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BARYON LOADING OF GAMMA-RAY BURST BY NEUTRON PICKUP

Amir Levinson[1] and David Eichler[2]

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ABSTRACT

It is proposed that the baryons in gamma-ray burst (GRB) fireballs originate as "pickup" neutrons that leak in sideways from surrounding baryonic matter and convert to protons in a collision avalanche. The asymptotic Lorentz factor is estimated and, in the absence of collimation, is shown to be angle-dependent. Reasonable agreement is obtained with existing limits on the GRB baryonic component. The charged decay and collision products of the neutrons become ultrarelativistic immediately, and an ultra–high-energy neutrino burst is produced with an efficiency that can exceed 0.5. Other signatures may include lithium, beryllium, and/or boron lines in the supernova remnants associated with GRBs and the high polarization of the gamma rays.

Subject headings: gamma rays: bursts — gamma rays: theory — radiation mechanisms: nonthermal

1. INTRODUCTION

An outstanding question concerning gamma-ray burst (GRB) fireballs is the fraction of baryons within them. It is suspected that this fraction is low because they seem to expand with ultrarelativistic Lorentz factors, $\Gamma \geq 10^2$. While the striking paucity of baryons could be accounted for by invoking energy release on field lines where baryons are confined, say by an event horizon or strong binding to strange quark matter, the question would then arise as to whether the mechanism that enforces baryon purity would be so effective that there would be none whatsoever in the fireball.

This is possible; the fireball could consist of just pairs, gamma rays, and low-frequency Poynting flux, but then another question would arise: How do the pairs survive recombination while expanding from an extremely compact region? Were the fireball adiabatically expanding, baryon-free and thermal (Paczyński 1986; Goodman 1986), the e^+-e^- pairs would mostly annihilate at an internal temperature of about 15 keV, corresponding to a radius of not much more than $\sim 10^9$ cm. By contrast, proton-electron pairs would face no such problem but would raise the first question: If there are so few, why are there any at all? (The afterglow from the giant 1998 August 27 flare [Frail, Kulkarni, & Bloom 1999] from SGR 1900+14 was sufficiently weak that the outburst seems to have not put much of its energy into escaping pairs [Eichler 2002], in marked contrast to long, cosmologically distant GRBs. This illustrates that a material fireball that mostly survives the compact regions of its origin should not be taken for granted.)

A theory of baryon content in GRB fireballs could answer these questions. In this Letter, we estimate the baryon content that would arise if the fireball originated entirely on magnetic field lines that connect to an event horizon (or anything that enforces total baryon purity). We assume that the fireball's only baryons arrive as neutrons leaking from baryon-rich field lines to the baryon-free outflow. The basic idea has been discussed in Eichler & Levinson (1999), but here we note a particular instability that exists in this situation: a collisional avalanche. This leads to particularly efficient neutron pickup and neutrino production.

Neutrons and neutrinos have also been discussed by other authors (Derishev, Kocharovsky, & Kocharovsky 1999a, 1999b; Bahcall & Mészáros 2000; Beloborodov 2003). In these papers, the mechanism of baryon contamination is not addressed. The level of this contamination is chosen to fit known GRB constraints and to allow significant acceleration of protons relative to neutrons, and resultant neutrino emission at modest energy (10 GeV). Lemoine (2002) argued that fusion of neutrons and protons to ^{4}He should precede decoupling (cf. Beloborodov 2003) but did not discuss viscous heating at the interface between the fireball and its surroundings. Here we consider such effects and argue that free neutrons and baryonic contamination via their leakage into the GRB fireball can persist out to larger scales ($r \gg 10^{10}$ cm). This scenario allows the baryon contamination to be calculated rather than assumed.

