5-10 GeV Neutrinos from Gamma-Ray Burst Fireballs

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A gamma-ray burst fireball is likely to contain an admixture of neutrons, in addition to protons, in essentially all progenitor scenarios. Inelastic collisions between differentially streaming protons and neutrons in the fireball produce $\nu_n(\bar{\nu}_n)$ of $\sim 10$ GeV as well as $\nu_e(\bar{\nu}_e)$ of $\sim 5$ GeV, which could produce $\sim 7$ events/year in km$^3$ detectors, if the neutron abundance is comparable to that of protons. Photons of $\sim 10$ GeV from $n^0$ decay and $\sim 100$ MeV $\bar{\nu}_e$ from neutron decay are also produced, but will be difficult to detect. Photons with energies $\lesssim 1$ MeV from shocks following neutron decay produce a characteristic signal which may be distinguishable from the proton-related MeV photons.

I. INTRODUCTION

Gamma-ray burst (GRB) sources are distributed throughout the universe and their output energy is measured to be a substantial fraction of a solar rest mass equivalent. A variety of observations support the interpretation that these events are caused by cataclysmic stellar collapse or compact mergers, producing a fireball with bulk expansion Lorentz factor $\Gamma \sim 10^2 - 10^3$. In the standard GRB model a fireball made up of $\gamma, e^\pm$ and magnetic fields with an admixture of baryons is produced by the release of a large amount of energy $E \gtrsim 10^{53}$ ergs in a region $r_o \sim 10^7 r_o \eta$ cm (e.g. [8]). The observations indicate that typical fireballs are characterized by a luminosity $L \sim 10^{52}$ $L_{\odot}$ erg s$^{-1}$ and durations $t_o = 10 t_{rel} s$ in the observer frame, with a large spread in both quantities. The outflow is controlled by the value of the dimensionless entropy $\eta = (L/Mc^2)$ injected at $r_o$. Previous discussions of fireball models have generally focused on the charged particle component, since they determine directly the photon signal. However, consideration of a neutron component introduces qualitatively new effects.

In a $n, p$ fireball, for values of $\eta \gtrsim 400$, the neutrons and protons acquire a relative drift velocity causing inelastic $n, p$ collisions and creating neutrinos. We investigate here the neutrino and photon signals from $n, p$ collisions following decoupling in GRB. The $\sim 10$ GeV neutrinos from this mechanism depend upon the presence of neutrons in the original explosion, but the neutrinos are created in simple physical processes occurring in the later stages of the fireball. On the other hand, the $10^5$ GeV neutrinos discussed in refs. [8] require the acceleration in shock waves of ultra-high energy protons interacting with photons. Thus the 10 GeV and the $10^5$ GeV neutrinos reflect very different astrophysical processes and uncertainties. Other processes, e.g. neutrinos from $p, p$ collisions, also require shocks but have lower efficiencies, while 10-30 MeV neutrinos from the original explosion are much harder to detect due to the lower cross sections.

We show that the 10 GeV neutrinos could be detectable by future km$^3$ size detectors. The associated $\sim 10$ GeV $\gamma$-ray fluences are compatible with current detection rates, and may be detectable with future space missions. The dependence of these signals on the neutron/proton ratio $\xi$ provides a new tool to investigate the nature of the GRB progenitor systems. Moreover the predicted neutrino event rate depends on the asymptotic bulk Lorentz factor of the neutrons, which is linked to that of the protons. The latter affects all the electromagnetic observables from the GRB fireball, including the photospheric and shock radii, as well as the particle acceleration and non-thermal photon production.

II. DYNAMICS, N-P DECOUPLING AND PIONS

Above the fireball injection radius $r_o$ the outflow velocity increases through conversion of internal energy into kinetic energy, the bulk Lorentz factor $\Gamma$ varying as $\Gamma \sim T_o/T' = r/r_o$, where $T'$ is the comoving temperature and $T_o = 1.24^{1/4} \eta^{-1/2} r_o^{1/2} \Gamma^{-1/2}$ MeV is the initial temperature at $r_o$ (henceforth denoting with primes quantities measured in the comoving frame). The flow may be considered spherical, which is a valid approximation also for a collimated outflow of opening angle $\theta_j > \Gamma^{-1}$, for the conditions discussed here.

