High-Energy Neutrinos from Gamma Ray Bursts

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We treat high-energy neutrino production in gamma ray bursts (GRBs). Detailed calculations of photomeson neutrino production are presented for the collapsar model, where internal nonthermal synchrotron radiation is the primary target photon field, and the supranova model, where external pulsar-wind synchrotron radiation provides important additional target photons. Detection of $\gtrsim 10$ TeV neutrinos from GRBs with Doppler factors $\gtrsim 200$, inferred from γ-ray observations, would support the supranova model. Detection of $\lesssim 10$ TeV neutrinos is possible for neutrinos formed from nuclear production. Only the most powerful bursts at fluence levels $\gtrsim 3 \times 10^{-4}$ erg cm^{-2} offer a realistic prospect for detection of ν_μ.

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Two leading scenarios for the nature of the sources that power long-duration gamma ray bursts (GRBs) are the collapsar [1] and supranova (SA) [2] models. The core of a massive star collapses directly to a black hole in the collapsar model, but only after an episode of neutron-star activity in the SA model [3]. This delay means that a shell of enriched material, which could help explain observations of x-ray features, surrounds the GRB source in the SA model [2]. The colliding shells operating in the collapsar model occur at distances $\Gamma^2 c\Delta t \sim 3 \times 10^{15}\Gamma_{300}^2 \Delta t(s)$ cm from the central sources, where $\Gamma = 300\Gamma_{300}$ is a typical wind Lorentz factor and Δt is the time between shell ejection events [4]. GRB pulses of $\sim$0.1–10 s durations and separations are typical [5], but even for $\Delta t \sim 1$ ms, the shell collisions take place far outside the photospheric radii of likely GRB stellar progenitors. The most important radiation field for photomeson neutrino production in the collapsar scenario is thus the internal synchrotron radiation [6].

The presence of a pulsar wind (PW) within an expanding supernova remnant (SNR) shell in the SA model means that the radiation environments in the collapsar and SA models are vastly different [3]. To maintain stability against prompt collapse to a black hole, the neutron star must rotate with periods near 1 ms [2]. The neutron-star radiates electromagnetic, leptonic, and possibly also hadronic energy in the form of a powerful relativistic "cold" magnetized wind consisting of quasimonoenergetic e^+-e^- pairs and ions. The ordered flow of the wind is disrupted at the wind shock formed within the SNR shell. Here we consider only the emission from quasimonoenergetic leptons that are injected at the PW shock which provide, primarily through synchrotron losses, the main external photon target for photomeson interactions. The quasithermal radiation field of the SNR shell is neglected, as well as the nonthermal radiations from particles accelerated at the PW shock.

We find that the external lepton-wind synchrotron radiation alone improves prospects for neutrino detection by orders of magnitude over values calculated in a standard external-shock/GRB blast-wave scenario [7] that explains well the phenomenology of GRBs with smooth fast-rise/slow-decay γ-ray light curves. The presence of the external field can increase the number of detectable neutrinos by an order of magnitude or more over a colliding shell scenario that is generally invoked to explain highly variable GRB light curves.

Here we report detailed calculations of photomeson neutrino production for the collapsar and SA models that take into account nonthermal proton injection followed by photomeson energy loss, which is computed numerically by adapting our photohadronic model for blazar jets [8]. We also calculate the corresponding cutoff spectral energy $\epsilon_{\gamma\gamma}$ due to $\gamma\gamma$ pair-production attenuation. High-energy neutrino observations of very bright GRBs, especially if combined with data from the *Gamma-ray Large Area Space Telescope* (GLAST) or other gamma-ray detectors, can test the collapsar and SA models, as we now show.

