is shown in Figure 2. The black circle in Figure 2 shows the hottest spot after the completion of the sky scan. The best fit to flare parameters for this hot spot are listed in Table 1.

R.A.	Dec	$\hat{n}_s$	$\hat{t}_0[MJD]$	$\hat{\sigma}_w[days]$	p-value	p-value post-trial
268.75°	54.25°	13.528	56107.8	5.89	4.1751	56%

Table 1: Best-fit values for flare location, duration, strength and time.

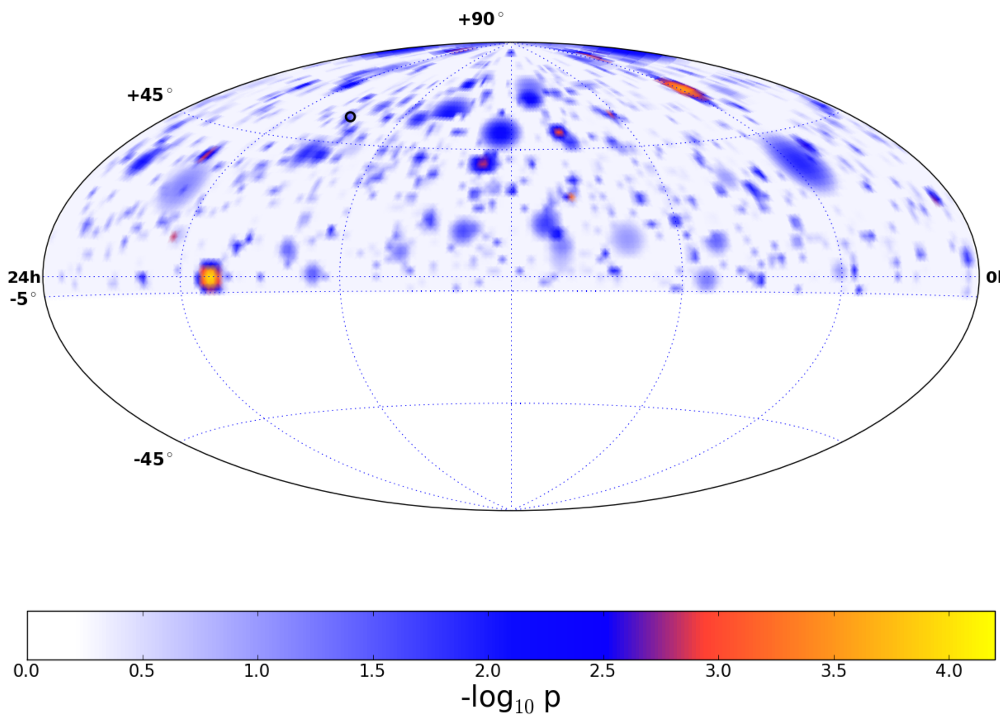

Fig. 2.— Sky map of pre-trials p-values for best fit flares per bin. The black circle identifies the location of the most significant flare found at RA = 268.75° and Declination = 54.25°.