Additional baryon loading could conceivably arise from mixing, owing to hydrodynamic instabilities at the interface between the baryon-poor jet (BPJ) and the baryon-rich wind (BRW) or the enveloping material of the host star. However, the degree of mixing may depend strongly on changes in the magnetic topology and other obscure matters. It is hard to see how mixing could penetrate to the BPJ center without disrupting the BPJ entirely, so any mixing would be restricted by this consideration to load only the periphery of the BPJ.

2. EJECTION OF A NEUTRON-RICH WIND

In GRB scenarios that invoke a stellar-type progenitor, the ejection of a baryon-poor fireball follows a catastrophic event that results in the formation of a system consisting of a compact object surrounded by a hot disk or torus. Here we assume that the fireball emanates from the immediate vicinity of the compact object (a black hole, say) essentially devoid of baryons. This degree of baryon purity is natural if the fireball is generated on field lines that thread the black hole (Levinson & Eichler 1993), either by neutrino annihilation or by extraction of the black hole rotational energy.

During the ejection of the fireball, the matter in the central parts of the disk surrounding the compact object is hot and emits a BRW with a luminosity $L_w \sim 10^{51}$ ergs s^{-1} (Levinson & Eichler 1993; van Putten & Levinson 2003) that propagates at a subrelativistic speed and confines the BPJ.

The large optical depth of the expelled wind ($\tau_T \sim 10^8 L_{w51}/r_{10}$) and the extremely short cooling time render the wind pressure radiation-dominated. Assuming for simplicity

[1] School of Physics and Astronomy, Tel Aviv University, Tel Aviv 69978, Israel; levinson@wise.tau.ac.il.

[2] Physics Department, Ben-Gurion University, P.O. Box 653, Beer-Sheva 84105, Israel; eichler@bgumail.bgu.ac.il.

that the wind velocity $v_w = \beta_w c$ is constant, we obtain a wind temperature

$$T_w \simeq 10^{8.5} L_{w51}^{1/4} \beta_w^{-1/4} (\psi^2 - \theta^2)^{-1/4} r_{10}^{-1/2} \text{ K} \quad (1)$$

and a baryon density

$$n_p = 10^{23} L_{w51} / r_{10}^2 \beta_w^3 (\psi^2 - \theta^2) \text{ cm}^{-3}, \quad (2)$$

where ψ and θ are the opening angles of the BRW and BPJ, respectively.

If the torus is a remnant of a degenerate star, then it is by mass nearly half-neutrons. Above the nuclear dissociation temperature (0.5–0.7 MeV), the neutrons (n) and protons (p) become free. The n/p ratio ξ_n would then be either the initial value or, if the weak interaction equilibration time, $t_{\rm weak} \simeq 5 \times 10^{-2} (T/3 \text{ MeV})^{-5}$ s, is shorter than the outflow time, $t_{\rm exp}$, the equilibrium value, $\xi_n \simeq \exp[(m_p - m_n)/T]$. If freezeout of the weak interaction occurs at $T > (m_n - m_p) \simeq 1$ MeV, then $\xi_n \sim 1$ is generally expected (Derishev et al. 1999b).

Above the critical point, the temperature in the wind declines with radius. Once it drops below $T_{\rm rec} \simeq 77$ keV (depending weakly on density), the free protons and neutrons recombine to form deuterium. The reaction rate for deuterium formation is $\langle \sigma_d v \rangle \simeq 5 \times 10^{-20}$ cm^3 s^{-1}. The corresponding recombination time is $t_{\rm rec} \simeq 10^{-3.5} (\psi^2 - \theta^2) \beta_w^3 r_{10}^2 L_{w51}^{-1}$ s, where equation (2) has been used. Recombination is effective at radii $r_{10} < 10^3 L_{w51} \beta_w^{-4} (\psi^2 - \theta^2)^{-1}$, at which $t_{\rm rec} \ll t_{\rm exp}$, if the temperature there is below $T_{\rm rec}$. Given $T_{\rm rec} \simeq 77$ keV and equation (1), we conclude that free neutrons can exist in the wind out to a radius

$$r_n \simeq 2 \times 10^9 L_{w51}^{1/2} (\psi^2 - \theta^2)^{-1/2} \beta_w^{-1/2} \text{ cm}. \quad (3)$$

For reasonable wind parameters, r_n should lie in the range between a few times 10^9 and a few times 10^{11} cm.

