AMANDA Search for High-Energy Neutrinos Accompanying Gamma Ray Bursts

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Abstract

The photo-meson production of pions from shock-accelerated protons could result in a burst of $\sim 10^{14}$ eV neutrinos coincident with gamma ray bursts (GRBs) which generates an appreciable signal in the Antarctic Muon and Neutrino Detector Array (AMANDA). Satellite coincidence provides both spatial and temporal information, which greatly reduces AMANDA background and permits positive detection even with small neutrino fluxes. With tight enough temporal correlation on internal-shock time scales of a few seconds or less, a signal can be extracted without directional reconstruction. It might also be possible to detect muon secondaries produced by gamma showers in the Earth's atmosphere in order to observe the GRB flux beyond GeV energies, which eludes small satellite-borne instruments. A search method is described here, and quantitative results will be given in the oral presentation.

1 Motivation

Afterglow observations have established that most gamma ray bursts are at cosmological distances and testify to an energy release in gammas alone between 10^{51} and 10^{54} ergs assuming isotropic emission. They also provide confirmation of a generic relativistic fireball shock model. An inner engine produces a flow of gammas and electron-positron pairs which is initially optically thick to pair production. The plasma accelerates to $\Gamma \approx 100$ and the gammas escape with a non-thermal spectrum. The fireball may contain a small baryon load, and eventually most of its energy will be converted to kinetic energy of these baryons. A "baryon contamination" of more than about $10^{-4} M_\odot$ will cause the acceleration to saturate at a $\Gamma = \frac{E}{Mc^2}$ that is too low for escape. Once the flow becomes optically thin, shocks convert the bulk wind energy to radiation. The inner engine must be sufficiently variable over the duration of the burst so that shells with Γ differing by a factor 2 or so collide internally over time scales of seconds and length scales of 10^{12} to 10^{14} cm to produce the prompt gamma emission. External shocks between the outflow and the interstellar medium over a Sedov length scale of about 10^{16} cm are probably responsible for the afterglow at longer wavelengths, which may continue on time scales of days (Piran, 1998, and references therein).

It is natural to consider GRBs to be the relativistic analog to supernova remnants. The two phenomena involve comparable energies and both convert kinetic energy of ejected matter into radiation: gamma ray emission as a result of internal shocks in the case of GRBs, and optical emission as a result of external shocks in the case of supernova remnants. But whereas supernovae have a large optical depth, non-relativistic outflow ($\Gamma < 1.02$) and notoriously low efficiency, GRBs require small optical depth, relativistic outflow, and reasonably high efficiency to avoid energy constraints. Just as supernovae are invoked to explain cosmic ray energies up to 10^{15} eV, GRBs represent a prime candidate source for cosmic rays beyond the "ankle" at 10^{18} eV. The injection rate of gammas by GRBs is consistent with that needed to produce the high energy tail of cosmic rays.

Waxman and Bahcall have shown that within the fireball shock model, such GRBs should provide an astrophysical environment for a beam dump, in which a burst of high-energy neutrinos is produced through photo-meson production of pions (Waxman & Bahcall, 1997) (Vietri, 1998). Protons in the flow are shock-accelerated to a power law spectrum $N(\epsilon_p) \propto \epsilon_p^{-2}$ consistent with that observed in extremely high-energy cosmic rays. These protons then interact through the Δ-resonance with GRB photons, primarily those at the BATSE break energy of 300keV. Neutrinos of energy ~100TeV are produced, provided that energy

