Signatures of γ ray bursts in neutrino telescopes

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We show that the detection of neutrinos from a typical γ ray burst requires a kilometer-scale detector. We argue that large bursts should be visible with the neutrino telescopes under construction. We emphasize the three 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 γ rays and (iii) showers made by relatively low energy ($\simeq$100 MeV) electron neutrinos. The timing of neutrino-photon coincidences may yield a measurement of the neutrino mass to order 10^{-4}–10^{-5} eV. [S0556-2821(96)01616-5]

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I. INTRODUCTION

The origin of γ ray bursts (GRB's) 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 GRB's emit most of their energy in neutrinos [2–4] as expected in the (presently favored) cosmological models.

It is not the purpose of this paper to study the modeling of GRB's. We will consider two cosmological scenarios: ultrarelativistic 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 $F_\gamma \gtrsim 10^{-9}$J m^{-2}, (ii) they are concentrated, on average, at a redshift of $z\simeq 1$, (iii) some bursts last less than 10 sec, and (iv) they do not repeat on a time scale of 1 yr 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 GRB's 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 GRB's requires kilometer-scale neutrino telescopes. GRB's 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 nonobservation 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 three techniques by which neutrino telescopes can search for GRB's. All detectors [8], such as the Deep Underground Muon and Neutrino Detector (DUMAND) and NESTOR deep ocean experiments, can search for short bursts of high energy muons of ν_μ 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 γ ray observations. The shallower detectors such as the Antartic Muon and Neutrino Detector Array (AMANDA) and Baikal can also search for the muons made in air showers initiated by TeV γ rays [9] of GRB origin. Finally, AMANDA can use its supernova trigger [10] to identify excess counting rates in the optical modules associated with a flux of MeV–GeV ν_e's for the duration of a γ ray burst.

It has not escaped our attention that the observation of coincident bursts of neutrinos and γ 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 $m_\nu = E_\nu \sqrt{2ct_d/D}$. With t_d possibly of order milliseconds, distances D of thousands of Megaparsecs and energies E_ν similar to that of a supernova, neutrino observations from GRB's could improve the well-advertised limit obtained from SN 1987A by a factor exceeding 10^4. The sensitivity of order 10^{-3}–10^{-4} eV is close to the range of masses 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. From a theoretical point of view, it determines the mass of a single flavor whereas the solar neutrino anomaly implies nonvanishing values of the difference of the squares of masses of different flavors.

II. 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 $R \simeq 10^2$ km$\simeq c\Delta t$. The shortest time scales, with Δt of order milliseconds, determine the size of the initial fireball [5]. Only neutrinos escape because the fireball is opaque to photons. In GRB's 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} [5]. It is then theorized that a relativistic shock, with $\gamma \simeq 10^2$ 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 $F=10^{-9}$J m^{-2} and a distance $z=1$ the energy required is

$$E_\gamma = 2\times 10^{51}\ \mathrm{erg}\left(\frac{D}{4000\ \ \mathrm{Mpc}}\right)^2\left(\frac{F}{10^{-9}\ \ \mathrm{J}\ \ \mathrm{m}^{-2}}\right), \qquad (1)$$

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

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

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

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

For neutrinos

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

For a merger of neutron stars for instance, the release of a solar mass of energy of 2×10^{53} erg implies a total energy emitted in neutrinos $\sim 10^2 E_\gamma$. The γ'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 Eqs. (3),(4) we obtain $T_\nu \simeq 2.5 T_\gamma \simeq 20$ MeV. Using this and a total neutrino energy in the fireball of $10^2 E_\gamma$ we obtain

$$E_\nu = 3.15 T_\nu = 65\ \mathrm{MeV}\left(\frac{E_{\nu\ \mathrm{tot}}}{2\times 10^{53}\ \mathrm{erg}}\right)^{1/4}\left(\frac{100\ \mathrm{km}}{R}\right)^{3/4} \qquad (5)$$

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

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

$$N_\nu = 10^4\ \ \mathrm{m}^{-2}\left(\frac{E_{\nu\ \mathrm{tot}}}{2\times 10^{53}\ \mathrm{erg}}\right)\left(\frac{65\ \mathrm{MeV}}{E_\nu}\right)\left(\frac{4000\ \mathrm{Mpc}}{D}\right)^2 \qquad (7)$$

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 ~ 100 MeV neutrinos are below the muon threshold of high energy neutrino telescopes, the $\overline{\nu_e}$ will initiate electromagnetic showers. We consider water or ice detectors for which neutrino absorption is dominated by the reaction ($\overline{\nu_e} + p \rightarrow n + e^+$) which will, for instance, be counted by the AMANDA supernova trigger.

