

## Neutral beam model for the anomalous $\gamma$ -ray emission component in GRB 941017

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**Abstract.** González et al. (2003) have reported the discovery of an anomalous radiation component from  $\approx 1$ –200 MeV in GRB 941017. This component varies independently of and contains  $\geq 3\times$  the energy found in the prompt  $\sim 50$  keV–1 MeV radiation component that is well described by the relativistic synchrotron-shock model. Acceleration of hadrons to very high energies can give rise to two additional emission components, one produced inside the GRB blast wave and one associated with an escaping beam of ultra-high energy (UHE;  $\geq 10^{14}$  eV) neutrons,  $\gamma$  rays, and neutrinos. The first component extending to  $\sim 100$  MeV is from a pair-photon cascade induced by photomeson processes with the internal synchrotron photons coincident with the prompt radiation. The outflowing UHE neutral beam can undergo further interactions with external photons from the backscattered photon field to produce a beam of hyper-relativistic electrons that lose most of their energy during a fraction of a gyroperiod in the assumed Gauss-strength magnetic fields of the circumburst medium. The synchrotron radiation of these electrons has a spectrum with  $\nu F_\nu$  index equal to +1 that can explain the anomalous component in GRB 941017. This interpretation of the spectrum of GRB 941017 requires a high baryon load of the accelerated particles in GRB blast waves. It implies that most of the radiation associated with the anomalous component is released at  $\geq 500$  MeV, suitable for observations with *GLAST*, and with a comparable energy fluence in  $\sim 100$  TeV neutrinos that could be detected with a km-scale neutrino telescope like IceCube.

**Key words.** gamma ray bursts – cosmic rays – radiation processes

### 1. Introduction

Based on joint analysis of BATSE LAD (Large Area Detector) and the EGRET TASC (Total Absorption Shower Counter) data, González et al. (2003) recently reported the detection of an anomalous MeV emission component in the spectrum of GRB 941017 that decays more slowly than the prompt emission detected with the LAD in the  $\approx 50$  keV–1 MeV range. The multi-MeV component lasts for  $\geq 200$  s (the  $t_{90}$  duration of the lower-energy prompt component is 77 s), and is detected with the BATSE LAD near 1 MeV and with the EGRET TASC between  $\approx 1$  and 200 MeV. The spectrum is very hard, with a photon number flux  $\phi(\epsilon) \propto \epsilon^{-1}$ , where  $\epsilon = h\nu/m_e c^2$  is the observed dimensionless photon energy.

This component is not predicted or easily explained within the standard leptonic model for GRB blast waves, though it possibly could be related to Comptonization of reverse-shock emission by the forward shock electrons

(Granot & Guetta 2003), including self-absorbed reverse-shock optical synchrotron radiation (Pe'er & Waxman 2004). Another possibility is that hadronic acceleration in GRB blast waves could be responsible for this component.

We propose a model involving acceleration of hadrons at the relativistic shocks of GRBs. A pair-photon cascade initiated by photohadronic processes between high-energy hadrons accelerated in the GRB blast wave and the internal synchrotron radiation field produces an emission component that appears during the prompt phase. Photomeson interactions in the relativistic blast wave also produce a beam of UHE neutrons, as proposed for blazar jets (Atoyan & Dermer 2003). Subsequent photopion production of these neutrons with photons outside the blast wave produces a directed hyper-relativistic electron-positron beam in the process of charged pion decay and the conversion of high-energy photons from  $\pi^0$  decay. These energetic leptons produce a synchrotron spectrum in the radiation reaction-limited regime extending to  $\geq$ GeV energies, with properties in the 1–200 MeV range similar to that measured from GRB 941017. If our model is correct, detection of this

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component therefore gives important evidence for the acceleration of UHE cosmic rays in GRB blast waves, and would be confirmed by the detection of UHE neutrinos from GRBs.