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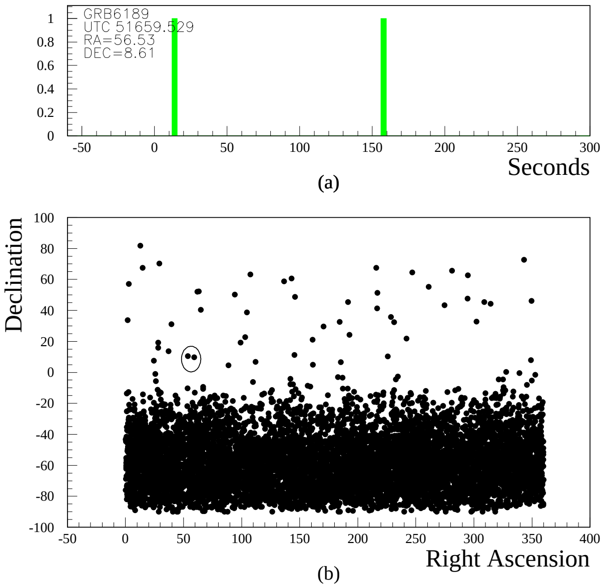
losses within the cascade are not significant. The event rate at 10^{14} eV in a km^2 detector is predicted to be 10 to 100/year. Proton acceleration to ultra high energies might continue on longer time scales within external shocks (Vietri, 1998).

A measurement of the GRB neutrino flux can test this hypothesis of GRBs as the origin of the highest energy cosmic rays, and also some aspects of the fireball shock model. Since no ν_τ are expected to be produced in the source, an appearance would be clear evidence of neutrino oscillation at a value of Δm^2 as low as 10^{-16} eV^2. Like SN1987A, GRBs could permit even stronger tests of the neutrino limiting speed and the weak equivalence principle at levels of 10^{-16} and 10^{-6}, respectively, due to their short duration.

2 Method

AMANDA is a high-energy neutrino telescope being constructed within the South Pole ice cap (see Hill, 1999). During the 1997 austral winter the array consisted of 302 8” optical modules arranged on 10 strings at depths between 1.5 and 2 km in roughly a right cylinder of 60 meter radius, presenting an effective area for muon tracking on the order of $10,000$ m^2. The Burst and Transient Source Experiment (BATSE) onboard the Compton Gamma Ray Observatory reported 304 bursts in 1997 (Meegan et al.), and AMANDA was online for about 70% of the year. Including roughly half of this live time results in a data set of 100 GRBs, of which 53 occurred in the Northern Hemisphere. BATSE reports both the statistical error radius of a 68% confidence ellipse, as well as a 73% probability systematic error of $1.9°$. These are combined in quadrature to give the total BATSE error bin, and this is then added in quadrature to 1.6 times the AMANDA angular resolution to give the joint error box (Alexandreas et al., 1983). Coincident events are those which fall inside and are less than $15°$ from the center of the circle. This angle is chosen arbitrarily in order to exclude those events which are far off in direction but still qualify because of large BATSE errors for weak bursts.



(a)

(b)

Figure 1: The time profile (a) of events passing the error circle cut (b) within [-1,5] minutes of the BATSE trigger time for a particular burst. All events contain at least 5 optical module responses within [-15,25] nanoseconds of the Čerenkov time, presumably from minimally scattered photons. The dense field of points across the bottom in (b) is the downgoing atmospheric muon background.

The bursts can be examined as a complete composite sample or in smaller subsets. The number of coincidences is counted versus time, inferred burst energy, and other BATSE observables. The total fluence and peak flux are available for most bursts when BATSE is able to capture a complete time profile, although the experiment could have significant energy biases. Their highly variable light curves make the “start” of GRBs difficult to define and absolute times are generally not known to better than 64 milliseconds (Meegan, 1998). Time zero can be taken as the BATSE trigger time, or the beginning of the T90 interval should it come earlier. It is also reasonable to search on a scale relative to the time of the peak in flux. GRBs separate somewhat into two classes, those shorter than 1 second with relatively hard spectra, and those which are longer and generally softer. While the specific nature of the progenitor is not of vital importance in the fireball shock description, some suggest the possibility of two different mechanisms corresponding to two classes of progenitors at appreciably different distance

