Neutrinos from Gamma Ray Bursts

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Abstract

We show that the detection of neutrinos from a typical gamma ray burst requires a kilometer-scale detector. We argue that large bursts should be visible with the neutrino telescopes under construction. We emphasize the 3 techniques by which neutrino telescopes can perform this search: by triggering on i) bursts of muons from muon neutrinos, ii) muons from air cascades initiated by high energy gamma rays and iii) showers made by relatively low energy ($\approx 100$ MeV) electron neutrinos. Timing of neutrino-photon coincidences may yield a measurement of the neutrino mass to order $10^{-5}$ eV, an interesting range in light of the solar neutrino anomaly.
1. Introduction

The origin of gamma ray bursts (GRBs) is arguably astronomy’s most outstanding puzzle[1]. Contributing to its mystery is the failure to observe counterparts in any other wavelength of light. It should therefore be a high priority to establish whether GRBs emit most of their energy in neutrinos[2, 3, 4] as expected in the (presently favored) cosmological models.

It is not the purpose of this paper to study the modelling of GRBs. We will consider two cosmological scenarios: ultra-relativistic fireballs[5] and cosmic strings[6] and reduce their predictions to dimensional analysis, omitting details which represent at best unfounded speculations. After imposing experimental constraints on the dimensional analysis, it suffices to quantitatively frame the question of neutrino emission. The “experimental facts”, which will later constrain our model parameters, can be encapsulated as follows[3]: i) there are about 100 bursts per year with an average fluency in photons of $F_{\gamma} \gtrsim 10^{-9} \text{J m}^{-2}$, ii) they are concentrated, on average, at a redshift of $z \simeq 1$, iii) some bursts last less than 10 s, and iv) they do not repeat on a time-scale of 1 year or less. Our predictions will be presented in a form in which they can be scaled to fit varying interpretations of the experimental situation. Our interpretation of the observational situation, as well as the models presented, seem to be currently favored, although there are some dissenters. For example, some advocate that the origin of GRBs can be traced to an extended halo population of neutron stars. However, the predictions of such models for neutrino emission may in the end differ only slightly, since the reduced luminosity, compared to large-redshift sources, is compensated for by a reduced distance to the source.

Our results can be summarized as follows. The detection of typical GRBs requires kilometer-scale neutrino telescopes. GRBs provide us with yet another example of Nature’s conspiracy to require kilometer-size detectors for exploring our science goals[7], from dark matter searches to the study of active galaxies. Rare, large bursts may however be within reach of the present experiments. Our results will demonstrate that non-observation will lead to meaningful constraints on the models. In particular, it is unlikely that cosmic string models can escape the scrutiny of the detectors presently under construction, because they predict a fluency in neutrinos which exceeds that for photons by a factor of order $10^8$ or more.
Furthermore, we will emphasize the 3 techniques by which neutrino telescopes can search for GRBs. All detectors, such as the DUMAND and NESTOR deep ocean experiments, can search for short bursts of high energy muons of $\nu_\mu$-origin. Sensitivity is good, i.e. atmospheric backgrounds small, because the signal integrates over very short times and does not have to be searched for; one looks at times given by the gamma ray observations. The shallower detectors like AMANDA and Baikal can also search for the muons made in air showers initiated by TeV gamma rays of GRB origin. Finally, AMANDA can use its supernova trigger to identify excess counting rates in the optical modules associated with a flux of MeV-GeV $\nu_e$’s for the duration of a gamma ray burst.

It has not escaped our attention that the observation of coincident bursts of neutrinos and gamma rays can be used to make a measurement of the neutrino mass. The mass is determined from the time delay $t_d$ by simple relativistic kinematics with $m_\nu = E_\nu \sqrt{2c t_d/D}$. With $t_d$ possibly of order milliseconds, distances $D$ of thousands of Megaparsecs and energies $E_\nu$ similar to that of a supernova, neutrino observations from GRBs could improve the well-advertised limit obtained from supernova SN1987A by a factor $10^6$. The sensitivity of order $10^{-5}$ eV is in the range implied by the solar neutrino anomaly. The measurement would be greatly facilitated by the fact that, unlike for rare supernova events, repeated observations are possible.