In a pure proton outflow the linear growth of $\Gamma$ saturates when it reaches an asymptotic value $\Gamma_f \leq \eta \sim$ constant, the value $\eta$ being achieved when the fireball converts all its luminosity into expansion kinetic energy. For an $n, p$ fireball, beyond the injection radius $r_o$ the comoving temperature is low and nuclear reactions are rare, so the $n/p$ ratio $\xi$ remains constant. Since the thermal velocities are non-relativistic, decoupling of the $n$ and $p$ fluids is essential for high-energy neutrino production.

At the base of the outflow the $n$ and $p$ components are coupled by nuclear elastic scattering. In terms of the CM relative energy $\epsilon_{rel}$ and the relative velocity $v_{rel}$ between nucleons, $\sigma_{el} \epsilon_{rel} \sim \sigma_{el}$. The CM energy dependence $\sigma_{el} \propto \epsilon_{rel}^{-1/2} \propto v_{rel}^{-1}$ is approximately
valid between energies $\sim$ MeV and the pion production threshold $\sim$ 140 MeV, and $\sigma_n \sim \sigma_\pi \sim 3 \times 10^{-26}$ cm$^2$ is the pion formation cross section above threshold. The $p$ and $n$ are cold in the comoving frame, and remain well coupled until the comoving $n$, $p$ scattering time $t'_{np} \sim (n'_p \sigma_o c)^{-1}$ becomes longer than the comoving expansion time $t'_{c,exp} \sim r/c\Gamma$. Denoting the comoving neutron density $n'_n = \xi n'_p$ with $\xi \lesssim 1$, mass conservation implies $n'_p = L/[(1+\xi)4\pi r^2 m_p c^2 \Gamma \eta]$. The $n$, $p$ decoupling occurs in the coating or accelerating regimes depending on whether the dimensionless entropy $\eta$ is below or above the critical value

$$\eta_\pi = \left( \frac{L \sigma_o}{4 \pi m_p c^3} r_0 (1 + \xi) \right)^{1/4} \approx 3.9 \times 10^2 L^{1/4} r_0^{-1/4} (1 + \xi/2)^{-1/4}.$$  

(1)

Figure 1 shows the dependence of $\Gamma$ on radius for different $\eta$. For low values, $\eta \ll \eta_\pi$, the condition $t'_{np} \sim t'_{c,exp}$ is achieved at a radius $r_{np}/r_0 = \eta_\pi (\eta/\eta_\pi)^{\frac{3}{4}}$, which is beyond the saturation radius $r_{s}/r_0 \sim \eta$ at which both $n$ and $p$ start to coast with $\Gamma \sim \eta$ constant. In this case, even after decoupling both $n$ and $p$ continue to coast together due to inertia, and their relative velocities never reach the threshold for inelastic collisions.

![FIG. 1. Schematic behavior of the bulk Lorentz factor $\Gamma$ as a function of radius $r$ for various values of the dimensionless entropy $\eta$, the decoupling radius $r_{np}$ being indicated with a diagonal slash. Curve 1 is for $\eta < \eta_\pi$, where the $n$ and $p$ achieve the same asymptotic $\Gamma_{np} \sim \Gamma_{np} \sim \eta$. Curve 2 is for $\eta > \eta_\pi$, and in this case $n$, $p$ decoupling occurs before protons have reached their asymptotic Lorentz factor, which is larger than that of neutrons. This leads to inelastic $n$, $p$ collisions, pion formation and neutrino emission at $r_{np,2}$.](image)