The detection efficiency in water or ice of upward-going muon neutrinos (ν_μ) with energies $\epsilon_\nu = 10^{14}\epsilon_{14}$ eV is $P_{\nu\mu} \cong 10^{-4}\epsilon_{14}^{\chi}$, where $\chi = 1$ for $\epsilon_{14} < 1$, and $\chi = 0.5$ for $\epsilon_{14} > 1$ [9]. For a neutrino fluence spectrum parametrized by $\nu\Phi_\nu = 10^{-4}\phi_{-4}\epsilon_{14}^{\alpha_\nu}$ erg cm^{-2}, the number of ν_μ detected with a km-scale ν detector such as IceCube with area $A_\nu = 10^{10}A_{10}$ cm^2 is therefore

$$N_\nu(\geq \epsilon_{14}) \approx \int_{\epsilon_\nu}^{\infty} d\epsilon_1 \frac{\nu\Phi_\nu}{\epsilon_1^2} P_{\nu\mu} A_\nu \simeq 0.6 \frac{\phi_{-4}A_{10}}{\frac{1}{2} - \alpha_\nu} \begin{cases} 1 + (\frac{1}{2\alpha_\nu} - 1)(1 - \epsilon_{14}^{\alpha_\nu}), & \text{for } \epsilon_{14} < 1, \\ \epsilon_{14}^{\alpha_\nu - 1/2}, & \text{for } \epsilon_{14} > 1. \end{cases} \quad (1)$$

For a $\nu\Phi_\nu$ spectrum with $\alpha_\nu \simeq 0$, the number of ν_μ to be expected are $N_\nu \simeq 1.2\phi_{-4}A_{10}(1 + \frac{1}{2}\ln\epsilon_{14}^{-1})$ for $\epsilon_{14} < 1$, and

$N_\nu \simeq 1.2\phi_{-4}A_{10}/\sqrt{\epsilon_{14}}$ for $\epsilon_{14} > 1$. If the nonthermal proton energy injected in the proper frame is comparable to the radiated energy required to form GRBs with hard x-ray/soft γ-ray fluences $\gtrsim 10^{-4}$ erg cm^{-2}, then extremely bright GRBs are required to leave any prospect for detecting ν_μ with km-scale neutrino detectors. About 2–5 GRBs per year are expected with hard x-ray/soft γ-ray fluence $> 3 \times 10^{-4}$ erg cm^{-2} [10].

Because GRB blast waves accelerate electrons, it is probable that they also accelerate nonthermal hadrons. Coincidence between the GRB power radiated at hard x-ray/soft γ-ray energies within the Greisen-Zatsepin-Kuzmin (GZK) radius and the power required to account for super-GZK ($\gtrsim 10^{20}$ eV) cosmic rays (CRs) suggests that GRBs might be the progenitor sources of ultrahigh energy ($\gtrsim 10^{19}$ eV) cosmic rays (UHECRs), CRs with energies between the knee and the ankle of the CR spectrum, and GeV-PeV CRs [7,11].

In our calculations, we inject protons with a number spectrum $\propto \epsilon_p^{-2}$ at comoving proton energies $\epsilon_p > 300\Gamma_{300}$ GeV up to a maximum proton energy determined by the condition that the particle Larmor radius is smaller than both the size scale of the emitting region and the photomeson energy-loss length [8]. The observed synchrotron spectral flux in the prompt phase of the burst is parametrized by the expression $F(\nu) \propto \nu^{-1}(\nu/\nu_{br})^{\alpha}$, where $h\nu_{br} = 300$ keV, $\alpha = -0.5$ above ν_{br}, and $\alpha = 0.5$ when 30 keV $\leq h\nu \leq h\nu_{br}$. At lower energies, $\alpha = 4/3$. The observed total hard x-ray/soft γ-ray photon fluence $\Phi_{tot} \cong t_{dur}\int_0^\infty d\nu F(\nu)$, where t_{dur} is the characteristic duration of the GRB. In our calculations we assume a source at redshift $z = 1$, and let $\Phi_{tot} = 3 \times 10^{-5}$ erg cm^{-2}.