A supernova with properties similar to those of SN 1987A can cause a 10 sec burst of neutrinos in the AMANDA detector which produce neutrinos of 20 MeV energy. They produce positrons in the detector with roughly the same energy. Detailed simulations [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

$$N_{\nu\ \mathrm{obs}} \simeq N_\nu(\pi d^2)\left(\frac{d}{\lambda_{\mathrm{int}}}\right). \qquad (8)$$

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

$$\lambda_{\mathrm{int}}^{-1} = \frac{2}{18} A \rho \sigma_0 E_\nu^2 \qquad (9)$$

with

$$\sigma_0 = 7.5\times 10^{-40}\ \mathrm{m}^2\ \ \mathrm{MeV}^{-2}. \qquad (10)$$

A is Avogadro's number and ρ 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 ~ 100 MeV.

We have checked by Monte Carlo simulation [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 [12] this upper limit is outside the range of where we will apply Eq. (8). Therefore, the number of neutrino events for a GRB is given by Eq. (8) with $d = 7.5$ m$(65\ \mathrm{MeV}/20\ \mathrm{MeV})^{1/3}$. Here 65 MeV is the positron energy which is roughly 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

$$S = 2\times 10^{-3}\ \ \mathrm{events}\ \left(\frac{N_{\nu\ \mathrm{obs}}}{10^{-5}}\right)\left(\frac{D_{\mathrm{PMT}}}{20\ \mathrm{cm}}\right)^2\left(\frac{N_{\mathrm{PMT}}}{200}\right), \qquad (11)$$

$$N = 60\ \ \mathrm{events}\ \left(\frac{\Delta t}{0.3\ \mathrm{msec}}\right)\left(\frac{N_{\mathrm{back}}}{1\mathrm{kHz}}\right)\left(\frac{N_{\mathrm{PMT}}}{200}\right), \qquad (12)$$

$$S/\sqrt{N} = 3\times 10^{-4}\left(\frac{N_{\mathrm{back}}}{1\ \mathrm{kHz}}\right)^{-1/2}\left(\frac{D_{\mathrm{PMT}}}{20\ \mathrm{cm}}\right)^2\left(\frac{N_{\mathrm{PMT}}}{200}\right)^{1/2}. \qquad (13)$$

AMANDA has been chosen for reference with 200 PMT's with a diameter D_{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.

The event rate for an *average* burst is predicted to below. We will argue nevertheless that observation is possible and clearly guaranteed for kilometer-scale detector with several thousand PMT's. First, the parameters entering the calculation are uncertain. The event rate increases with neutrino energy as E_ν^3 because of the increase of the PMT seeing distance d and the neutrino interaction cross section σ_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 (which occurs every few years in cosmological models) and 10 times more energetic is observable with a significance of well over 10 σ in the exisiting 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. Events at the 4σ level should happen yearly.

Another plausible source for high energy neutrinos from a GRB involves the interaction of the fireball with clouds of nucleons in the interstellar medium [13]. The neutrinos are produced in the interaction

$$N+N\rightarrow N+N+\pi^{\pm}, \tag{14}$$

$$\pi^{\pm}\rightarrow\mu+\nu. \tag{15}$$

This scenario has been invoked to explain the delayed photons observed in the GRB event GRB 940217 where a 25 GeV photon arrived with a delay of $\simeq 77$ min. It requires that the shock runs into a gas cloud with density $n\sim 2\times 10^{11}\mathrm{cm}^{-3}$ [13]. The flux of neutrinos is roughly equal to the photon flux which we estimate on the basis of this event:

$$\begin{aligned} N(>E) &= \frac{2\times 10^{-6}}{E(\mathrm{TeV})}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1} \\ &= \frac{2\times 10^{-3}}{E(\mathrm{TeV})}\ \mathrm{cm}^{-2}\ \text{ assuming } 10^3 \text{ sec.} \end{aligned} \tag{16}$$