## 2. Hadronic model for GRB 941017

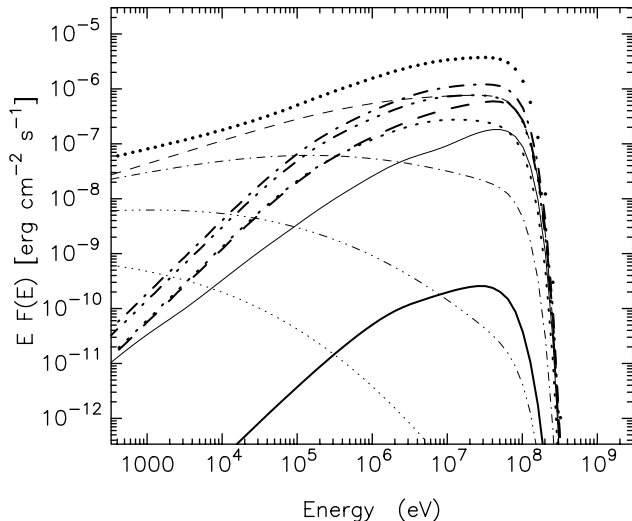
We assume that efficient proton acceleration to ultra-relativistic energies takes place in GRB blast waves, as required in models where GRBs accelerate high-energy cosmic rays (Vietri 1995; Waxman 1995; Dermer 2002). Photopion interactions of these protons with internal synchrotron photons and with photons from an external radiation field create neutral particles and charged pions that decay and initiate an electromagnetic cascade within the GRB blast wave.

During the prompt emission phase, an additional component of radiation is produced by the cascade occurring within the blast wave. Figure 1 shows the hadron-initiated cascade radiation for a model GRB at redshift  $z = 1$ , with hard X-ray fluence  $\Phi_{\text{tot}} = 3 \times 10^{-4} \text{ erg cm}^{-2}$ , a light curve of 100 s duration divided into 50 pulses of 1 s each, and Doppler factor  $\delta = 100$  (see Atoyan & Dermer 2003; Dermer & Atoyan 2003 for more details about the model). The total amount of accelerated proton energy  $E' = 4\pi d_L^2 \Phi_{\text{tot}} \delta^{-3} (1+z)^{-1}$  is injected into the comoving frame of the GRB blast wave.

The various generations of synchrotron and Compton radiation initiated by the cascade are shown in Fig. 1, along with the total radiation spectrum. As can be seen, the isotropic cascade radiation approaches the spectrum of an electron distribution cooling by synchrotron losses, that is, a photon number index between  $-1.5$  and  $-2$ . During intervals (a) and (b) of GRB 941017 when the prompt hard X-ray and soft  $\gamma$ -ray flux is brightest and the high-energy spectral index is hard though not well-measured (González et al. 2003), this component could make the dominant contribution to  $\geq 1$  MeV radiation fluence. The isotropic cascade radiation will decay at the same rate as the synchrotron radiation, after which a second component from the outflowing neutral beam begins to dominate.

Ultra-relativistic neutrons formed in the reaction  $p + \gamma \rightarrow n + \pi^0$  are not confined by the magnetic field in the GRB blast-wave shell and flow out to create an energetic neutron beam. These neutrons are subject to further photopion processes with photons in the surrounding medium to form charged and neutral pions. In the Gauss-type magnetic fields surrounding GRB sources that we assume here, charged  $\pi$  and  $\mu$  at energies  $\lesssim 10^{18}$  eV decay rather than lose energy through synchrotron emission (Rachen & Mészáros 1998). The charged pions decay into ultrarelativistic electrons and neutrinos, whereas the decay of  $\pi^0$  produces two  $\gamma$  rays that are promptly converted into electron-positron pairs on this same external radiation field. These energetic electrons (including positrons) are initially produced in the direction of the GRB jet.

The spectra of secondary electrons created by the neutron beam displays a sharp cutoff at energies  $\lesssim 10^{14}$  eV as a consequence of the high threshold for photomeson interactions (see calculations in Dermer & Atoyan 2003). Electrons with Lorentz factor  $\gamma$  lose energy through synchrotron radiation in an ordered magnetic field with strength  $B$  at the rate  $-d\gamma/dt = \sigma_T B^2 \gamma^2 \sin^2 \psi / (4\pi m_e c)$ , where  $\psi$  is the electron pitch angle.



**Fig. 1.** Photon energy fluence from an electromagnetic cascade initiated by photopion secondaries in a model GRB, with parameters given in the text. Five generations of Compton (heavy curves) and synchrotron (light curves) are shown. The first through fifth generations are given by solid, dashed, dot-dashed, dot-triple-dashed, and dotted curves, respectively. The total cascade radiation spectrum is given by the upper bold dotted curve.

The corresponding synchrotron energy-loss time scale  $t_{\text{syn}} = \gamma / |d\gamma/dt|$ . The gyration frequency  $\omega_B = eB/\gamma m_e c$ , and is independent of pitch angle. When  $\omega_B t_{\text{syn}} \ll 1$ , the electron loses almost all of its energy into synchrotron radiation in a time less than the gyroperiod. We use the term “hyper-relativistic” to refer to electrons in this radiation-reaction regime of synchrotron emission (Nelson & Wasserman 1991; Aloisio & Blasi 2002).