For $\eta \gtrsim \eta_\pi$, on the other hand, the $n$, $p$ decoupling condition $t'_{np} \gtrsim t'_{c,exp}$ occurs while the protons (and neutrons) are still accelerating as $\Gamma_p \simeq (r/r_0)$, at a radius

$$r_{np}/r_0 = \eta_\pi (\eta/\eta_\pi)^{-1/3}, \ \text{for} \ \eta \gtrsim \eta_\pi.$$ 

(2)

Beyond this decoupling radius the $p$ can still continue to accelerate with $\Gamma_p \propto r$ (as long as they remain coupled to the photons). However the neutrons are no longer accelerated, since they only interact with the protons, and they continue to coast with the value of $\Gamma \sim \Gamma_{np}$ constant achieved up to that point,

$$\Gamma_{np} = (3/4)|\eta_\pi (\eta/\eta_\pi)|^{-1/3} \ \text{for} \ \eta \gtrsim \eta_\pi$$

$$\simeq 3 \times 10^{2} L^{1/4} r_0^{-1/4} (1 + \xi/2)^{-1/4} (\eta/\eta_\pi)^{-1/3},$$

(3)

where the $(3/4)$ factor comes from a numerical solution of the coupling equations.

When the $n$, $p$ decoupling condition $\eta \gtrsim \eta_\pi$ is satisfied, the relative $n$, $p$ drift velocity $v_{rel} \rightarrow c$ and the inelastic pion production threshold $\epsilon' > 140$ MeV is reached. Since $\sigma_\pi \sim \sigma_\pi$, the condition $t'_{c,exp} \sim t'_{c,exp}$ implies that the optical depth to pion formation is of order unity. Thus, for $\eta \gtrsim \eta_\pi$, the radius $r_{np} \equiv r_0$ is not only a decoupling radius but also an effective “pionospheric” radius.

The lowest energy threshold processes at $r_\pi$ are

$$p + n \rightarrow p + p + \pi^- \rightarrow \mu^- + \nu_\mu \rightarrow e^- + \nu_e + \nu_\mu + \nu_\mu,$$

$$n + n + \pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \nu_\mu + \nu_\mu,$$

$$p + p + \pi^0 \rightarrow \gamma + \gamma,$$

(4)

which occur in approximately equal ratios and with near unit total probability. The corresponding $p + p$ $(n + n) \rightarrow \pi^\pm$, $\pi^0$ processes do not involve a relative drift velocity (as do the $p + n$), and are thus less probable. Processes leading to multiple baryons are also suppressed due to the higher threshold, and for simplicity we restrict ourselves to the above $p + n$ processes.

### III. 10 GeV Neutrinos and $\gamma$-rays

The total number of neutrons carried by the fireball is

$$N_n = \left( \frac{\xi}{1 + \xi} \right) \frac{E}{m_n c^2} \approx 0.83 \times 10^{53} E_{53} \left( \frac{1000}{\xi} \right) \left( \frac{1000}{\xi} \right),$$  

(5)

The comoving optical depth $\tau' \sim \eta'_{\pi} \sigma_\pi/\Gamma \propto \sigma/(\Gamma \Gamma')$ has the same dependence for pion formation and photon scattering, but $\sigma_\pi \ll \sigma_\pi$ (Thomson cross section), so the pionsphere $r_{\pi}$ occurs below the $\gamma$-photosphere $r_\gamma$. The $\gamma$-rays in equation (6) can only escape from a skin depth below the $\gamma$-sphere in the essentially laminar flow with probability $P_\gamma \lesssim \tau_\gamma(r_\gamma) \sim r_\gamma/r_\gamma \sim (\sigma_\pi/\sigma_\pi)(1+\xi/7)^2 \sim 1/25$, for $\eta \gtrsim \eta_\pi$. Each $n$ leads to a $1$ photon of CM energy $\epsilon'_\pi \sim 70$ MeV and observer energy centered broadly around $\epsilon_\gamma \sim 70 \Gamma_{np}/(1 + z)$ MeV $\sim 10$ GeV. Using a proper distance $D_p = 2.8 \times 10^{28} h_0^{-1} [1 - 1/\sqrt{1 + z}]$ cm with a Hubble constant $h_0 = H_0/65$ km/s/Mpc, the number fluence at Earth is $N_\gamma \sim N_n P_\gamma/4\pi D_p^2 \sim 10^{-5}$ cm$^{-2}$. This is below the sensitivity of the $\sim 200$ cm$^2$ area EGRET detector on the Compton Gamma Ray Observatory (e.g., $E$, but for rare nearby bursts it may be detectable by GLAST.)
The neutrinos originate at the pionospheric radius \( r_\pi \ll r_\gamma \) where \( r_\pi \sim 1 \). In this region the stable charged products and \( \gamma \)-rays from the reactions (3) remain in the fireball, and each \( n \) leads on average to one \( \nu \) and one \( \bar{\nu} \). We list below the average neutrino energies for pions and muons decaying at rest. The neutrinos from muon decay have a continuum spectrum. Also, the energies are Doppler broadened by \( \nu_{\text{rel}}/c \sim 0.5 \).

