High-Energy Neutrinos from Gamma Ray Bursts

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Abstract

We treat high-energy neutrino production in 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 $\gtrsim 10\text{ TeV}$ neutrinos from GRBs with Doppler factors $\gtrsim 200$, inferred from $\gamma$-ray observations, would support the supranova model. Detection of $\lesssim 10\text{ TeV}$ neutrinos is possible for neutrinos formed from nuclear production. Only the most powerful bursts at fluence levels $\gtrsim 3 \times 10^{-4}\text{ erg cm}^{-2}$ offer a realistic prospect for detection of $\nu_\mu$.

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Two leading scenarios for the nature of the sources that power long-duration GRBs are the collapsar and supranova (SA) 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. 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. The colliding shells thought to operate in the collapsar model take place at distances $\Gamma^2c\Delta t \sim 3 \times 10^{15}\Gamma_{300}^2\Delta t(s)$ cm from the central ejection source, where $\Gamma = 300\Gamma_{300}$ is a typical wind Lorentz factor and $\Delta t$ is the time between shell ejection events. GRB pulses of $\sim 0.1$-10 s durations and separations are typical, 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.

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. To maintain stability against prompt collapse to a black hole, the neutron star must rotate with periods near 1 ms. The neutron star radiates electromagnetic, leptonic, and possibly also hadronic energy in the form of a powerful relativistic ‘cold’ magnetized wind consisting of quasi-monoenergetic $e^+e^-$ 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 quasi-monoenergetic leptons that are injected at the PW shock which provide, primarily through synchrotron losses, the main external photon target for photomeson interactions. The quasi-thermal radiation field of the SNR shell is neglected, as well as the nonthermal synchrotron and Compton-scattered 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 blastwave scenario that explains well the phenomenology of GRBs with smooth fast-rise/slow decay $\gamma$-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 photo-hadronic 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 \textit{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 ultrarelativistic upward-going muon neutrinos \((\nu_\mu)\) with energies \( \epsilon_\nu = 10^{14} \epsilon_{14} \) eV is \( P_{\nu_\mu} \approx 10^{-4} \epsilon_{14}^{\chi} \), where \( \chi = 1 \) for \( \epsilon_{14} < 1 \), and \( \chi = 0.5 \) for \( \epsilon_{14} > 1 \) \[9\]. For a neutrino fluence spectrum parameterized by \( \nu \Phi_\nu = 10^{-4} \phi_{-4} \epsilon_{14}^{\alpha_\nu} \) erg cm\(^{-2}\), the number of \( \nu_\mu \) detected with a km-scale \( \nu \) detector such as IceCube with area \( A_\nu = 10^{10} A_{10} \) cm\(^2\) is therefore

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

For a \( \nu \Phi_\nu \) spectrum with \( \alpha_\nu \approx 0 \), the number of \( \nu_\mu \) 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 \( \gamma \)-ray fluences \( \gtrsim 10^{-4} \) ergs cm\(^{-2}\), then extremely bright GRBs are required to leave any prospect for detecting \( \nu_\mu \) with km-scale neutrino detectors. About 2-5 GRBs per year are expected with hard X-ray/soft \( \gamma \)-ray fluence \( > 3 \times 10^{-4} \) ergs cm\(^{-2}\) \[10\].

Because GRB blast waves are believed to accelerate nonthermal electrons, it is probable that they also accelerate nonthermal hadrons. Coincidence between the GRB power radiated at hard X-ray/soft \( \gamma \)-ray energies within the GZK radius and the power required to account for super-GZK \( (\gtrsim 10^{20} \) eV) cosmic rays suggests that GRBs might be the progenitor sources of ultra-high energy \( (\gtrsim 10^{19} \) eV) cosmic rays, cosmic rays above the ankle of the cosmic ray spectrum, and GeV-TeV cosmic rays \[11\][7].