While we have assumed that the BPJ is ensheathed by a neutron-rich outflow that we expect exists, we could instead have assumed that the BPJ is in direct contact with the envelope of the host star that collimates it. Neutrons would be freed up at the interface because the inner wall of the envelope would be heated by the BPJ.

3. NEUTRON PICKUP

The free protons and neutrons in the wind are coupled by nuclear elastic scattering. At the temperatures of interest, the corresponding rate is $\langle \sigma_{\rm el} v \rangle \simeq \langle \sigma_0 c \rangle = 10^{-15}$ cm^3 s^{-1}, independent of center-of-mass energy. The flux of neutrons diffusing into the BPJ through the BPJ-BRW interface is $J_D(r) = \lambda_{n\text{-}p} v_{\rm is} \partial n_n / \partial x = \lambda_{n\text{-}p} v_{\rm is} (n_n / l)$, where $v_{\rm is} = \beta_{\rm is} c = (kT/m_p)^{1/2}$ is the ion thermal speed, $\lambda_{n\text{-}p} = \beta_{\rm is} / (n_p \sigma_0)$ is the mean free path for n-p collisions, x denotes the cylindrical radius, and l denotes the gradient length scale (which may vary with r).

Assuming that the boundary between the BPJ and the BRW is very sharp at the BPJ injection radius ($r_0 \sim 10^7$ cm), the gradient length scale at some larger radius r is $l \simeq (\lambda_{n\text{-}p} v_{\rm is} t_{\rm exp})^{1/2}$, with $t_{\rm exp} = r/v_w$ being the wind expansion time. The total number of neutrons diffusing into the BPJ below some radius r is given by $N_{\rm diff}(r) \simeq 2\pi\theta r^2 t_{\rm exp} J_D(r) = 2\pi\theta r^2 l n_n$. Combining the above results, one finds

$$N_{\rm diff}(r) \simeq 10^{50} \xi_n [(\psi/\theta)^2 - 1]^{-1/2} (\beta_{\rm is}/\beta_w^2) r_{10}^{3/2} L_{w51}^{1/2}, \quad (4)$$

where $\xi_n = n_n/n_p$. If the density gradient length scale, l, at the BPJ-BRW interface is larger than assumed above, e.g., as a result of some mixing, then the gradient would be smeared, and the diffusive flux would be reduced, but presumably advection would replace it and keep the neutron-proton mixture hot.

The fraction of neutrons drifting through the BPJ that decay, $t_{\rm cross}/\tau_n \simeq 10^{-3.5} \theta \beta_{\rm is}^{-1} r_{10}$, where $t_{\rm cross} = \theta r / v_{\rm is}$ is the BPJ crossing time and $\tau_n = 900$ s is the neutron lifetime, is small. However, each decay liberates a proton that generates more protons via collisions with the undecayed neutrons. The proton fraction thus grows exponentially in what we term a collision avalanche, until becoming comparable to the neutron fraction. To estimate the growth length of the shower, we note that the density of target neutrons inside the BPJ (static in the lab frame) is $(t_{\rm cross}/t_{\rm exp})(N_{\rm diff}/\pi\theta^2 r^3)$ and that the optical depth for a collision of a picked-up baryon with the target neutrons is $\tau_{n\text{-}p} = \sigma_{n\text{-}p} r (t_{\rm cross}/t_{\rm exp})(N_{\rm diff}/\pi\theta^2 r^3) = 10^{4.5} \beta_w^{1/2} (\psi^2 - \theta^2)^{-1/2} r_{10}^{-1/2} L_{w51}^{1/2}$, where a cross section for inelastic p-n collisions of $\sigma_{p\text{-}n} = 40$ mbarn has been adopted (Hagiwara et al. 2002). Evidently, the growth length of the shower is much shorter than the injection radius, and it will saturate already at the base of the BPJ. At this point, every neutron diffusing into the BPJ is picked up via a collision with a fast baryon coming from below.