\[
\epsilon'_\nu \sim 30\text{MeV}, \quad \epsilon'_\bar{\nu} \sim 30\text{MeV} \quad \text{from } \pi^\pm \\
\epsilon'_\nu \sim 50\text{MeV}, \quad \epsilon'_\bar{\nu} \sim 50\text{MeV} \quad \text{from } \mu^+ \\
\epsilon'_\nu \sim 30\text{MeV}, \quad \epsilon'_\bar{\nu} \sim 30\text{MeV} \quad \text{from } \mu^-
\]

The relevant cross section for detection averaged over \( \nu \) and \( \bar{\nu} \) is \( \sigma_{\nu,\bar{\nu}} \sim 0.5 \times 10^{-38}(\epsilon_{\nu,\bar{\nu}}/\text{GeV})^2 \text{cm}^2 \) at the observed energy \( \epsilon_{\nu,\bar{\nu}} \). The observer frame energy is \( \epsilon' = \epsilon' \alpha \Gamma_{nf}/(1+z) \), where \( \alpha \sim 1 \) near threshold. For the CM \( \nu\bar{\nu} \) production energies of equation (3), the average \( \nu + \bar{\nu} \) CM energy per neutron is \( \epsilon' \sim 100 \text{MeV} \). Taking \( \alpha \sim 1 \) the observer \( \nu + \bar{\nu} \) energy per neutron is \( \epsilon \sim 0.1 \Gamma_{nf}/(1+z) \text{GeV} \), and the effective detection cross section per neutron is \( \sigma_{\nu,\bar{\nu}} \sim 5 \times 10^{-40} \Gamma_{nf}(1+z)^{-1} \text{cm}^2 \). Multiplying by a burst rate within a Hubble distance of \( R_b \sim 10^5 R_{\text{Hubble}} \) per year, for a \( 1 \text{km}^3 \) detector containing \( N_t \sim 10^{30} N_{\text{th}} \) target protons, the rate \( R_{\nu,\bar{\nu}} \sim \eta_{\nu,\bar{\nu}} \) is

\[
R_{\nu,\bar{\nu}} \sim 7 E_{53} N_{\text{th}} N_t \left( \frac{3}{1+z} \right) \left( \frac{4}{\eta} \right)^{1/3} \times h_{53}^2 \left( \frac{2-\sqrt{2}}{1+z} \right)^2 \text{year}^{-1},
\]

events in the detector in coincidence with GRB electromagnetic flashes. The energies of the events are

\[
\epsilon_{\nu,\bar{\nu}} \sim 10\text{GeV}, \quad \epsilon_{\nu,\bar{\nu}} \sim 5\text{GeV},
\]

which scale \( \sim E_{53}^{1/3} t_w^{-1/4} \Gamma_{nf}^{−1/4} (2/[1 + \xi])^{1/4} (2/[1 + z]) \) \( \eta_{\nu,\bar{\nu}}^{-1/3} \).