We inject a total amount of accelerated proton energy $E' = 4\pi d_L^2 \Phi_{tot}\delta^{-3}(1+z)^{-1}$ into the comoving frame of the GRB blast wave. Here δ is the Doppler factor and d_L is the luminosity distance. The energy deposited into each of N_{sp} light-curve pulses (or spikes) is therefore $E'_{sp} = E'/N_{sp}$ ergs. We assume that all the energy E'_{sp} is injected in the first half of the time interval of the pulse, which effectively corresponds to a characteristic variability time scale $t_{var} = t_{dur}/2N_{sp}$. The proper width of the radiating region forming the pulse is $\Delta R' \cong t_{var}c\delta/(1+z)$, from which the energy density of the synchrotron radiation can be determined [8]. We set the GRB prompt duration $t_{dur} = 100$ s, and let $N_{sp} = 50$, corresponding to $t_{var} = 1$ s. The magnetic field is determined by assuming equipartition between the energy densities of the magnetic field and the electron energy.

Figure 1 shows the optical depth $\tau_{\gamma\gamma}$ for $\gamma\gamma$ pair-production attenuation as a function of observer photon energy, calculated for $\delta = 100$, 200, and 300. Curves 1, 2, and 3 show the $\gamma\gamma$ opacity from internal synchrotron radiation only, corresponding to the collapsar scenario. The rapid decrease of $\tau_{\gamma\gamma}$ with increasing δ is explained by the decline of the internal radiation energy density in the comoving frame as $u'_{syn} \simeq L'_{syn}/2\pi R'^2 c \propto (\nu F_\nu)_{obs}/\delta^6$, which implies a rapid decline (approximately $\tau_{\gamma\gamma} \propto \delta^{-4}$, depending precisely on the radiation spectrum) of the $\tau_{\gamma\gamma}$ opacity in the synchrotron field. Relativistic flows with $\delta \gtrsim 100$ are required to explain observations of > 100 MeV γ rays with EGRET [12]. GLAST observations may imply more stringent limits on δ.

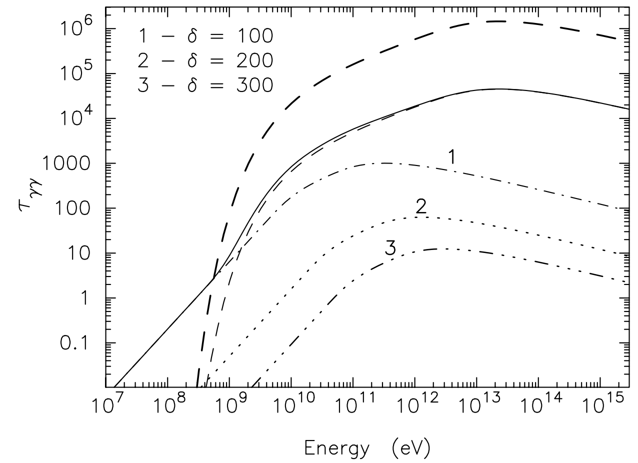

FIG. 1. Opacity $\tau_{\gamma\gamma}$ to pair-production attenuation for γ rays which are detected with observer energy given on the abscissa. The radiating region moves with Doppler factor δ with respect to the observer. The internal synchrotron radiation field is typical of GRBs observed with BATSE, and the injected energy corresponds to a measured fluence of 3×10^{-5} erg cm^{-2}, which is radiated in 50 equal pulses. The heavy and light dashed curves give the $\gamma\gamma$ opacity through the external radiation field over the size scale of the supernova remnant and the pulse emitting region, respectively. The thin solid curve gives the total opacity for a model pulse in the external shock/SA model.

