

Searches for Neutrinos from Gamma Ray Bursts with AMANDA-II and IceCube

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Abstract. The hadronic fireball model predicts a neutrino flux in the TeV to several PeV range simultaneous with the prompt photon emission of GRBs. The discovery of high energy neutrinos in coincidence with a gamma ray burst would help confirm the role of GRBs as accelerators of high energy cosmic rays. We summarize the methods employed by the AMANDA experiment in the search for neutrinos from GRBs and present results from several analyses.

1. Neutrinos From GRBs

Gamma Ray Bursts (GRBs) are one of the most plausible sources of ultra-high energy cosmic rays [1, 2]. Detection of high energy neutrinos from a burst would provide corroborating evidence for the production of ultra-high energy cosmic rays inside GRBs.

It is believed that gamma rays produced by GRBs originate from electrons accelerated in internal shock waves associated with relativistic jets (with Lorentz boost $\Gamma \sim 300$). These gamma rays have energies in the range from 10 keV to greater than 10 MeV. The gamma ray spectrum can be described as a broken power law, with a softer spectrum above a break energy which is typically 0.25-1 MeV. Gamma ray bursts can last anywhere from a few milliseconds up to a few hundred seconds. The distribution of durations is usually considered to be composed of two separate classes, with short bursts lasting less than 2 seconds and long bursts lasting more than 2 seconds [3]. Gamma ray bursts are reviewed in [4] and [5].

If protons and/or nuclei are also accelerated in the jets, then high energy neutrinos ($\sim 10^{14}$ eV) are produced [1] via the process:

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

The neutrino flavor ratio $\nu_e:\nu_\mu:\nu_\tau$ is thus 1:2:0 at source. Taking into account neutrino oscillations, the flavor ratio observed at Earth is 1:1:1 [6]. However, Kashti and Waxman [7] point out that at energies greater than ~ 1 PeV, the μ^+ in Equation (1) loses energy through synchrotron radiation before decaying. This energy loss changes the source neutrino flavor ratio at high energies from 1:2:0 to 0:1:0, leading to a ratio at Earth of 1:1.8:1.8.

Neutrino production is predicted to be simultaneous with gamma ray production. AMANDA GRB analyses use the Waxman-Bahcall [1] broken power law neutrino spectrum as a reference hypothesis (see Fig. 1). However, other models of prompt neutrino emission have also been

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tested. These include the parameterization of Murase and Nagataki [8], who arrive at a similar spectrum to Waxman-Bahcall under different assumptions, as well as the supranova scenario (now disfavored due to evidence from the Swift satellite) which assumes GRB jet interactions with an external matter field created by a supernova preceding the burst by ~ 1 week [9]. Predictions have also been made for precursor [10] and afterglow [11] emission.

2. The AMANDA Detector

The Antarctic Muon and Neutrino Detector Array (AMANDA) [12, 13] is located at the South Pole. From 1997 to 1999, AMANDA consisted of 302 optical modules on 10 strings and was referred to as AMANDA-B10. The final configuration, AMANDA-II, was commissioned in the year 2000 and consists of a total of 677 optical modules on 19 strings. Each module contains a photomultiplier tube and supporting hardware inside a pressurized glass sphere. The optical modules are used to indirectly detect neutrinos by measuring the Cherenkov light from secondary charged particles produced in neutrino-nucleon interactions.

AMANDA uses two detection channels. Muon tracks are produced through interactions of ν_μ , while cascades (particle showers) are produced from interactions of all three neutrino flavors. The muon channel has a larger effective area because of the longer range of muons compared to cascades. It also has better pointing resolution because muons produce linear tracks rather than spherical showers. Separating neutrino signals from the dominant atmospheric muon background is accomplished by removing downgoing events, so muon analyses have $\sim 2\pi$ sr sky coverage. Cascades are differentiated from downgoing muons by their shape and therefore cascade analyses have full (4π sr) sky coverage. Cascade events also have better energy resolution than muon tracks, since the energy of all particles produced in the shower is accounted for.