Combining equations (3) and (4) and taking $\beta_{\rm is} = 10^{-2}$ (the ion thermal speed at the recombination temperature) yield the total number of neutrons captured by the BPJ:

$$N_{\rm cap} = N_{\rm diff}(r_n) \simeq 10^{47} \xi_n \theta (\psi^2 - \theta^2)^{-5/4} \beta_w^{-11/4} L_{w51}^{5/4}. \quad (5)$$

Adopting for illustration $\theta = \psi/2 = 0.1$, $\xi_n = 1$, and $\beta_w = 0.3$, we obtain $N_{\rm cap} \simeq 3 \times 10^{49} L_{51}^{5/4}$.

Now the fact that the avalanche growth is so rapid shows that the inwardly drifting neutrons may be converted back to having a $\frac{1}{2}$ proton component shortly after crossing into the BPJ and will merely line the BPJ outer boundary with a hot viscous layer. The short mean free path also means that relative Lorentz factor differences across it are likely to be much less than the total difference. The important assumption is that the inner side is exposed to contact with the more relativistic BPJ and is kept hot enough to have a free neutron component. In the hot viscous layer, density decreases toward the axis. Below some density, the neutrons stream freely into the interior of the BPJ.

Let us define the free-streaming density $n_{\rm fs}$ to be that at which the proper hydrodynamic time $r/c\Gamma$ equals the proper collision time $\Gamma/n \langle \sigma v \rangle$; i.e., $n_{\rm fs} \equiv \Gamma^2 c / r \langle \sigma v \rangle$. If the bulk Lorentz factor Γ is determined by the density of picked-up neutrons, then using $n_{\rm fs}$ above we obtain

$$\Gamma_{\rm fs} = L_j / (n_{\rm fs} m c^2 \pi \theta^2 r^2 c h) = 26 r_{12}^{-1/3} L_{j50}^{1/3} \theta^{-2/3} h^{-1/3}, \quad (6)$$

where L_j is the BPJ luminosity and h is the specific enthalpy of the fluid in units of $m_p c^2$. The free-streaming density is $n_{\rm fs} = (L_j / \pi\theta^2 m_p c^3 h)^{2/3} r^{-5/3} \sigma^{-1/3}$.

The number of neutrons per unit time crossing the free-streaming boundary inward within radius r is given roughly by

$$dN_{\rm cr}/dt = \pi\theta r^2 n_{\rm fs} c / \Gamma = 8 \times 10^{49} r_{12}^{2/3} L_{j50}^{1/3} \theta^{1/3} h^{-1/3} \text{ s}^{-1}, \quad (7)$$

where we assume that the random component of the neutron velocity at the free-streaming boundary is close to c. Thus, at

$r_{12} \sim 1$, most of the neutrons that diffused into the BPJ at $r_{10} \leq 1$ are already free-streaming.

When $n \gg n_{fs}$, h is assumed to be close to unity. In the free-streaming zone, where $\Gamma \gg \Gamma_{fs}$, the neutrons are subjected to large shear in the BPJ, and as they move toward the axis, they find themselves moving relative to the local frame at the lab angle χ and nearly backward with a local Lorentz factor $\gamma' = \Gamma\Gamma_{fs}(1 - \beta\beta_{fs}\cos\chi)$. Thus, h may be estimated as $\Gamma\Gamma_{fs}(1 - \beta\beta_{fs}\cos\chi)$ in the free-streaming zone. At the free-streaming surface, h is very geometry-dependent and can be between 1 and Γ_{fs}^2.