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 parameterized by the expression \( F(\nu) \propto \nu^{-1}(\nu/\nu_{br})^\alpha \), where \( h\nu_{br} = 300 \) keV, \( \alpha = -0.5 \) above \( \nu_{br} \), and \( \alpha = 0.5 \) when \( 30 \) keV \( \leq \nu \leq h\nu_{br} \). At lower energies, \( \alpha = 4/3 \).
The observed total hard X-ray/soft γ-ray photon fluence $\Phi_{tot} \approx t_{dur} \int_0^\infty d\nu F(\nu)$, where $t_{dur}$ is the characteristic duration of the GRB. In our calculations we assume a source at redshift $z = 1$, and let $\Phi_{tot} = 3 \times 10^{-5} \text{erg cm}^{-2}$. Two or three GRBs should occur each month above this fluence level.

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 $\delta$ 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 $\Delta R' \approx t_{var} c \delta/(1 + z)$, from which the energy density of the synchrotron radiation can be determined. We set the GRB prompt duration $t_{dur} = 100 \text{s}$, and let $N_{sp} = 50$, corresponding to $t_{var} = 1 \text{s}$. The magnetic field is determined by assuming equipartition between the energy densities of the magnetic field and the electron energy.

Fig. 1 shows the optical depth $\tau_{\gamma\gamma}$ for $\gamma\gamma$ pair production attenuation as a function of observer photon energy, calculated for $\delta = 100, 200, 300$. 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 $\delta$ is explained by the rapid decrease of the energy density of the internal radiation in the comoving frame as $u'_\text{syn} \approx L'_\text{syn}/2\pi R'^2 c \propto \nu F(\nu)_{obs}/\delta^6$, 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 $> 100 \text{ MeV}$ $\gamma$ rays with EGRET. GLAST observations may imply more stringent limits on $\delta$.

An external radiation field given by the expression $\nu L_\nu \propto \nu^{1/2} \exp(-\nu/\nu_{ext})$, with $h\nu_{ext} = 0.1 \text{ keV}$, is assumed to be present in the SA model. 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 $L_{pw} \approx (10^{53} \text{ erg})/t_{\text{delay}}$, assuming that a total of $\approx 10^{53} \text{ erg}$ of pulsar rotation energy is radiated during the time $t_{\text{delay}}$ (which is here set equal to 0.1 yr) from the rotating supramassive neutron star before it collapses to a black hole. The energy $h\nu_{ext} \approx 0.1 \text{ keV}$ 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 $\approx 10 \text{ G}$. 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 \( \approx 300 \) MeV.

Fig. 2 shows the total \( \nu_\mu \) 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 \( \nu_\mu \) that a km-scale detector such as IceCube would detect are \( N_\nu = 3.2 \times 10^{-3}, 1.5 \times 10^{-4}, \) and \( 1.9 \times 10^{-5} \), respectively. (The effect of neutrino flavor oscillations could reduce these numbers by a factor \( \approx 2 \).) There is no prospect to detect \( \nu_\mu \) 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 \( 1.9 \) kG and \( 0.25 \) kG, respectively. The external radiation field in the SA model makes the neutrino detection rate insensitive to the value of \( \delta \) (as well as to \( t_{var} > \sim 0.1 \) s, as verified by calculations), but there is still little hope that a km\(^3\) detector could detect such GRBs.

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 \( N_\nu \approx 0.027, 0.012, \) 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 \( E_\gamma \approx 80 \) MeV when \( \delta = 200 \), and at \( E_\gamma \approx 500 \) 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

\[
B(\geq \epsilon_{14}) \approx \int d\Omega \int dt \int_{\epsilon_{14}}^\infty d\epsilon_1 \frac{F_{atm}^{\nu}}{\epsilon_1^{1.4}} P_{\nu\mu} A_\nu \simeq 5 \times 10^{-8} t_2 A_{10} \left( \frac{\theta}{1^\circ} \right)^2 \int_{\epsilon_{14}}^\infty dx x^{-\beta+\chi-2} \ll 1. \tag{2}
\]