Subsequent to decoupling and \( n, p \) collisions, each neutron decay \( n \to p + e^- + \bar{\nu}_e \) leads to an additional \( \bar{\nu}_e \) of CM energy \( \epsilon'_{\nu,e,d} \sim 0.8 \text{MeV} \), which boosted in the observer frame by \( \Gamma_{nf}/(1+z) \) is \( \lesssim 120 \text{MeV} \). The cross section is \( \sigma_{\nu,e} \sim 2 \times 10^{-40} \text{cm}^2 \) and the expected rate in a \( 1 \text{km}^3 \) detector is less than one event per year.

IV. MEV \( \gamma \)-RAYS

The non-thermal MeV \( \gamma \)-rays are thought to be produced in collisionless shocks (4) which occur at a radius \( r_{sh} > r_{\gamma} > r_\pi \), after the bulk Lorentz factor has saturated to its asymptotic value. For an \( n, p \) outflow, shocks can occur in the original \( p \), as well as in the \( n \) component after the latter have decayed, and this can influence the external shock light curves (4). A separate and important consequence of neutron decay is that it should also affect the internal shock gamma-ray light-curves. In the proton component internal shocks occur at \( r_{sh} \sim c_n T_{nf}^{1/2} \), where \( t_w \) is the variability timescale, and \( \Gamma_{pf} \) is the asymptotic proton Lorentz factor. From energy conservation, for \( \eta > \eta_{\pi} \) this is \( \Gamma_{pf} \sim (E_{53}/10^{53} \Gamma_{nf}^{1/4}) \sim (\eta_{\pi}/\eta)^{1/3} \), and taking into account photon drag one can show that an upper limit is \( \Gamma_{pf,\text{max}} \lesssim 8.3 \times 10^2 \Gamma_{53}^{1/4} \Gamma_{nf}^{-1/4} (1 + \xi/7)^{-1/4} \).

The \( \gamma \)-rays start to arrive at an observer time \( t_w \sim 10^{-3} t_w - 3 \) s, lasting for a time \( t_w \) (where \( 10^{-3} \lesssim t_w \lesssim 10^3 \) s). For the \( n \) component, \( r_{sh} \sim c_n\min\Gamma_{nf}^2 \), with \( \Gamma_{nf} \) from equation (3) and \( t_{\text{min}} \sim \min(t_w, t_w' \Gamma_{nf}^{-1}) \), where \( t_w' \sim 10^3 \) s is the comoving frame neutron decay time. Taking \( \xi \sim 1 \) in the estimates below, for \( 20 \lesssim \eta \lesssim \eta_{\pi} \sim 400 \) the neutrinos decay and shock beyond the proton shock for any \( t_w \lesssim 10^3 \eta^{-1} \), at observer times \( t_n = [50s, 3s] \), while for \( \eta \lesssim \eta_{\pi} \sim 400 \) the neutrinos decay and shock beyond the proton shock for any \( t_w \lesssim 3(\eta_{\pi}/\eta)^{1/3} \) s. The typical observed duration of the decay, including the blue shift due to the bulk motion towards the observer, is \( t_n \sim 10^3 /\Gamma_{nf} \), where \( \Gamma_{nf} \sim \eta_{\pi} / \eta_{\nu,\bar{\nu}} \) for any \( \eta_{\pi} \sim 400 \) and \( \eta_{\nu,\bar{\nu}} \). Thus \( t_n \) decreases from approximately 50 s to 3 s for \( 20 \lesssim \eta \lesssim \eta_{\pi} \sim 400 \), and then slowly increases again as \( t_n \sim 3(\eta_{\pi}/\eta_{\nu,\bar{\nu}})^{1/3} \) for \( \eta \gtrsim \eta_{\nu,\bar{\nu}} \sim 400 \), with both \( \eta_{\pi} \) and \( t_n \) scaling \( \propto [(1 + \xi)/2]^{-1/4} \).