The local spread of neutron velocities at the free-streaming boundary is of order $1/\Gamma_{fs}$, so if $\theta \geq 1/\Gamma$, the transverse velocity of an "inwardly" free-streaming neutron may point away from the axis, as long as it does so less than the average local velocity, and $\chi \leq 1/\Gamma_{fs}$. Some fraction ($\sim 1/e$) of the inwardly streaming neutrons will encounter further collisions, thus loading a "collisional annulus" of thickness $1/\Gamma_{fs}$ and radius θ, while the rest may continue farther inward until they decay. If $\Gamma_{fs}^2\Delta t/2$, where Δt is the GRB duration, exceeds the neutron lifetime of $900\Gamma_{fs}$ s, then most of the neutrons decay within the fireball; otherwise, they decay behind it (Beloborodov 2003) and leave a baryon-pure core ahead.

The fluid parameters in the collisional annulus are similar to those described by Derishev et al. (1999a, 1999b), where the radial acceleration just happens to proceed on a scale comparable to the mean collision time, inducing a modestly relativistic relative velocity between the neutrons and the protons. In our picture, this apparent numerical coincidence is in fact natural for the annulus defined by marginally freely streaming neutrons. The annulus occupies $2/\theta\Gamma_{fs} \sim 0.03 r_{12}^{1/3} L_{j50}^{-1/3} \theta^{-1/3}\ h^{1/3}$ of the beam solid angle. For $\theta = 0.1$ and $h^{1/3} \sim 6$, this is comparable to the solid angle of the core and suggests the possibility that many of the GRBs we see are just these annuli. Nevertheless, the observational effects as seen by an observer in the beam of the much higher Γ core are worth considering.

It may be that the BPJ is collimated and that some or all of it converges at the BPJ axis. The density can increase downstream, and neutrons that have already passed through the free-streaming boundary (according to the formal local definition) may then with high probability collide farther downstream with an impact angle $\chi \gg \Gamma_{fs}^{-1}$ in a region of $\Gamma \gg \Gamma_{fs}$. (Even in the case of an asymptotically conical BPJ [Levinson & Eichler 2000], the fact that Γ_{fs} decreases with r means that neutrons free-streaming inward from a point $r_1 \ll 10^{12}$ cm will graze those free-streaming from farther upstream at point $r_2 \leq 10^{12}$ cm where $r_2 \geq r_1$. The impact angle as viewed in the lab frame is of order $\Gamma_{fs,2}^{-1}$.)

When $\chi \gg 1/\Gamma_{fs}$, freely axisward-streaming neutrons are "broadsided" by a faster interior plasma at an impact angle $\chi \geq 1/\Gamma_{fs}$, and their optical depth toward baryons in the interior plasma is *enhanced* by a factor $\theta^2\Gamma_{fs}^2$. Thus, the optical depth presented by axisward-streaming neutrons toward the interior plasma is at least of order unity, and neutrino production by picked-up particles is efficient. The energy of the neutrinos released in this avalanche is of order 0.05 of the typical ex-neutron energy.