Here the chosen time window has duration \( t_w = 10^2 t_2 \) s, \( \theta \) is the half-opening angle, and the cosmic-ray induced atmospheric neutrino background flux at the nadir is \( F_{\nu}^{atm} \approx 8 \times 10^{-11} \epsilon_{14}^{-\beta} \) ergs cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\), with \( \beta \approx 1.7 \) 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 \( \epsilon_\nu \gg \epsilon_{min} \approx 3.6(t_2 A_{10})^{0.59}(\theta/1^\circ)^{1.18} \) GeV in order to have \( B \ll 1 \). Note that IceCube’s angular resolution is predicted to be \( \sim 1^\circ \) at TeV energies, 0.5\(^\circ\) at 50-100 TeV energies, and 0.6\(^\circ\) at PeV energies \([9]\). Therefore a detection of only 2 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.
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 \(\gamma\)-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 \(\Phi_{tot}\). The factor of 3 accounts for the fraction of secondary energy emitted in the form of \(\nu_\mu\). 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 \(0.1 f_{-1} R_{16}\) and radius \(R = 10^{16} R_{16}\). The \(pA \rightarrow \pi^{\pm,0}\) energy-loss time scale \(t_{pA}\) in the stationary frame is given by 
\[t_{pA}^{-1} = K_p n_A \sigma_{pA} c \cong 4.3 \times 10^{-7} m_{SNR}/(A^{1/3} R_{16}^2 f_{-1}) \text{s}^{-1},\]
given an inelasticity \(K_p \approx 0.5\) and a strong interaction cross section \(\sigma_{pA} \cong 30 A^{2/3} \text{mb}\). Thus 
\[\eta_p \cong 5 \times 10^{-3} m_{SNR} R_{16}^{-2} A^{-1/3}.\]
These neutrinos are formed at energies \(\approx 0.05 \Gamma m_p c^2 \approx 15 \Gamma_{300}\) 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 \[15\], or by accelerating particles at external or internal shocks. The \(\nu_\mu\)-production efficiency \(\eta_{pp} \cong t_{ava}'/3t_{pp}'\), where \(t_{ava}' \lesssim R/\Gamma c\) is the available time in the comoving frame, 
\[t_{pp}'^{-1} = n'_{p} \sigma_{pp} c = E_{iso} \sigma_{pp} c/(4\pi R^2 \Delta R' \Gamma m_p c^2)\]
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 \(\approx 0.05 \Gamma^2 m_p c^2 \approx 4 \Gamma_{300}^2\) TeV. Only GRBs with large values of \(E_{52}\) or small values of \(\Gamma_{300}, R_{16}\), and \(t_{var}(s)\) provide reasonable efficiencies for \(\nu_\mu\) production, and these would exhibit strong \(\gamma\gamma\) attenuation with comparable fluences in \(\nu_\mu\) 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 \[16\] for neutrino emission from the \textit{pp} interaction of PW protons with the SNR shell during the time \(t_{\text{delay}}\) 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 \textit{before} the GRB event, which would be hard to miss in all-sky X-ray and \(\gamma\)-ray observations. A recent study of neutrino production during the prompt GRB phase in the SA model \[17\] finds similar estimates for the number of expected neutrinos which, however, are predicted to be mostly at much higher energies, \(> 1000\,\text{TeV}\). Moreover, photomeson interactions of protons on the internal synchrotron radiation field as well as \(\gamma\gamma\) attenuation are not studied in Ref. \[17, 18\], 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 \(\nu_\mu\) fluence and therefore of secondary gamma-rays for the assumed injection of relativistic protons is at the level \(\lesssim 3 \times 10^{-6} \, \text{erg cm}^{-2} \sim 0.1 \Phi_{\text{tot}}\). It would therefore still be possible to assume acceleration of protons with a power up to a factor \(\approx 10\) higher than in Fig. 2, which would increase the number of \(\nu_\mu\) expected for IceCube to \(\sim 0.1\) in the SA model. The detection of a few neutrinos would then be possible in the prompt phase of GRBs at the flux level \(\Phi_{\text{tot}} \gtrsim 3 \times 10^{-4} \, \text{erg/cm}^2\). 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 \(\delta\), and are most favorable when the \(\sim 100\,\text{MeV} - \text{GeV}\ \gamma\gamma\) 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 \(\delta\) 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 \(\gamma\)-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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[1] S. E. Woosley, Astrophys. J. 405, 273 (1993); W. Wang and S. E. Woosley, Proc. of 3D
Stellar Evolution Workshop, Livermore, CA (July 2002) (astro-ph/0209482); C. L. Fryer, S.
E. Woosley, and D. H. Hartmann Astrophys. J. 526, 152 (1999).

