Results from high-energy neutrino searches from gamma-ray bursts with IceCube

N Whitehorn 1, for the IceCube Collaboration

1 Department of Physics, University of Wisconsin - Madison, Madison, WI 53706 USA
E-mail: nwhitehorn@icecube.wisc.edu

Abstract. IceCube, a cubic kilometer neutrino detector located in glacial ice at the South Pole, has recently become the first neutrino telescope with a sensitivity below the TeV-PeV neutrino flux predicted from gamma-ray bursts if GRBs are responsible for the observed extragalactic cosmic-ray flux. IceCube has so far not detected any evidence for the predicted neutrino fluxes, and so is beginning to constrain models of cosmic ray acceleration in GRBs.

1. Introduction
Gamma-ray bursts (GRBs) have long been proposed [1, 2] as the acceleration sites of the highest energy cosmic rays due to an aggregate power density in photons nearly matching that in cosmic rays. This hypothesis is difficult to verify experimentally – the transient nature of the sources makes direct correlation of cosmic rays impossible, and identifying hadronic signatures in gamma ray spectra is difficult. However, interactions of high-energy protons with the intense radiation in the environment of the burst should produce neutrinos by the following reactions [3]:

\[
p + \gamma \rightarrow n + \pi^+ \\
\pi^+ \rightarrow \mu^+ + \nu_\mu \\
\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e
\] (1)

These neutrinos are then expected to arrive at Earth with energies of approximately 100 TeV [3] with fluxes at a level that can be detected with large terrestrial detectors such as IceCube (Fig. 1). Observation of this neutrino flux would then provide unambiguous evidence for hadronic acceleration in GRBs, and strongly suggest that GRBs are responsible for some fraction of the ultra high-energy cosmic ray flux.

Here we present results from searches for these neutrinos using IceCube during construction, from the 40- and 59-string configurations of the detector (April 5, 2008 - May 31, 2010). Earlier results from only the 40-string configuration [4] observed no evidence for this flux, with a sensitivity slightly below the model predictions. Here we improve on the earlier study’s sensitivity by a factor of four, and continue to see no evidence for these neutrinos, with theoretical models [3, 5, 6, 7] predicting between 4 and 80 events during this period in IceCube.
2. The IceCube Detector

The IceCube detector [8] is a km$^3$ neutrino telescope embedded in antarctic glacial ice at the South Pole. It detects neutrinos by observing Cherenkov light from secondary charged particles produced in neutrino-nucleon interactions in the ice. This light is detected by an array of 5160 digital optical modules (DOMs), each containing a photomultiplier and readout electronics housed in a glass pressure sphere. These are arranged into an array of 86 vertical strings, each containing 60 DOMs at depths between 1450 m and 2450 m. Although sensitive to all neutrino flavors from all directions, IceCube’s highest sensitivity is to $\nu_\mu$ charged-current interactions from the northern sky: muons have good angular resolution ($\sim 1^\circ$) and their long track lengths in ice at the energies relevant to GRBs (10 km) allows IceCube sensitivity to neutrinos interacting outside the detector, improving its effective volume. Northern hemisphere neutrino searches also have much lower backgrounds than southern-hemisphere ones, as passing through the Earth eliminates cosmic ray muon backgrounds from the northern hemisphere; the requirement of time and space coincidence with a GRB provides enough background rejection, however, to allow some sensitivity in the south.

3. GRB Searches in IceCube

We conducted two analyses of the IceCube data, both searching for neutrino emission coincident with satellite detections of gamma-ray bursts, as reported through the GRB Coordinates Network [9]. Both used stacked catalogs (combining the event sample for all observed GRBs) and employed the same methods as in the 40-string search [4].

In a model-dependent analysis, we searched specifically for the predicted neutrino flux during the period of gamma-ray emission using the spectral prediction of [6] (Fig. 3). In a complementary model-independent analysis, we searched more generically for neutrinos with a wider range of energies and arrival times. The model-independent search, instead of examining the fixed time range of the bursts’ gamma-ray emission, used an expanding time window centered

Figure 2. Expected neutrino flux from GRBs in the 40-string sample from Guetta et al. [6], assuming the proton to electron energy ratio $\epsilon_p/\epsilon_e = 10$ (proportional to the flux), in light solid lines (some individual bursts) and in dark solid (in aggregate). The flux prediction from Waxman and Bahcall [3], normalized as in [10] is shown in a dashed line.
Figure 3. Limits from the model-independent analysis. One low-energy event was observed 30 seconds after GRB 091026A (pictured), but was 4.5 degrees off-source and triggered the IceTop surface air shower array [8] and thus is unlikely to be a neutrino.

(a) Limits on an $E^{-2}$ spectrum from the model-independent analysis. $\Delta t = t$ implies all events between $t$ seconds before the GRBs and $t$ seconds afterward.