The "top-down" nature of pickup suggests that much energy can be dissipated in extremely energetic collisions. A high-Γ flow that is slowed by neutron pickup can be viewed as slowing down in stages, such that at each stage $\epsilon(r)\dot{N}(r) \sim L_j$, where $\epsilon(r)$ is the average energy per baryon at radius r and $\dot{N}$ is the rate of pickup within radius r. For each new collisional pickup, about half the original energy is dissipated into pion decay products. (In each collision between a moving baryon and a target neutron, many pions are produced. The leading pion has about 0.2 of the original baryon energy, and the muon neutrino from its decay will have about 0.05 of the original, provided that the impact angle exceeds $1/\Gamma_{fs}$. Thus, neutrinos of up to $\sim 0.05\epsilon$ will emerge, and they will contain about 5% of the jet energy. Another 10% or so is in the soft pions, which have a lab-frame Lorentz factor somewhat larger but of order the center-of-mass Lorentz factor.) In the crude approximation that the neutrino losses are a small fraction of the collision energy, the spectrum of neutrinos is then $dN/dE \propto E^{-2}$ over a dynamical range that depends on how many optical depths the avalanche proceeds through; including neutrino losses leads to an even harder spectrum. Even if neutron pickup is extremely inefficient, this would still allow efficient neutrino emission in fewer, higher energy neutrinos. In the extreme scenario in which there is only neutron decay and a single optical depth for collisions, there are about $6 \times 10^{49} c\Delta t/\tau_n\Gamma_{fs} \sim 10^{48}/\Gamma_{fs}$ neutrons that decay within the fireball. This suggests an asymptotic Γ of 10^4 and a maximum proton energy of $10^8 m_p c^2$. Most of this energy will be liberated as neutrinos over an optical depth of several. Note that for BPJ proton energies of order $10^8 m_p c^2$, even the soft pions can decay into $E \gg 1$ TeV neutrinos. Such extremely hard spectra would be a highly distinctive signature of the model, and the optical depth crossed by the avalanche would be manifested in the neutrino spectrum.

It is also instructive to view the problem from the point of view of a free-streaming neutron. It has a better-than-even chance of not making another collision once entering the free-streaming zone. However, the rare collision is with extremely relativistic plasma, and the energy liberated per collision goes as Γ^2. Writing the expected energy release per path length as $\langle dE/ds\rangle = n\,\langle\sigma v\rangle\,\Gamma^2$, and estimating Γ^2 as $L/\pi r^2\theta^2 n$, we notice that $\langle dE/ds\rangle$ is then independent of density, and much of the energy release can be in the form of rare but very energetic collisions.

An isotropic equivalent neutrino output of $10^{52}F_{52}$ ergs could be detected at the 1 count level with a 1 km^2 neutrino detector at a distance of F_{52} Gpc. As noted earlier (Eichler & Levinson 1999; Mészáros & Waxman 2001), smothered GRBs could also be detected in (and probably only in) neutrinos.

4. LIGHT-ELEMENT PRODUCTION

Eichler & Letaw (1987) noted that light-element abundances constrain cosmic-ray production by number in the early stages of typical supernovae. However, the limits on total cosmic-ray energy content are less significant in the case of very hard spectra. Also, an intense burst of particles on the same surface would produce an "overkill"—i.e., light elements produced by spallation would then be further degraded by repeated spallation. This is significant at a high-energy particle fluence exceeding 10^{26} cm^{-2}, although instabilities at the head of the jet could lessen the overkill by constantly providing a fresh surface.

In any case, a GRB-associated supernova is not typical. It may therefore be worth searching for excess light-element lines in the young supernova remnants associated with GRBs. Enhancements of 2 orders of magnitude above the cosmic abundance could exist. The original GRB-associated supernova SN 1998bw had a remarkably large outflow velocity, $c/6$, suggesting that the parts of the ejecta that dominated the line emission may have been dragged by the collimated fireball within. While energetic protons that could be channeled away from the enveloping material by electromagnetic forces might never interact with the surrounding ejecta, neutrons would easily penetrate the envelope if the ejecta collimate the GRB fireball, for then the walls of the BPJ curve inward.