2. **Accelerator I: The Relativistic Fireball Scenarios**

Although the details can be complex, the overall idea of fireball models is that a large amount of energy is released in a compact region of radius $R \approx 10^2$ km $\approx c \Delta t$. The shortest time-scales, with $\Delta t$ of order milliseconds, determine the size of the initial fireball. Only neutrinos escape because the fireball is opaque to photons. In GRBs a significant fraction of the photons is indeed above pair production threshold and produce electrons. It is straightforward to show that the optical depth of the fireball is of order $10^{13}$. It is then theorized that a relativistic shock, with $\gamma \approx 10^2$ or more, expands into the interstellar medium and photons escape only when the optical depth of the shock has been sufficiently reduced. The properties of the relativistic shock are a matter of speculation. They fortunately do not
affect the predictions for neutrino emission.

For a fluency $F = 10^{-9} \text{ J m}^{-2}$ and a distance $z = 1$ the energy required is

$$E_\gamma = 2 \times 10^{51} \text{ erg} \left( \frac{D}{4000 \text{ Mpc}} \right)^2 \left( \frac{F}{10^{-9} \text{ J m}^{-2}} \right),$$

using $E_\gamma = 4\pi D^2 F$. The temperature $T_\gamma$ is obtained from the energy density

$$\rho = \frac{E_\gamma}{V} = \frac{1}{2}h a T^4,$$

where $h$ represents the degrees of freedom ($h_\gamma = 2$ and $h_\nu = 2 \cdot 3 \cdot \frac{7}{8}$ for 3 species of neutrinos and antineutrinos), $V$ the volume corresponding to radius $R$ and $a = 7.6 \times 10^{-16} \text{ J m}^{-3} \text{ K}^{-4}$.

We find that

$$T_\gamma = 8 \text{ MeV} \left( \frac{E_\gamma}{2 \times 10^{51} \text{ erg}} \right)^{1/4} \left( \frac{100 \text{ km}}{R} \right)^{3/4}. \tag{3}$$

For neutrinos

$$T_\nu = \left( \frac{E_\nu}{h_\nu h_\gamma} \right)^{1/4} T_\gamma. \tag{4}$$

For a merger of $n$-stars, for instance, the release of a solar mass of energy of $2 \times 10^{53} \text{ erg}$ implies a total energy emitted in neutrinos $\sim 10^2 E_\gamma$. The $\gamma$’s are most likely produced by bremsstrahlung of electrons from $\nu\bar{\nu}$ annihilation. The actual predictions for the energy and time structure of the photon signal depend on the details of the shock which carries them outside the opaque fireball region of size $R$. The data suggest that the structure of these shocks is complex. Neutrinos, on the contrary, promptly escape and carry direct information on the original explosion. From (3),(4) we obtain $T_\nu \simeq 2.5T_\gamma \simeq 20 \text{ MeV}$. Using this and a total neutrino energy in the fireball of $10^2 E_\gamma$ we obtain

$$E_\nu = 3.15 T_\nu = 65 \text{ MeV} \left( \frac{E_\gamma}{2 \times 10^{51} \text{ erg}} \right)^{1/4} \left( \frac{100 \text{ km}}{R} \right)^{3/4}, \tag{5}$$

$$\Delta t_{\text{obs}} = 0.3 \text{ msec} \left( \frac{R}{100 \text{ km}} \right). \tag{6}$$

The neutrino fluency is obtained from $E_\nu_{\text{tot}}/(4\pi D^2)$

$$N_\nu = 10^4 \text{ m}^{-2} \left( \frac{E_\nu_{\text{tot}}}{2 \times 10^{53} \text{ erg}} \right) \left( \frac{65 \text{ MeV}}{E_\nu} \right) \left( \frac{4000 \text{ Mpc}}{D} \right)^2 \tag{7}$$
or more than $10^{57}$ $\nu$’s at the source. Notice that this prediction is rather model-independent because it just relies on the fact that a solar mass of energy is released in a volume of 100 kilometer radius which is determined by the observed duration of the bursts.
Although the $\sim 100$ MeV-neutrinos are below the muon threshold of high energy neutrino telescopes, the $\bar{\nu}_e$ will initiate electromagnetic showers by the reaction $\bar{\nu}_e + p \rightarrow n + e^+$ which will be counted by the AMANDA supernova trigger.