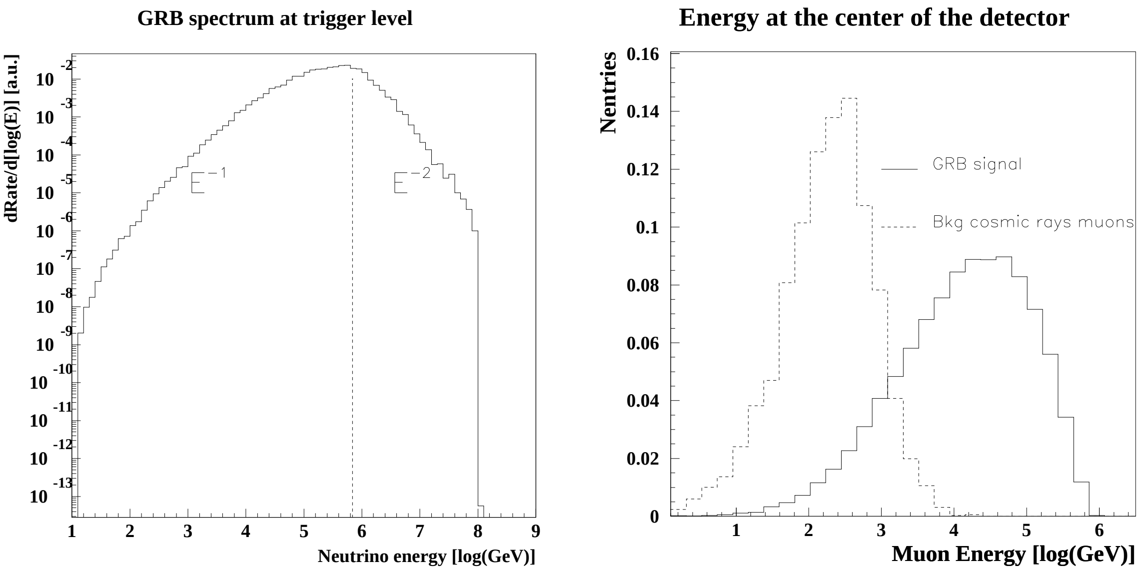


Figure 2: (*Left*) Monte Carlo calculation gives the event rate in arbitrary units as a function of energy. The rate is a convolution of the neutrino flux and the probability of conversion to a muon within range of the detector. (*Right*) The GRB signal should be discernible from background in energy. (Barouch & Hill, 1999)

scales (Fryer, Woosley, & Hartmann, 1999).

Neutrino candidate searches in the current AMANDA typically involve a battery of event quality cuts which suppresses signal by 99% (Karle, 1999) (Hundertmark, 1999). Since GRBs are a transient phenomenon and BATSE provides both position and time, quality criteria can be relaxed and the sensitivity greatly increased. An internal-shock time scale of several seconds or less is experimentally the most promising to reduce background to manageable levels. With no event quality cuts, requiring directional coincidence decreases background by an additional factor of ~ 1000. Within very short intervals, temporal coincidence alone could provide sufficient background rejection in cases where reconstruction is poor, for instance for large events which develop too far outside the fiducial volume or for showers. GRBs in the Southern Hemisphere, a region of the sky which is generally difficult to search for neutrino sources with AMANDA due to a large downgoing atmospheric muon background, could also be observed, effectively doubling the size of the data sample. The optimal cut levels for such a measurement are determined through Monte Carlo simulation (see Fig. 2).

The AMANDA background is at minimum a function of direction and the temperature of the atmosphere (Bouchta, 1999), and such complications can be accounted for with an on-off source method. The off-source error circle is taken at the same zenith and azimuth as the GRB but at a different time, either from the same data run sufficiently before the GRB or an average in that error bin over the course of the year. The AMANDA angular resolution is comparable to that of BATSE and the prescription of Li and Ma may be applied (Funk, 1997) (Li & Ma, 1983),

$$S = \frac{N_{on} - N_{off}}{\sqrt{N_{on} + N_{off}}},$$

in which fluctuations of both signal and background are accounted for in any measure of significance.

On time scales of less than a second, it might be possible to observe the *gamma* flux at energies beyond those accessible to satellite-borne instrumentation (Alvarez-Muñiz & Halzen, 1999). The high-energy emission of GRBs is not well understood, and radiation of TeV energy and higher from GRBs above the horizon can be observed by detecting muon secondaries produced by the gammas showering in the atmosphere using low threshold, large area detectors such as Milagro or possibly AMANDA. Signal integration time should be limited in order to manage the large background.

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