5. CONCLUSIONS

We have elaborated on an earlier suggestion that baryon loading of GRB fireballs is accomplished by picked-up exneutrons that crept across magnetic field lines into the path of the collimated fireball from the collimating material. For a GRB lasting 30 s, $r_{12} \sim 1$, and having a conical collimation θ, we find that there is a free-streaming annulus at which the flow has a Lorentz factor Γ_{fs} of about $35L_{50}^{1/4}(\theta/0.1)^{-1/2}$. (In this estimate, we assumed that the specific enthalpy h, which is rapidly varying at this point, is roughly Γ_{fs}, and we note that the result is only weakly dependent on it.) The thickness of the annulus is about $1/\Gamma_{fs}$, and $0.6(\theta/0.1)^{-1/2}$ of the solid angle within the cone of opening angle θ is subtended by the annulus. Well inside the annulus, i.e., when $\theta \gg 1/\Gamma$, the bulk Lorentz factor may be considerably higher, and the spectrum could be considerably harder. *This suggests the possibility of extremely hard GRBs that yield ultra–high-energy (UHE) photons and/or neutrinos while being relatively inconspicuous in soft gamma rays.* Outside the annulus, the baryon loading is greater, Γ is considerably lower, and this part of the outflow could be responsible for X-ray flashes (Berezinsky & Prilutsky 1985), when the viewing angle happens to coincide with it. A universal transverse structure, however, is not predicted by this model, and the opening angles and transverse gradients could vary from case to case.

If the GRB is collimated by surrounding material, such as the envelope of a host star, enough that $\theta \leq \Gamma_{fs}$, then the transverse structure is much closer to being uniform.

The baryons in the fireball can, of course, then go on to generate further neutrinos downstream of their point of origin as in several previous discussions (Eichler 1994; Paczyński & Xu 1994; Waxman & Bahcall 1997). In this Letter, on the other hand, we have presented a scenario for baryon loading whereby UHE neutrinos are a logical consequence.

The neutrinos that result have individual energies of order $\Gamma^2 m_\pi \sim 10^{12}$–$10^{15}$ eV, which are easier to detect with large underwater and under-ice neutrino detectors than those at several GeV, which could result from the differential acceleration of protons and neutrons by fireball pressure. They would have a very hard spectrum and be a highly distinctive feature of the pickup model. Remarkably, the total energy output in neutrinos can in principle be as high as that of the observed fireball or even higher.

The ability to catch GRB-associated supernovae at an early stage should be greatly enhanced by *Swift*, and it may be possible to search for spallation-induced light-element enhancement in the young supernova ejecta.

The emission of gamma rays from an annulus just inside an optically thick wall should give rise to a strongly polarized reflected component, as noted by Eichler & Levinson (1999). A quantitative discussion of this will be given in a subsequent paper.

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REFERENCES

Bahcall, J. N., & Mészáros, P. 2000, Phys. Rev. Lett., 85, 1362
Beloborodov, A. M. 2003, ApJ, 588, 931
Berezinsky, V. S., & Prilutsky, O. F. 1985, Proc. 19th Int. Cosmic-Ray Conf. (La Jolla), 1, 29
Derishev, E. V., Kocharovsky, V. V., & Kocharovsky, Vl. V. 1999a, ApJ, 521, 640
———. 1999b, A&A, 345, L51
Eichler, D. 1994, ApJS, 90, 877
———. 2002, MNRAS, 335, 883
Eichler, D., & Letaw, J. R. 1987, Nature, 328, 783
Eichler, D., & Levinson, A. 1999, ApJ, 521, L117
Frail, D., Kulkarni, S., & Bloom, J. S. 1999, Nature, 398, 127
Goodman, J. 1986, ApJ, 308, L47
Hagiwara, K., et al. 2002, Phys. Rev. D, 66, 010001
Lemoine, M. 2002, A&A, 390, L31
Levinson, A., & Eichler, D. 1993, ApJ, 418, 386
———. 2000, Phys. Rev. Lett., 85, 236
Mészáros, P., & Waxman, E. 2001, Phys. Rev. Lett., 87, 171102
Paczyński, B. 1986, ApJ, 308, L43
Paczyński, B., & Xu, G. 1994, ApJ, 427, 708
van Putten, M. V. P., & Levinson, A. 2003, ApJ, 584, 937
Waxman, E., & Bahcall, J. 1997, Phys. Rev. Lett., 78, 2292