A supernova with properties similar to those of SN1987A can cause a 10 second burst of neutrinos in the AMANDA detector with $E_\nu \simeq 40$ MeV. They produce positrons with, on average, half that energy. Detailed simulations\cite{10} of the supernova signal in the AMANDA detector have shown that each photomultiplier tube (PMT) has a seeing radius $d \simeq 7.5$ m for 20 MeV positrons. The number of events per PMT is given by

$$\#N_{\nu \text{obs}} \simeq N_\nu (\pi d^2) \left( \frac{d}{\lambda_{\text{int}}} \right).$$

(8)

The last factor estimates the probability that the $\bar{\nu}_e$ produces a positron within view of the PMT. Here

$$\lambda_{\text{int}}^{-1} = \frac{2}{18} A \rho \sigma_0 E_\nu^2,$$

(9)

with

$$\sigma_0 = 7.5 \times 10^{-40} \text{ m}^2 \text{ MeV}^{-2}.$$  

(10)

$A$ is Avogadro’s number and $\rho$ the density of the detector medium. One should not forget here that the dependence of the cross section on neutrino energy is linear rather than quadratic above $\sim 100$ MeV.

We have checked by Monte Carlo\cite{11} that the seeing volume scales linearly in the energy of the positron, or neutrino, up to TeV energies. Eventually the radius will cease to grow due to attenuation of the light. With absorption lengths of several hundred meters\cite{12} this upper limit is outside the range of where we will apply (8). Therefore, the event rate for GRBs is given by (8) with $d = 7.5$ m $\left(\frac{30 \text{ MeV}}{20 \text{ MeV}}\right)^{1/3}$. Here 30 MeV is the positron energy which is, on average, half the neutrino energy given by Eq. (5).

Can this signal be detected by simple PMT counting? Signal $S$, noise $N$ and $S/\sqrt{N}$, for an average burst, are given by

$$S = 10^{-3} \text{ events } \left( \frac{N_{\nu\text{obs}}}{5 \times 10^{-6}} \right) \left( \frac{D_{\text{PMT}}}{20 \text{ cm}} \right)^2 \left( \frac{N_{\text{PMT}}}{200} \right),$$

(11)

$$N = 60 \text{ events } \left( \frac{\Delta t}{0.3 \text{ msec}} \right) \left( \frac{N_{\text{back}}}{1 \text{ kHz}} \right) \left( \frac{N_{\text{PMT}}}{200} \right),$$

(12)

$$S/\sqrt{N} = 10^{-4} \left( \frac{N_{\text{back}}}{1 \text{ kHz}} \right)^{-1/2} \left( \frac{D_{\text{PMT}}}{20 \text{ cm}} \right)^2 \left( \frac{N_{\text{PMT}}}{200} \right)^{1/2}.$$

(13)
AMANDA has been chosen for reference with 200 PMTs with a diameter $D_{\text{PMT}}$ of 20 cm and a background counting rate of roughly 1 kHz. With such low rates in millisecond times, observation obviously requires a dedicated trigger.

Obviously the event rate for an average burst is predicted to be low. We will argue nevertheless that observation is possible and clearly guaranteed for kilometer-scale detector with several thousand PMTs. First, the parameters entering the calculation are uncertain. The event rate increases with neutrino energy as $E_\nu^3$ because of the increase of the PMT seeing distance $d$ and the neutrino interaction cross section $\sigma_0$. With increased energy the average burst may become observable. Individual burst can yield orders of magnitude higher neutrino rates because of intrinsically higher luminosity and/or smaller than average distance to earth. For example, a burst 10 times closer than average and 10 times more energetic is observable with a significance of well over 10 $\sigma$ in the existing AMANDA detector. Given the uncertainties in the model and its parameters as well as the chaotic nature of the phenomenon (there is no such thing as an average GRB), this event represents a plausible possibility.

As demonstrated by the $\gamma$-ray observations, the structure of the shock producing the gamma rays is complex. The interaction of multiple shocks can also produce neutrinos on other time-scales and with different, sometimes much higher, energies[2]. So one should have an open mind when searching for bursts. This is underscored by the rather different predictions obtained from string-type models, which we discuss next.