The number of neutron decays is \( \sim 1 - \exp(-t/t_n) \), so the envelope of the neutron-related light curve is the mirror image of a “fred” (fast rise - exponential decay), i.e. an “anti-fred” (or generally, slow rise - fast decay). In general, photon emission starts at \( t_w \) from the proton-related component, which lasts a time \( t_w \) with an arbitrary shape envelope, modulated by spikes of minimum duration \( t_w < t_w \) depending on the chaotic behavior of the central engine producing the outflow. The neutron-related component starts at a later time \( t_n > t_w \), and has an anti-fred shaped envelope modulated by spikes of \( t_n \) and a total duration \( t_w \). If \( t_w > t_n \), the anti-fred component would be hard to distinguish because of the superposition of the ongoing \( p \) and \( n \) components. However, for short bursts with \( t_w < t_n \sim 3 \) s, the \( p \) and \( n \) components are separated: first there is a pulse of duration \( t_w \) with a random envelope, followed after a time \( \sim t_n \) by a pulse with an anti-fred envelope of duration \( t_n \), and characteristic photon energy softer than the previous by \( \epsilon_{n}/\epsilon_{p} \sim t_w/t_n \) (which if small could be below the BATSE band, but may be detectable with the Swift satellite). The latter pulse is a signature for neutron decay in the burst.

V. DISCUSSION

For characteristic parameters, GRB outflows produce 5-10 GeV \( \nu \bar{\nu} \) and \( \nu \bar{\nu} e^\pm \) from internal inelastic \( p, n \) collisions that create pions. The \( \nu \bar{\nu} \) energy output \( E_{\nu,\bar{\nu}} \sim \)
\(5 \times 10^{51} E_{53}(2\xi/[1+\xi])(2/[1+z])(\eta_e/\eta)^{1/3}\) ergs depends on the total energy \(E\) of the GRB and on the neutron fraction \(\xi\) as well as on the dimensionless entropy \(\eta\). For a \(\text{km}^3\) detector, approximately 5 to 10 neutrino events above 10 GeV are predicted per year, for a neutron/proton ratio \(\xi = 1\). These events will be coincident with GRB electromagnetic flashes in direction and in time (to an accuracy of \(\sim 10\) s), which can enable their separation from the atmospheric neutrino background. Underground water detectors of the type being planned by BAIKAL, NESTOR, ANTARES, and the Antarctic detector ICECUBE could potentially detect these relatively low energy neutrino events if a sufficiently high density of phototubes were used. About 80% of these neutrinos are \(\nu\) and \(\bar{\nu}\) (in approximately equal numbers) and the remainder are \(\nu_e\) and \(\bar{\nu}_e\). These 5-10 GeV \(\nu\bar{\nu}\) are followed by \(\sim 120\) MeV \(\bar{\nu}_e\) from neutron decay, but the event rate from neutron-decay neutrinos is very low. The higher energy neutrinos are produced for neutron/proton ratios \(\xi > 0\) when the dimensionless entropy \(\eta = L/\dot{M}c^2\) exceeds \(\eta_\tau \simeq 4 \times 10^{52} \frac{1}{52} r_{\pi}^{-1/4} (2/[1+z])^{1/4}\), and are accompanied by \(\sim 10\) GeV photons which may be detectable in low redshift cases with GLAST. For a typical GRB at redshift \(z \sim 1\) the number fluxes in 10 GeV neutrinos are \(N(\bar{\nu}_e + \nu_e) \sim 0.5N(\nu_\mu + \nu_\mu) \sim 10^{-4}\) cm\(^{-2}\) s\(^{-1}\), and one order of magnitude less for GeV photons.

In all bursts where \(\xi > 0\) the lower energy (~120 MeV) neutrinos are produced, and neutron decay occurs on an observer timescale \(t_n \sim 3L_{52}^{-1/4} r_{\pi}^{1/4} (1+z)^{1/4} (\eta/\eta_\tau)^{1/3}\) s. For outflows of duration \(t_w\), these decays will be associated with MeV electromagnetic pulses of duration \(\min[t_n, t_w]\), which are additional to the MeV pulses expected from shocks in the original proton component. For short bursts with \(t_w \lesssim 3\) s, the proton electromagnetic pulse appears first and is separated from a subsequent neutron electromagnetic pulse, the latter having a slow rise-fast decay envelope and a softer spectrum, which may be detectable with the Swift satellite. A systematic study of the time histories of GRB emission would be useful to search for evidence of delayed pulses that might be caused by neutron decay.