An external radiation field given by the expression $\nu L_\nu \propto \nu^{1/2}\exp(-\nu/\nu_{ext})$, with $h\nu_{ext} = 0.1$ keV, is assumed to be present in the SA model [3]. The intensity of this field is determined by the assumption that the integral power $L_{ext} = \int_0^\infty L_\nu d\nu$ is equal to the power of the pulsar wind $L_{pw} \approx (10^{53}$ ergs$)/t_{delay}$, assuming that a total of $\approx 10^{53}$ ergs of pulsar rotation energy is radiated during the time t_{delay} (which is here set equal to 0.1 yr) from the rotating supramassive neutron-star before it collapses to a black hole. The energy $h\nu_{ext} \simeq 0.1$ keV is the characteristic energy of synchrotron radiation emitted by electrons (of the pulsar wind) with Lorentz factors $\gamma_{pw} \sim 3 \times 10^4$ in a randomly ordered magnetic field of strength ≈ 10 G. The radius R is determined by assuming $v = 0.05c$ is the mean speed of the SNR shell, and the external photon energy density $\propto L/2\pi R^2$. The thin solid curve is the combined opacity in a SA-model pulse when $\delta = 100$. In this case, the pulses will be highly attenuated above ≈ 300 MeV.

Figure 2 shows the total ν_μ fluences expected from a model GRB with $N_{sp} = 50$ pulses. The thin curves show collapsar model results at $\delta = 100$, 200, and 300. The expected numbers of ν_μ that a km-scale detector such as

IceCube would detect are $N_\nu = 3.2 \times 10^{-3}$, 1.5×10^{-4}, and 1.9×10^{-5}, respectively. (The effect of neutrino flavor oscillations could reduce these numbers by a factor ≈ 2.) There is no prospect to detect ν_μ from GRBs at these levels. The heavy solid and dashed curves in Fig. 2 give the SA-model predictions of $N_\nu = 0.009$ for both $\delta = 100$ and $\delta = 300$. The equipartition magnetic fields are 1.9 and 0.25 kG, respectively. The external radiation field in the SA model makes the neutrino detection rate insensitive to the value of δ (as well as to $t_{var} \gtrsim 0.1$ s, as verified by calculations).

Neutrino production efficiency would improve in the collapsar and SA models if $t_{var} \sim 1$ ms and $N_{sp} = 5 \times 10^4$ to provide the same total fluence. We obtain $N_\nu \cong 0.027$, 0.012, and 0.0046 for $\delta = 100$, 200, and 300, respectively. Such narrow spikes are, however, then nearly opaque to gamma rays, with $\tau_{\gamma\gamma} = 1$ at $E_\gamma \cong 80$ MeV when $\delta = 200$, and at $E_\gamma \cong 500$ MeV when $\delta = 300$. When $t_{var} \gg 1$ s, the GRB blast wave is optically thin to its internal synchrotron radiation at multi-GeV energies. In the absence of an external radiation field, the produced fluxes of neutrinos are not, however, detectable.

Neutrino detection from GRBs can be assured only if the number of background counts

$$N_B(\geq \epsilon_{14}) \cong \int d\Omega \int dt \int_{\epsilon_\nu}^{\infty} d\epsilon_1 \frac{F_\nu^{atm}}{\epsilon_1^2} P_{\nu\mu} A_\nu$$
$$\simeq 5 \times 10^{-8} t_2 A_{10} \left(\frac{\theta}{1^\circ}\right)^2 \int_{\epsilon_{14}}^{\infty} dx x^{-\beta+\chi-2} \ll 1. \quad (2)$$

Here the chosen time window has duration $t_w = 10^2 t_2$ s, θ is the half-opening angle, and the cosmic-ray induced atmospheric neutrino background flux at the nadir is $F_\nu^{atm} \approx 8 \times 10^{-11} \epsilon_{14}^{-\beta}$ erg cm^{-2} s^{-1} sr^{-1}, with $\beta \cong 1.7$ for $\epsilon_{14} < 1$, and $\beta = 2$ for $\epsilon_{14} > 1$ [9]. This expression places a lower bound on the energy above which background counts may be neglected, namely, that the neutrino energy $\epsilon_\nu \gg \epsilon_{min} \cong 3.6(t_2 A_{10})^{0.59}(\theta/1^\circ)^{1.18}$ GeV in order to have $N_B \ll 1$. Note that IceCube's angular resolution is predicted to be $\sim 1^\circ$ at TeV energies, 0.5° at 50–100 TeV energies, and 0.6° at PeV energies [9]. Therefore a detection of only two neutrinos during the time interval of the prompt phase of a GRB, especially if at energies $\epsilon_\nu \gtrsim 10$ TeV predicted by photohadronic interactions, will be highly significant.