3. Accelerator II: Cosmic String-Type Scenarios

The dimensional analysis relevant to accelerators such as cosmic strings is synchrotron emission from a beam of ultra-relativistic particles. The time of emission is now given by

$$\Delta t_{\text{lab}} = \frac{L}{c\gamma^3}. \quad (14)$$

Here $L$ is the size of the accelerator and $\gamma = I_{\text{saturation}}/I$ is a ratio of electric currents, which is some large number. One main difference with the previous scenario is that the emission is relativistically beamed in a solid angle of size $\gamma^{-2}$. The idea is that when accelerated currents reach a value $I_{\text{saturation}}$ it is energetically more favorable to radiate away the mass of the accelerating cosmic source, rather than sustain the high current. This happens for
instance at cusps in oscillating loops where the current becomes, theoretically, infinitely large. A mass $\mu$ per unit length $L$ is radiated away in a time $\Delta t$. In dimensionless units, $\mu$ is,

$$\epsilon = \frac{\mu}{c^2}.$$  \hspace{1cm} (15)

A dimensional estimate for $L$, the size of the cosmological accelerator, can be made as follows. The time over which a cosmic accelerator loses mass is clearly proportional to $L/\mu$ or, in correct units, $L/\epsilon c$. We equate this to the only time in the problem: the lifetime of the universe at the redshift of the accelerator,

$$\frac{L}{\epsilon c} = \xi \frac{t_0}{(1 + z)^{3/2}},$$  \hspace{1cm} (16)

where $ct_0 = 6 \times 10^{27}$ cm and the proportionality factor $\xi = 1$. So $L = \xi \epsilon c t_0 / (1 + z)^{3/2}$ and we can now calculate the duration of the burst

$$\Delta t_{\text{observ}} = (1 + z) \Delta t_{\text{lab}} = (1 + z) \frac{L}{c \gamma^3} = 10^{17} \xi \frac{\epsilon}{\gamma^3}$$ seconds. \hspace{1cm} (17)

In the accelerator frame (comoving frame)

$$\Delta t_{\text{com}} \approx \xi \left(\frac{\epsilon}{10^{-11}}\right) \left(\frac{\gamma}{10^3}\right)^2 \text{ seconds},$$  \hspace{1cm} (18)

The choice of units will become clear further on. The energy loss per unit length is independent of $\epsilon$ with

$$\frac{\mu c^2}{\Delta t_{\text{com}}} = \frac{1}{\xi} \times 10^{33} \left(\frac{\gamma}{10^3}\right)^2 \text{ J m}^{-1} \text{s}^{-1}.$$  \hspace{1cm} (19)

A fraction $\eta_\gamma$ is radiated away in $\gamma$-rays.

The above equations are valid for cosmological strings or loops of false vacuum in grand unified theories. Near cusps in oscillating loops the particle currents become very large, creating a situation where the energy density exceeds that of the topological defect and the energy is released in a short localized burst of radiation. In string models there is a proportionality factor multiplying the r.h.s. of (13) which is of order $\xi = 10^3$ rather than unity; see e.g. Ref. [6]. From now on we will include this factor, so that our results can be directly compared to these models.
Imposing the “experimental facts”, listed in the introduction, on the dimensional analysis (with $\xi = 10^3$) yields the following constraints[3, 6]:

$$10^2 < \gamma < 10^5$$

$$10^{-12} < \epsilon < 10^{-11}$$

$$10^{-10} < \eta_\gamma < 10^{-9}$$

The critical result here is that to accommodate the time-scales as well as the fluencies in a large redshift source of this type, the fraction of energy loss into gamma rays is actually very small, $10^{-10}$ to $10^{-9}$. Theoretical arguments[3] lead to the expectation that most of the energy is radiated into $\nu$'s. This fits well with the observational fact that the missing energy is not emitted in any other wavelength of light.

Before proceeding it is important to point out that the small fraction of the burst energy going into gamma rays is not a surprise. Cosmic strings belong to the class of highly inefficient models in which the whole accelerator is boosted by a Lorentz factor $\gamma$. In contrast, conventional fireball models describe a collisionless shock of protons which carries kinetic energy far outside the opaque fireball where it is transformed into a burst of photons.