The detection of 5-10 GeV \(\nu\bar{\nu}\) in coincidence with GRB photon flashes will not be easy, but would provide unique astrophysical information. Constraints on the neutron fraction could provide information about the progenitor stellar system giving rise to GRB. For instance, core collapse of massive stars would lead to an outflow from an Fe-rich core with \(\xi \sim 2/3 - 1\), while neutron star mergers would imply \(\xi \geq 1\). Photodissociation during collapse or merger, as well as \(n, p\) decoupling and inelastic collisions, would both drive \(\xi\) toward unity, although this equalization process is likely to remain incomplete. For low \(\eta \lesssim \eta_\tau\), inelastic collisions are not expected and the 5-10 GeV \(\nu\bar{\nu}\) are absent, producing only the harder to detect \(\sim 100\) MeV \(\bar{\nu}_e\) from neutron decay. An initially non-baryonic outflow of, e.g., \(e^\pm\) and magnetic fields, would acquire a baryonic load by entrainment from the progenitor environment, with \(\xi \ll 1\) from massive stellar envelopes, but \(\xi \gtrsim 1\) for, e.g., compact mergers. Thus, lower values of \(\xi\), leading to lower ratios of 5-10 GeV \(\nu\bar{\nu}\) and a lower ratio of neutron decay MeV photons to total fluences would be expected from massive progenitors than from compact mergers.

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[1] Fishman, G.J. & Meegan, C.A. 1995, ARAA, 33, 415; van Paradijs, J, Kouveliotou, C & Wijers, R, 2000, ARAA, in press
[2] Mészáros, P 1999, Prog.Theor.Phys. S.136[astro-ph/9912546]
[3] Derishev, EV, Kocharovsky, VV & Kocharovsky, VL 1999, ApJ 521, 640
[4] Waxman, E & Bahcall, JN 1997, Phys Rev Lett. 78, 2292; Waxman, E & Bahcall, JN 1999, hep-ph/9909286; Vietri, M, 1998, Phys Rev Lett. 80, 3690; Rachen, J & Mészáros, P, 1998, Phys Rev D, 58, 123005
[5] Paczyński, B & Xu, G., 1994, ApJ, 427, 708
[6] Kumar, P, 1999, ApJ, 523, L113
[7] Catelli, J, Dingus, B. & Schneid, P 1998, in Gamma-Ray Bursts, eds Meegan, C et al (AIP:New York) p.309
[8] Gehrels, N & Michelson, P 1999, Apstarphys.Phy, 11, 277
[9] Gaisser, T.K., 1990, Cosmic Rays and Particle Physics (Cambridge: Cambridge Univ. Press); Vogel, P, Phys.Rev D, 29, 1918
[10] Derishev, EV, Kocharovsky, VV & Kocharovsky, VL 1999, Astron.Ap, 345, L51
[11] Rees, M.J. & Mészáros, P, 1994, ApJL, 430, L93
[12] Swift homepage, http://swift.gsfc.nasa.gov
[13] Beloplatikov, I.A. et al, 1997, Astroparticle Phys, 7,263
[14] Tracatti, L, 1998, in 5th Int’l Workshop “Topics in Astroparticle & Underground Physics” (IAUP97), Gran Sasso, Italy; eds. A. Bottini et al, Nucl. Phys B 70, 442
[15] Feinstein, F, in 5th Int’l Workshop “Topics in Astroparticle & Underground Physics” (IAUP97), Gran Sasso, Italy; eds. A. Bottini et al, Nucl. Phys B 70, 445
[16] Halzen, F 1999, 17th Intl conf. Weak Interactions and Neutrinos, Cape Town, South Africa[astro-ph/9908135]