The flux of secondary muons is given by

$$\text{No. muons}=\text{area}\int_{\text{det thresh}}^{E_{\max}}\frac{2\times 10^{-3}}{E}P_{\nu\rightarrow\mu}dE, \tag{17}$$

where $P_{\nu\rightarrow\mu}=1.3\times 10^{-6}E^{2.2}$ [8] is the probability that a neutrino produces a muon within the effective area of the detector. All units are TeV and cm^2. Therefore

$$\begin{aligned} \text{No. muons} &= \text{area}\times(2\times 10^{-3})(1.3\times 10^{-6})\frac{E_{\max}^{2.2}}{2.2} \\ &= \text{area}\times 10^{-9}E_{\max}^{2.2}(\mathrm{TeV}), \end{aligned} \tag{18}$$

showing that detectors with area$\gg 10^9$ $\mathrm{cm}^2\simeq 0.1$ km^2 are required.

As demonstrated by the γ-ray observations, the structure of the shock producing the γ 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.

III. ACCELERATOR II: COSMIC STRING-TYPE SCENARIOS

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

$$\Delta t_{\mathrm{lab}}=\frac{L}{c\gamma^3}. \tag{19}$$

Here L is the size of the accelerator and $\gamma=I_{\mathrm{saturation}}/I$ 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 γ^{-2}. The idea is that when accelerated currents reach a value $I_{\mathrm{saturation}}$ 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 μ per unit length L is radiated away in a time Δt. In dimensionless units, μ is

$$\epsilon=\mu\frac{G}{c^2}. \tag{20}$$

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/μ 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,

$$\frac{L}{\epsilon c}=\xi\frac{t_0}{(1+z)^{3/2}}, \tag{21}$$

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

$$\Delta t_{\mathrm{observ}}=(1+z)\Delta t_{\mathrm{lab}}=(1+z)\frac{L}{c\gamma^3}=10^{17}\xi\frac{\epsilon}{\gamma^3}\ \text{sec.} \tag{22}$$

In the accelerator frame (comoving frame)

$$\Delta t_{\mathrm{com}}\cong\xi\frac{(\epsilon/10^{-11})}{(\gamma/10^3)^2}\ \text{sec.} \tag{23}$$

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

$$\frac{\mu c^2}{\Delta t_{\mathrm{com}}}=\frac{1}{\xi}8\times 10^{33}\left(\frac{\gamma}{10^3}\right)^2\ \mathrm{J\ m^{-1}\ sec^{-1}}. \tag{24}$$

A fraction η_γ is radiated away in γ 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 right-hand side (RHS) of Eq. (21) 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]:

$$10^2 < \gamma < 10^5, \quad 10^{-12} < \epsilon < 10^{-11},$$
$$10^{-10} < \eta_\gamma < 10^{-9}. \tag{25}$$

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 γ 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 ν'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 γ rays is not a surprise. Cosmic strings are typical for a class of highly inefficient models in which the whole accelerator is boosted by a Lorentz factor γ. 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 η_γ^{-1} is radiated into ν's of energy $E_{\nu\,\mathrm{obs}}$. The flux for a typical burst is

$$N_\nu = \frac{1}{\eta_\gamma}\,\frac{10^{-9}\mathrm{J\,m^{-2}}}{E_{\nu\,\mathrm{obs}}} \tag{26}$$

or

$$N_\nu \text{ per cm}^2 = 10^8\left(\frac{\eta_\gamma}{10^{-10}}\right)^{-1}\left(\frac{E_{\nu\,\mathrm{obs}}}{100\ \mathrm{MeV}}\right)^{-1}\left(\frac{F_\gamma}{10^{-9}\ \mathrm{J\,m^{-2}}}\right) \tag{27}$$

during a time

$$\Delta t_{\mathrm{obs}} = \frac{1}{\gamma}\Delta t_{\mathrm{com}} = 1\,\mathrm{sec}\left(\frac{\epsilon}{10^{-11}}\right)\left(\frac{\gamma}{10^3}\right)^{-3}. \tag{28}$$

Here

$$E_{\nu\,\mathrm{obs}} = \gamma\ 3.15 T_{\nu\,\mathrm{com}}. \tag{29}$$

The thermal emission of the neutrinos in the accelerator frame follows a Fermi-Dirac distribution with temperature $T_{\nu\,\mathrm{com}}$. We will estimate it next following Ref. [3].