3. AMANDA GRB Analyses

In the majority of GRB analyses, searches are done in coincidence with γ -ray detections by satellites. Because these analyses only search for a neutrino signal during the time and (in the case of muon channel searches) in the location of measured bursts, there is almost no on-source background in these analyses. The period of time actually examined for a neutrino signal for each burst is equal to the measured duration of prompt gamma-ray emission, plus the uncertainty in this measurement, plus an additional second on each side of the on-time window. Background was measured for a period of one hour both before and after each burst, with the ten minute period immediately surrounding the burst remaining unexamined to avoid the possibility of contaminating the background with neutrino signal. In the muon channel, searches for prompt emission have been conducted for 312 bursts measured by the BATSE detector (aboard the CGRO satellite) and 95 bursts analyzed by the IPN3 satellite. Additionally, a search for precursor emission was conducted using 60 bursts from the 2001-2003 data sets [14]. Using the cascade channel, 73 bursts identified by the BATSE detector in the year 2000 have been studied [15]. No events have been observed in coincidence with any bursts studied so far, which is consistent with the expected background.

The *rolling* analysis provides a useful complement to these triggered searches. This method does not use satellite triggers, but scans an entire multi-year data sample for a statistical excess of events within one of two pre-set time windows (to account for both long and short burst classes). This allows this analysis to search for GRBs and other transients not identified by satellites. The rolling search has been conducted for the years 2001-2003 (after the BATSE detector was ceased operations and before the Swift satellite launched) using the cascade channel. Due to the larger amount of data analyzed relative to the triggered analyses, more stringent cuts on the data are required. Thus, background rejection was accomplished with a six cut-variable Support Vector Machine, optimized for the best chance for signal discovery. As in the case of the triggered searches, no evidence of astrophysical neutrinos has been found with this analysis

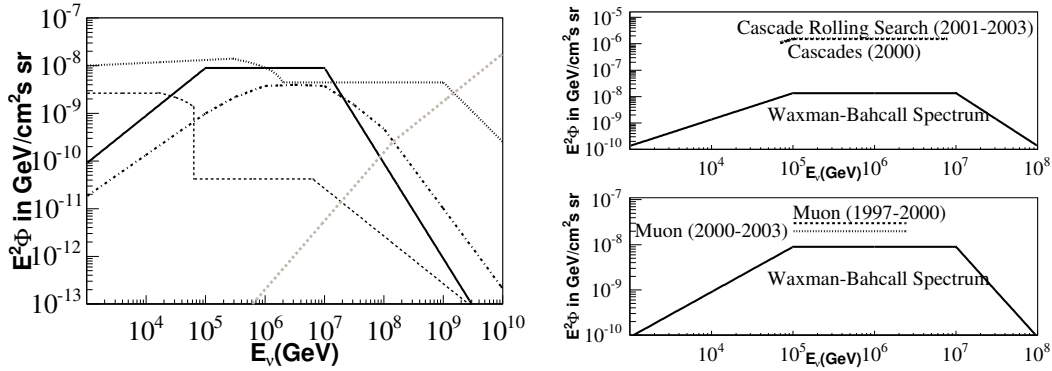


Figure 1. Left: Models of neutrino emission from GRBs: Solid: Waxman-Bahcall; Dotted: Supranova; Dash-Dotted: Murase-Nagataki; Light Dashed: Afterglow; Dark Dashed: Precursor Emission. Right: Experimental limits relative to Waxman Bahcall spectrum for cascade(top) and muon(bottom) channels, with displayed ranges containing 90% of simulated signal events.

method. The maximum number of observed events and the numbers of observed windows with multiple (2 or 3) events is consistent with the predicted background [15].

Although the Waxman-Bahcall neutrino spectrum functions as a reference for GRB analyses, it has been demonstrated that neutrino spectra from individual bursts can vary significantly from this “standard” spectrum [16, 17]. Current AMANDA analyses are using more sophisticated methods to predict the spectrum and neutrino rates for individual bursts rather than assuming averaged parameters. The particularly close and bright burst GRB030329 was the first burst to be given this individualized treatment [18]. Bursts detected by Swift, many of which have redshifts directly measured from afterglow data, will be especially conducive to this method.

IceCube, the successor to AMANDA, is currently under construction, with the final detector scheduled to be completed by 2011. Preliminary studies indicate that a triggered search using 300-500 bursts with the full IceCube array would suffice to either set limits at levels lower than the predictions by Waxman-Bahcall or find evidence of the existence of neutrinos in coincidence with GRBs with better than 5σ confidence.

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