(b) Limits on the spectrum from Guetta et al. [6] from the model-independent analysis, normalized to the proton/electron energy ratio $\epsilon_p/\epsilon_e = 10$, which is proportional to the neutrino flux.

on the burst time and expanding in 1-second increments in both directions to encompass a 2-day period centered on the GRB time. To avoid bias and maximize signal acceptance, the model-independent search also avoided hard event-quality cuts wherever possible, replacing them with weights. Both analyses shared a catalog of 215 northern-hemisphere GRBs during the IceCube 40 and 59 string runs, with an additional 85 southern-hemisphere bursts included in the 59-string model-independent search, and obtained similar results when evaluating the same models.

No signal-like events were observed in either analysis. One event was observed 30 seconds after GRB 091026A in the model-independent search, but is unlikely to be a neutrino: it arrived substantially off-source ($4.5^\circ$) and triggered the IceTop surface air shower array [8], which suggests it was produced in a cosmic ray shower. This non-observation can be used to set limits (Fig. 3) on all of the tested models [3, 5, 6, 7] substantially below their predictions.

4. Conclusions

There are two principle ways, aside from modifying the description of the burst physics, to adjust the models in a way that reduces the predicted neutrino fluxes into the region allowed by these results: modifications of the flux normalization, or modification of the spectrum to place the bulk of the events in regions where fluxes are lower or IceCube is not as sensitive. The flux normalization is proportional to the rate of $p\gamma$ interactions in the burst fireball. Above the threshold for the processes in (1), the neutrino flux is proportional to the densities of photons (measured) and protons (unknown). As such, it can be reduced by lowering the proton content of the fireball (below the level required to explain the cosmic ray spectrum). Alternatively, the threshold for pion production can be increased by increasing the Lorentz boost factor of the shocks ($\Gamma$), reducing the energies of the particles in the rest frame of the shock. Because of the increasing neutrino cross-section, the event rate in IceCube decreases only logarithmically with the threshold energy, and so $\Gamma$ must be increased to very high values (> 1000 in some cases) to be consistent with our limits. The normalization in some models [3, 6] is proportional to $\Gamma^{-4}$, so the limit is less stringent in those cases, but is still > 450, compared to the usual assumption of $\sim 300$.

These limits are especially stringent in the case of models that have cosmic rays escape the
fireball as neutrons [5, 7]. The neutrons are produced in the same $p\gamma$ reactions as the neutrinos (1), and so the neutrino flux is directly proportional to the cosmic-ray flux. In these cases, $\Gamma$ also sets the threshold energy for the escape of cosmic rays from the fireball. The very high values of this parameter required to be consistent with our models if the entire extragalactic cosmic-ray flux is produced in GRBs then severely constrain the allowed cosmic ray spectrum from these sources, nearly pushing its beginning above the point at which the extragalactic cosmic rays are believed to become dominant at $4 \times 10^{18}$ eV (Fig. 4).

Acknowledgments
This work was made possible through the NSF Graduate Research Fellowship Program.

References
[1] E. Waxman. Cosmological gamma-ray bursts and the highest energy cosmic rays. Phys. Rev. Lett., 75:386–389, July 1995.
[2] M. Vietri. The Acceleration of Ultra–High-Energy Cosmic Rays in Gamma-Ray Bursts. Astophysical Journal, 453:883, November 1995.
[3] E. Waxman and J. Bahcall. High energy neutrinos from cosmological gamma-ray burst fireballs. Phys. Rev. Lett., 78:2292–2295, March 1997.
[4] R. Abbasi et al. Limits on Neutrino Emission from Gamma-Ray Bursts with the 40 String IceCube Detector. Phys. Rev. Lett., 106:141101, 2011.
[5] J. P. Rachen and P. Mészáros. Cosmic rays and neutrinos from gamma-ray bursts. In C. A. Meegan, R. D. Preece, & T. M. Koshut, editor, Gamma-Ray Bursts, 4th Hunstville Symposium, volume 428 of American Institute of Physics Conference Series, pages 776–780, May 1998.
[6] D. Guetta, D. Hooper, J. Alvarez-Muñiz, F. Halzen, and E. Reuveni. Neutrinos from individual gamma-ray bursts in the batse catalog. Astroparticle Physics, 20:429–455, January 2004.
[7] M. Ahlers, M. C. Gonzalez-Garcia, and F. Halzen. GRBs on probation: Testing the UHE CR paradigm with IceCube. Astroparticle Physics, 35:87–94, September 2011.
[8] R. Abbasi et al. The IceCube data acquisition system: Signal capture, digitization, and timestamping. Nuclear Instruments and Methods in Physics Research A, 601:294–316, April 2009.
[9] GRB Coordinates Network. http://gcn.gsfc.nasa.gov.
[10] E. Waxman. Astrophysical sources of high energy neutrinos. Nucl. Phys. B Proc. Suppl., 118:353–362, April 2003.