A fraction $\eta_\gamma^{-1}$ is radiated into $\nu$'s of energy $E_{\nu\text{obs}}$. The flux for a typical burst is

$$N_\nu = \frac{1}{\eta_\gamma} \frac{10^{-9} \text{ J m}^{-2}}{E_{\nu\text{obs}}}$$

or

$$N_\nu \text{ per cm}^2 = 10^8 \left( \frac{\eta_\gamma}{10^{-10}} \right)^{-1} \left( \frac{E_{\nu\text{obs}}}{100 \text{ MeV}} \right)^{-1} \left( \frac{F_\gamma}{10^{-9} \text{ J m}^{-2}} \right)$$

during a time

$$\Delta t_{\text{obs}} = \frac{1}{\gamma} \Delta t_{\text{com}} = 1 \text{ sec} \left( \frac{\epsilon}{10^{-11}} \right) \left( \frac{\gamma}{10^3} \right)^{-3}.$$  (23)

Here

$$E_{\nu\text{obs}} = \gamma 3.15 \ T_{\nu\text{com}}.$$  (24)

The thermal emission of the neutrinos in the accelerator frame follows a Fermi-Dirac distribution with temperature $T_{\nu\text{com}}$. We will estimate it next following Ref. [4].

Consider an accelerator segment of loop of length $L$ and radius $R$. Assume black body radiation off its surface and apply the Stefan-Boltzmann law in a comoving frame. Using (19),

$$\frac{\mu c^2}{\Delta t_{\text{com}}} L = (2\pi R L) (\sigma T_{\nu\text{com}}^4),$$  (25)
where $\sigma$ is the Stefan-Boltzmann constant. We obtain

$$T_{\nu,\text{com}} = \frac{E_{\nu,\text{obs}}}{3.15 \gamma} = (10 \text{ MeV}) \left( \frac{\gamma}{10^3} \right)^{1/2} \left( \frac{10^{-7} \text{ m}}{R} \right)^{1/4}. \quad (26)$$

For a cosmic string $R = I_{\text{saturation}}/H_{\text{cr}}$, where $H_{\text{cr}}$ the critical field strength. $I_{\text{saturation}}$ was calculated by Witten[13], and is typically

$$10^{-8} \text{ m} < R < 10^{-6} \text{ m}. \quad (27)$$

The possibilities covered by this class of models range from thermal supernova-type energies to TeV-neutrinos. For illustration, we show results for a low and high energy neutrino scenario.

$$\gamma = 10^2 \quad R = 10^{-6} \quad E_{\nu,\text{obs}} = 560 \text{ MeV}$$
$$2 \times 10^7 < N_{\nu,\text{obs}} < 2 \times 10^8 \text{ per cm}^2$$
$$10^2 < \Delta t_{\text{obs}} < 10^3 \text{ seconds}$$

or

$$\gamma = 10^5 \quad R = 10^{-8} \quad E_{\nu,\text{obs}} = 60 \text{ TeV}$$
$$2 \times 10^2 < N_{\nu,\text{obs}} < 2 \times 10^3 \text{ per cm}^2$$
$$0.1 < \Delta t_{\text{obs}} < 1 \mu\text{sec}$$

Suppose neutrinos with $E_{\nu,\text{obs}} \simeq 40 \text{ MeV}$ produce electrons in the detector with energy $(1 - \langle y \rangle)E_{\nu}$, or about 20 MeV, just like SN1987A would have produced in AMANDA. We calculate a flux of $5 \times 10^8$ per cm$^2$ in a rather long burst. We know from the supernova analysis that each PMT has a seeing radius $d \simeq 7.5 \text{ m}$ in this case. The number of events, given by (8), is 10 per PMT for a typical, average burst. This is 10 times smaller than a supernova, but the GRB data indicates that we have 100 shots per year and there should be some big ones. Models suggest searches over $> 1 \text{ sec}$ intervals, maybe up to 1000 sec. Also notice that event rates grow with energy as $\sigma d^3/E$. Both $d, \sigma$ grow with energy. The signals should be spectacular for $E_{\nu,\text{obs}}$ values of hundreds of MeV or more.