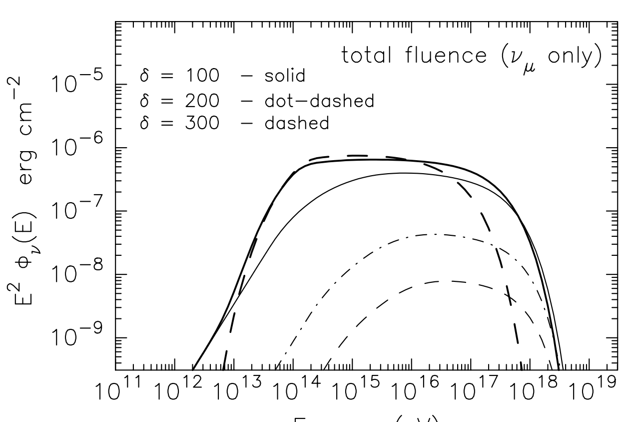

FIG. 2. Energy fluence of photomeson muon neutrinos for a model GRB. The thin curves show collapsar model results where only the internal synchrotron radiation field provides a source of target photons. The thick curves show the $\delta = 100$ and 300 results for the SA-model calculation, which includes the effects of an external pulsar wind radiation field.

The importance of low-energy (10 GeV–10 TeV) sensitivity in neutrino experiments is connected with the possibility to probe jet models with nuclear interactions. One possible scenario is a beam-on-target model where the GRB protons pass through and occasionally collide with particles in a dense target, namely, the SNR shell in the SA scenario [13]. Neutrinos created from the decay of mesons formed in interactions with SNR shell particles with mean atomic weight A are beamed into an angle no smaller than the opening angle of the GRB outflow. Thus the neutrino fluence is at most comparable to the hard x-ray/soft γ-ray fluence of a GRB multiplied by the conversion efficiency $\eta_p = t_{sh}/3t_{pA}$ of protons to neutrinos, again assuming as before that the GRB hadronic energy is determined by Φ_{tot}. The factor of 3 accounts for the fraction of secondary energy emitted in the form of ν_μ. Here the available time for the interaction of relativistic protons passing through the SNR shell is $t_{sh} \cong 3.3 \times 10^4 f_{-1} R_{16}$ s, assuming a uniform shell with a characteristic thickness $0.1 f_{-1} R$ and radius $R = 10^{16} R_{16}$. The $pA \to \pi^{\pm,0}$ energy-loss time scale t_{pA} in the stationary frame is given by $t_{pA}^{-1} \cong K_p n_A \sigma_{pA} c \simeq 4.3 \times 10^{-7} m_{SNR}/(A^{1/3} R_{16}^3 f_{-1})$ s^{-1}, given an inelasticity $K_p \simeq 0.5$ and a strong interaction cross section $\sigma_{pA} \cong 30 A^{2/3}$ mb. Thus $\eta_p \simeq 5 \times 10^{-3} m_{SNR} R_{16}^{-2} A^{-1/3}$. These neutrinos are formed at energies $\simeq 0.05 \Gamma m_p c^2 \simeq 15 \Gamma_{300}$ GeV. Neutrinos formed through beam/target interactions are therefore relatively low energy, and are not expected from GRBs unless $R_{16} \ll 1$, in which case the SNR shell would be very Thomson thick.