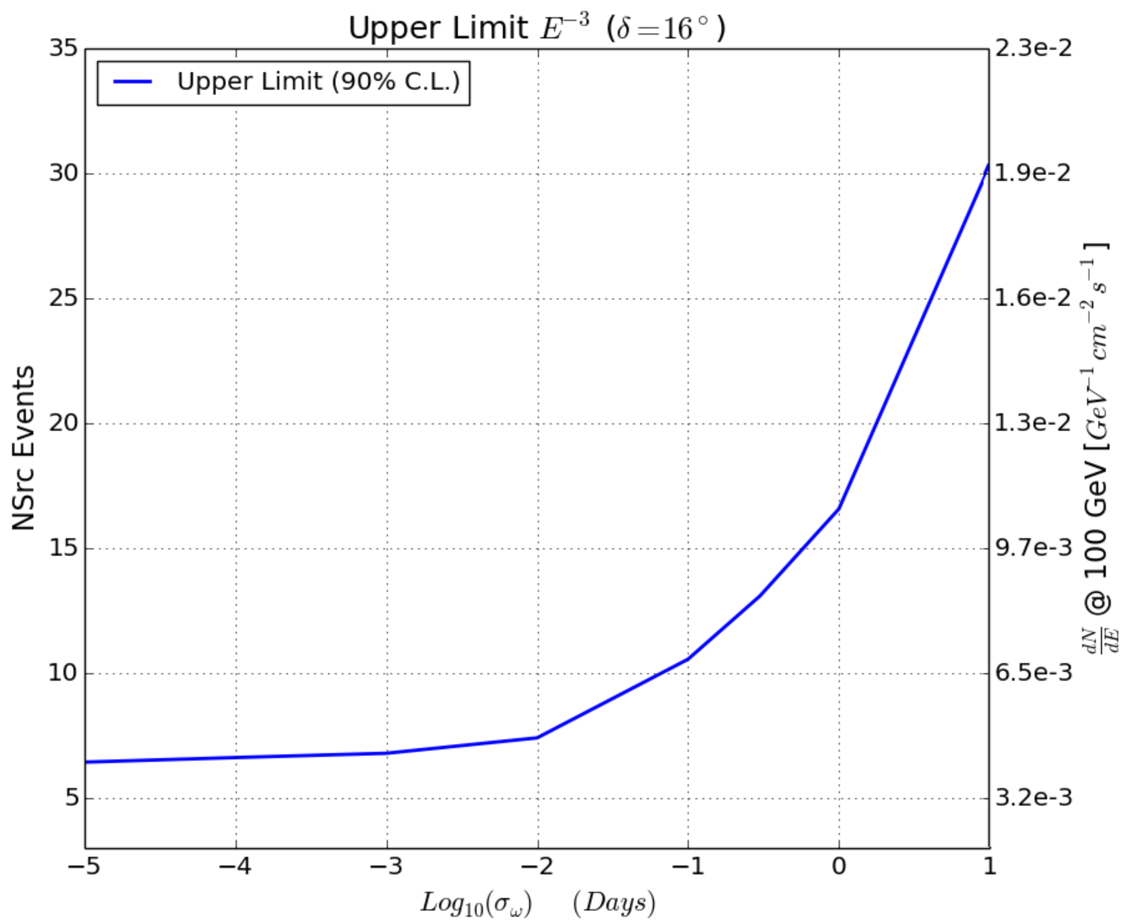

Fig. 3.— [add caption]

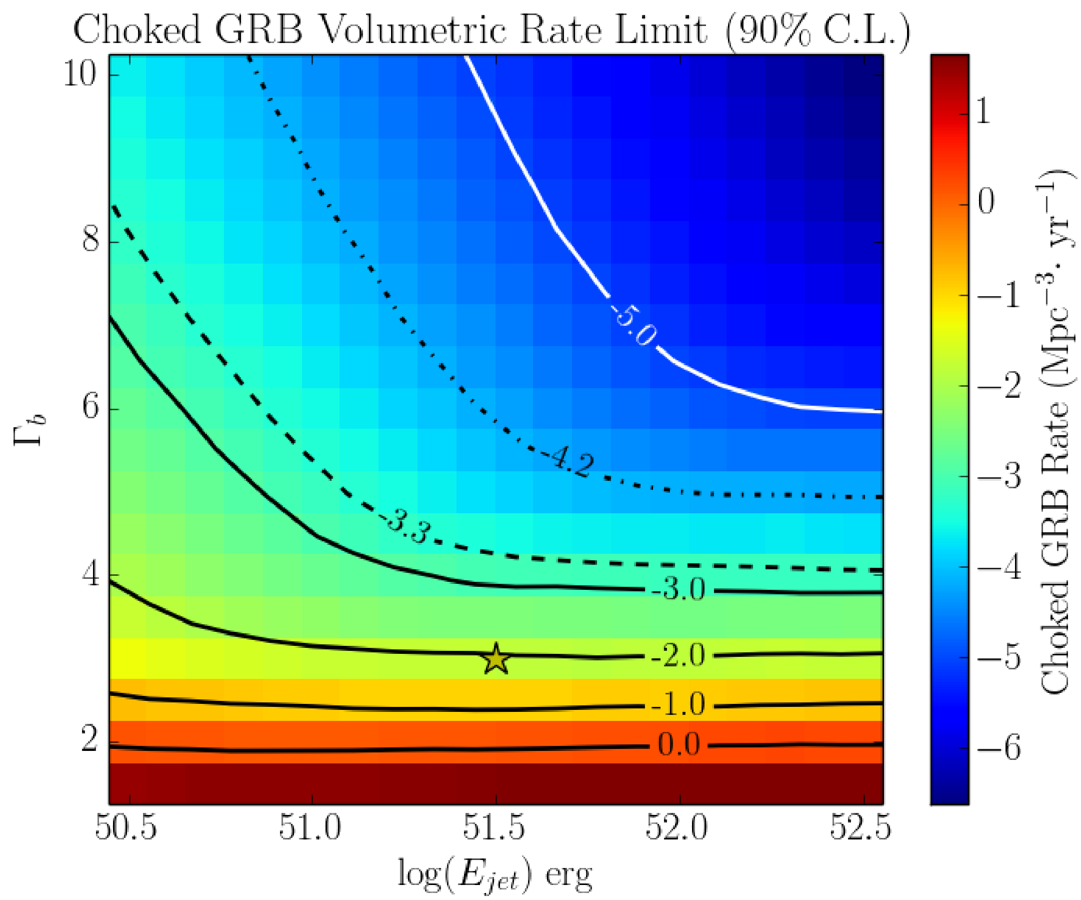

Fig. 4.— [add caption]

REFERENCES

Aartsen, M. G., Ackermann, M., Adams, J., et al. 2014, ApJ, 796, 109

—. 2015, ArXiv e-prints, arXiv:1503.00598

Abbasi, R., Abdou, Y., Abu-Zayyad, T., et al. 2012, Astroparticle Physics, 35, 615

Ando, S., & Beacom, J. F. 2005, Physical Review Letters, 95, 061103

Braun, J., Dumm, J., De Palma, F., et al. 2008, Astroparticle Physics, 29, 299

IceCube Collaboration, Achterberg, A., Ackermann, M., et al. 2006, Astroparticle Physics, 26, 155

Kent, J. T. 1982, Journal of the Royal Statistical Society. Series B (Methodological), 44, pp. 71

Razzaque, S., Mészáros, P., & Waxman, E. 2004, Physical Review Letters, 93, 181101

Taboada, I. 2010, Phys. Rev. D, 81, 083011