An extreme example on the high energy end yields $\sim 10^2$ neutrinos of tens of TeV energy per cm$^2$ in periods $\ll 1 \text{ sec}$. In this scenario, the secondary muons can be detected and reconstructed. This allows one to both count the neutrinos and reconstruct their direction with degree-accuracy. The event rates are now given by[8]:

$$N_{\text{events}} = N_{\nu} \text{ Area } P_{\nu \rightarrow \mu}, \quad (28)$$
\[ P_{\nu \rightarrow \mu} \simeq \rho \sigma_{\nu} R_{\mu} = \rho \left( 10^{-42} \text{m}^2 \frac{E_{\nu}}{\text{GeV}} \right) \left( 5 \text{ m} \frac{E_{\mu}}{\text{GeV}} \right). \]  

Here \( P_{\nu \rightarrow \mu} \) is the probability that the neutrino interacts and spawns a muon that reaches the detector; it is proportional to the density \( \rho \) of the detector medium, the neutrino interaction cross section \( \sigma_{\nu} \) and the muon range \( R_{\mu} \). For \( E_{\mu} \simeq \frac{1}{2} E_{\nu} \simeq 30 \text{ TeV} \) and \( \rho = \frac{11}{18} A \) per cm\(^3\) we have \( P_{\nu \rightarrow \mu} = 10^{-3} \) or \( 10^5 \) events for a detector as small as 100 m\(^2\) area detector!

Therefore, bursts associated with topological defects are unlikely to escape the scrutiny of both the supernova and the muon trigger. In part of the parameter space one should be able to rule out the cosmological models even for average bursts. In other regions, one can constrain the models only from a search for energetic bursts.

4. Detecting \( \gamma \)-Rays with Neutrino Telescopes?

What about seeing \( \gamma \)-rays? Shallow detectors like AMANDA and Baikal detect secondary muons produced by \( \gamma \)-showers in the atmosphere. For a vertical muon threshold of 180 GeV, AMANDA should be sensitive to TeV gamma rays. The number of photons is calculated from the fluency \( F_{\gamma} \) by

\[ N_{\gamma}(>E) = \frac{1}{\alpha} \frac{F_{\gamma}}{E_{\gamma}^{\alpha}}, \]  

where \( \alpha \) is the spectral index (\( \alpha = 1 \) for Fermi shocks). For \( \alpha = 1 \) and a fluency per burst of \( 10^{-9} \text{ J m}^{-2} \) we find that \( F_{\gamma} = 10^{-2} \ln^{-1}(\frac{E_{\gamma \text{max}}}{E_{\gamma \text{min}}}) \) per m\(^2\) per burst. There is a rather weak logarithmic dependence on the maximum and minimum energy of the photons in the burst. Notice that the TeV flux, even if it exists, is too small to be detected by satellite experiments. The maximum energy of GRBs is therefore an open question. It has been speculated that they may be the sources of the highest energy cosmic rays which implies a very high energy accelerator indeed.

The muon flux produced by above gamma ray flux can be computed following Halzen and Stanev[9]:

\[ N_{\mu}(>E_{\mu}) \simeq 2 \times 10^{-5} \frac{F_{\gamma}}{\cos \theta} \frac{1}{(E_{\mu}/\cos \theta)^{\alpha+1}} \ln \left( \frac{\cos \theta E_{\gamma \text{max}}}{10 E_{\mu}} \right) \left( \frac{E_{\mu}/\cos \theta}{0.04} \right)^{0.53}. \]  

Here \( E_{\mu} \) is the vertical threshold energy of the detector, e.g. 0.18 TeV for the AMANDA detector. \( \theta \) is the zenith angle at which the source is observed. This parametrization reproduces
the explicit Monte Carlo results.

We predict $10^{-6}$ muons per m$^2$ for an average burst, which can therefore be detected in a km$^2$ telescope! The probability that a 1 TeV $\gamma$ contains a detectable muon is about $10^{-4}$. We assumed here a burst in the 1 MeV to 10 TeV range and $\cos \theta = 1$. All this requires, of course, that the GRB flux extends to TeV energies. We do not know whether any do because satellite experiments have no sensitivity in this energy range. There is no atmospheric $\mu$ background in a pixel in the sky containing the GRB on a 1 second time scale. Big bursts may be detectable in the $10^4$ m$^2$ detectors presently under construction.

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