Another nuclear interaction scenario is where relativistic particles in the GRB blast wave collide with other particles in the ejecta. The relativistic particles are formed either by sweeping up and isotropizing particles captured from the external medium [14] or by accelerating particles at external or internal shocks. The ν_μ-production efficiency $\eta_{pp} \cong t'_{ava}/3t'_{pp}$, where $t'_{ava} \lesssim R/\Gamma c$ is the available time in the comoving frame, $t'^{-1}_{pp} = n'_p \sigma_{pp} c = E_{iso} \sigma_{pp} c/(4\pi R^2 \Delta R' \Gamma m_p c^2)$ is the inverse of the proper-frame nuclear-collision time scale, and $E_{iso} = 10^{52} E_{52}$ ergs is the apparent isotropic GRB energy release. Because $\Delta R' \sim \Gamma c t_{var}$, we find $\eta_{pp} \lesssim 6 \times 10^{-4} E_{52}/[R_{16} \Gamma_{300}^2 t_{var}(s)]$. Secondary neutrinos are formed at energies $\approx 0.05 \Gamma^2 m_p c^2 \cong 4 \Gamma_{300}^2$ TeV. Only GRBs with large values of E_{52} or small values of Γ_{300}, R_{16}, and t_{var} (s) provide reasonable efficiencies for ν_μ production, and these would exhibit strong $\gamma\gamma$ attenuation with comparable fluences in ν_μ and reprocessed electromagnetic radiation.

Thus detection of a few neutrinos by a km-scale detector generally requires an extremely bright event at the level reaching $\sim 10^{-3}$ erg cm^{-2}. Note in this regard that a model recently proposed [15] for neutrino emission from the pp interaction of PW protons with the SNR shell during the time $t_{\rm delay}$ between supernova and GRB events neglects the expected flux of accompanying electromagnetic radiation, such that a pre-GRB source in the SA scenario would be an extremely bright source significantly *before* the GRB event, which would be hard to miss in all-sky x-ray and γ-ray observations. A recent study of neutrino production during the prompt GRB phase in the SA model [16] finds similar estimates for the number of expected neutrinos which, however, are predicted to be mostly at much higher enegies, >1000 TeV. Moreover, photomeson interactions of protons on the internal synchrotron radiation field as well as $\gamma\gamma$ attenuation are not studied in Refs. [16,17], which is important to discriminate between different GRB models.

Another way to improve high-energy neutrino and UHECR model production efficiency is to assume that the radiating particles in the GRB blast waves are dominated by hadrons. As Fig. 2 shows, the integrated level of ν_μ fluence and therefore of secondary gamma rays for the assumed injection of relativistic protons is at the level $\lesssim 3 \times 10^{-6}$ erg cm$^{-2} \sim 0.1\Phi_{\rm tot}$. It would therefore still be possible to assume acceleration of protons with a power up to a factor ≈ 10 higher than in Fig. 2, which would increase the number of ν_μ expected for IceCube to ~ 0.1 in the SA model. The detection of a few neutrinos would then be possible in the prompt phase of GRBs at the flux level $\Phi_{\rm tot} \gtrsim 3 \times 10^{-4}$ erg cm^{-2}. It is important that from photomeson interactions only neutrinos above 10–20 TeV are to be expected, while a detection of lower energy neutrinos would significantly favor models with nuclear interactions in either the SA or the collapsar scenarios.

In this Letter, we have shown that the collapsar model is less efficient for neutrino production than the supranova model, as it lacks the external PW synchrotron radiation field. Neutrino predictions with the collapsar model are very sensitive to δ, and are most favorable when the $\sim$100 MeV-GeV $\gamma\gamma$ opacity is large. An inverse relation between the number of detectable neutrinos and cutoff spectral energy is found for a collapsar model. Neutrino production efficiency is relatively insensitive to δ in the SA model, though it does depend on model parameters of the PW synchrotron emission. There is no prospect for neutrino detection in the collapsar model when $\delta \gtrsim 200$. More optimistic estimates from the viewpoint of detecting GRB neutrinos could be found in proton-dominated GRB models. Without this hypothesis only the brightest GRBs can be expected to be detected with both high-energy γ-ray and neutrino detectors. Detection of high-energy neutrinos from GRBs would therefore have far-reaching impact on the collapsar and SA scenarios for GRBs, the hypothesis that GRBs sources can be powerful accelerators of ultrarelativistic CRs, and for our understanding of the origin of GRB radiation.

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