Consider an accelerator segment of loop of length L and radius R. Assume blackbody radiation off its surface and apply the Stefan-Boltzmann law in a comoving frame. Using Eq. (24),

$$\frac{\mu c^2}{\Delta t_{\mathrm{com}}} L = (2\pi R L)(\sigma T^4_{\nu\,\mathrm{com}}), \tag{30}$$

where σ is the Stefan-Boltzmann constant. We obtain

$$T_{\nu\mathrm{com}} = \frac{E_{\nu\,\mathrm{obs}}}{3.15\gamma} = (10\ \mathrm{MeV})\left(\frac{\gamma}{10^3}\right)^{1/2}\left(\frac{10^{-7}\mathrm{m}}{R}\right)^{1/4}. \tag{31}$$

For a cosmic string $R = I_{\mathrm{saturation}}/H_{\mathrm{cr}}$, where H_{cr} the critical field strength. $I_{\mathrm{saturation}}$ was calculated by Witten, [14] and is typically

$$10^{-8}\ \mathrm{m} < R < 10^{-6}\ \mathrm{m}. \tag{32}$$

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:

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

or

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

Suppose neutrinos with $E_{\nu\,\mathrm{obs}} \simeq 20$ MeV produce electrons in the detector with energy $\simeq E_\nu$, just like SN 1987A would have produced in AMANDA. We calculate a flux of 5×10^8 per cm^2 in a rather long burst. We know from the supernova analysis that each PMT has a seeing radius $d \simeq 7.5$ m in this case. The number of events, given by Eq. (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 sec intervals, maybe up to 1000 sec. Also notice that event rates grow with energy as $\sigma d^3/E$. Both d, σ grow with energy. The signals should be spectacular for $E_{\nu\,\mathrm{obs}}$ 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 $\leqslant 1$ 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]

$$N_{\mathrm{events}} = N_\nu \text{ area } P_{\nu\to\mu}, \tag{33}$$

$$P_{\nu\to\mu} \simeq \rho\sigma_\nu R_\mu = \rho\left(10^{-42}\ \mathrm{m}^2\ \frac{E_\nu}{\mathrm{GeV}}\right)\left(5\ \mathrm{m}\ \frac{E_\mu}{\mathrm{GeV}}\right). \tag{34}$$

Here $P_{\nu\to\mu}$ is the probability that the neutrino interacts and spawns a muon that reaches the detector; it is proportional to the density ρ of the detector medium, the neutrino interaction cross section σ_ν, and the muon range R_μ. For $E_\mu \simeq \frac{1}{2}E_\nu \simeq 30$ TeV and $\rho = \frac{11}{18}A$ per cm^3 we have $P_{\nu\to\mu} = 10^{-3}$ 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.

IV. DETECTING γ RAYS WITH NEUTRINO TELESCOPES?

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

$$N_\gamma(>E) = \frac{1}{\alpha}\frac{F_\gamma}{E_\gamma^\alpha}, \tag{35}$$

where α is the spectral index ($\alpha=1$ for Fermi shocks). For $\alpha=1$ and a fluency per burst of 10^{-9} J m^{-2} we find that $F_\gamma = 10^{-2}\ln^{-1}(E_{\gamma\,\max}/E_{\gamma\,\min})$ 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 GRB's 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 γ ray flux can be computed following Halzen and Stanev [9]:

$$N_\mu(>E_\mu) \simeq 2\times10^{-5}\frac{F_\gamma}{\cos\theta}\frac{1}{(E_\mu/\cos\theta)^{\alpha+1}}\ln\left(\frac{\cos\theta E_{\gamma\,\max}}{10E_\mu}\right) \times\left(\frac{E_\mu/\cos\theta}{0.04}\right)^{0.53}. \tag{36}$$

Here E_μ is the vertical threshold energy of the detector, e.g., 0.18 TeV for the AMANDA detector. θ 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 γ 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 μ background in a pixel in the sky containing the GRB on a 1 sec time scale. Big bursts may be detectable in the 10^4 m^2 detectors presently under construction.

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