[2] M. Vietri and L. Stella, Astrophys. J. 507, L45 (1998); M. Vietri and L. Stella, Astrophys.
J. 527, L43 (1999); D. Lazzati, in "Beaming and Jets in Gamma Ray Bursts", Copenhagen,
August 12-30, 2002 (astro-ph/0211174).

[3] A. Königl and J. Granot, Astrophys. J. 574, 134 (2002); S. Inoue, D. Guetta, and F. Pacini,
Astrophys. J. , 583, 379 (2003), Astrophys. J. , 583, 379; D. Guetta and J. Granot, Monthly
Not. Roy. Astron. Soc., 340, 115 (2003).

[4] F. Daigne and R. Mochkovitch, Monthly Not. Roy. Astron. Soc. 296, 275 (1998).

[5] J. P. Norris, et al., Astrophys. J. 459, 393 (1996); A. Lee, E. D. Bloom, and V. Petrosian,
Astrophys. J. Suppl. 131, 1 (2001).

[6] E. Waxman and J. N. Bahcall, Phys. Rev. Lett. 78, 2292 (1997); Z. G. Dai, and T. Lu,
Astrophys. J. 551 249 (2001); E. Waxman and J. N. Bahcall, Astrophys. J. 541, 707 (2000);
F. Halzen and D. W. Hooper, Astrophys. J. 527, L93 (1999); M. Böttcher and C. D. Dermer,
Astrophys. J. 499, L131 (1998).

[7] C. D. Dermer, Astrophys. J. 574, 65 (2002); C. D. Dermer and M. Humi, Astrophys. J. 556,
479 (2001).

[8] A. M. Atoyan and C. D. Dermer, Phys. Rev. Lett. 87, 22102 (2001); A. M. Atoyan and C.
D. Dermer, Astrophys. J. 586, 79, (2003).

[9] T. K. Gaisser, F. Halzen, and T. Stanev, Phys. Repts. 258(3), 173 (1995); A. Karle, et al.
2002 (astro-ph/0209556); http://icecube.wisc.edu/reviews_and_meetings /June2002_NRC-
Review/

[10] M. S. Briggs, et al., Astrophys. J. 524, 82 (1999); as reported in this paper, the > 20 keV fluence of GRB 990123 was $3 \times 10^{-4}$ ergs cm$^{-2}$ s$^{-1}$, placing it in the brightest 0.4% of BATSE GRBs.

[11] M. Vietri, Astrophys. J. 453, 883 (1995); E. Waxman, Phys. Rev. Lett. 75, 386 (1995).

[12] M. G. Baring and A. K. Harding, Astrophys. J. 491, 663 (1997); Y. Lithwick and R. Sari, Astrophys. J. , 555, 540 (2001).

[13] J. I. Katz, Astrophys. J., 432, L27 (1994).

[14] D. A. Frail et al., Astrophys. J. 562, L55 (2001); A. Panaitescu and P. Kumar, Astrophys. J. 554, 667 (2001).

[15] M. Pohl and R. Schlickeiser, Astron. Astrophys. 354, 395 (2000).

[16] D. Guetta and J. Granot, Phys. Rev. Lett. 90, 191102 (2003).

[17] D. Guetta and J. Granot, Phys. Rev. Lett. 90, 201103 (2003).

[18] Razzaque, S., Meszaros, P., and Waxman, E., Phys. Rev. Lett. 90, 241103 (2003).
FIG. 1: Opacity $\tau_{\gamma\gamma}$ to pair-production attenuation for $\gamma$ rays which are detected with observer energy given on the abscissa. The radiating region moves with Doppler factor $\delta$ 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 $3 \times 10^{-5}$ ergs 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.
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.