Electrons which cool before being deflected by an angle  $\theta$  equal to the jet opening angle  $\theta_j$  will emit most of their energy within  $\theta_j$ . The pitch angle  $\psi$  does not change in the process of synchrotron losses when  $\gamma \gg 1$ . Then  $\cos \theta = \cos^2 \psi + \sin^2 \psi \cos \phi$ , where  $\phi = \omega_B t$  is the rotation angle. In the limit of small  $\theta$  and  $\phi$ ,  $\theta \approx \phi \sin \psi$ . The condition  $\theta \leq \theta_j$  for times  $t \leq t_{\text{syn}}$  then results in the condition  $\gamma \gtrsim \gamma_{\text{hr}}(\theta_j) = \sqrt{4\pi e / (\theta_j \sigma_T B \sin \psi)} \approx 3 \times 10^8 / [\sqrt{(\theta_j/0.1) B(G) \sin \psi}]$  for the hyper-relativistic electrons. Here we have taken a typical jet opening half-angle  $\theta_j = 0.1$  because this is the average value implied by the analysis leading to the standard energy reservoir result of GRBs (Frail et al. 2001). Lower-energy electrons with  $\gamma < \gamma_{\text{hr}}(\theta_j)$  radiate their energy over a much larger solid angle.

The mean energy  $E_\gamma \equiv m_e c^2 \epsilon = E_j$  of synchrotron photons emitted by electrons with  $\gamma \approx \gamma_{\text{hr}}(\theta_j)$  is independent of  $\psi$  and  $B$ , and is given by

$$E_j \approx \frac{\hbar e B \sin \psi}{m_e c} \frac{\gamma_{\text{hr}}^2(\theta_j)}{(1+z)} \approx \frac{500}{(\theta_j/0.1)[(1+z)/2]} \text{ MeV.} \quad (1)$$

Hyper-relativistic electrons with  $\gamma > \gamma_{\text{hr}}(\theta_j)$  rapidly lose energy through synchrotron losses and deposit all of their energy along the direction of the jet. Electrons at lower energies are deflected to angles  $\theta > \theta_j$ , and their emission is not seen by an on-axis observer. Hence the distribution of electrons along the jet direction always has an effective low-energy cutoff at  $\gamma_{\text{hr}}(\theta_j)$ . The production spectrum of the electrons can

have an intrinsic cutoff  $\gamma_{\text{co}}$  due either to the low-energy cutoff in the escaping neutron spectrum, or to the neutron-induced photomeson secondary spectrum outside the GRB blast wave. If  $\rho \equiv \gamma_{\text{co}}/\gamma_{\text{hr}}(\theta_j) > 1$ , then the observed synchrotron spectrum is a power law with  $-1.5$  index for  $E_j \lesssim E_\gamma \lesssim \rho^2 E_j$ , and a photon spectrum with the same spectral index as the accelerated protons and escaping neutrons at photon energies  $E_\gamma \gtrsim \rho^2 E_j$  (Nelson & Wasserman 1991). If  $\rho < 1$ , then the observed photon spectrum at  $E_\gamma \gtrsim E_j$  has the same spectral index as the primary neutrons.

At photon energies  $E_\gamma \ll E_j$ , the observed spectrum is produced by the same hyper-relativistic electrons with  $\gamma \gtrsim \gamma_{\text{hr}}(\theta_j)$ , but at energies  $\epsilon$  well below the peak energy  $3\gamma^2 \epsilon_B$ , where  $\epsilon_B \equiv B/B_{\text{cr}}$  and  $B_{\text{cr}} = 4.41 \times 10^{13}$  G is the critical magnetic field. We now derive this spectrum.

The differential energy radiated per dimensionless energy interval  $d\epsilon$  per differential solid angle element  $d\Omega$  in the direction  $\theta$  with respect to the direction of an electron moving with Lorentz factor  $\gamma$  is given by

$$\frac{dE}{d\epsilon d\Omega} = \frac{e^2}{3\pi^2 \bar{\lambda}_C} \left( \frac{\epsilon}{\gamma \epsilon_B} \right)^2 (1 + \gamma^2 \theta^2)^2 (\Lambda_{\parallel} + \Lambda_{\perp}), \quad (2)$$

where  $\bar{\lambda}_C = \hbar/m_e c = 3.86 \times 10^{-11}$  cm is the electron Compton wavelength, and  $\Lambda_{\parallel} = K_{2/3}^2(\xi)$  and  $\Lambda_{\perp} = (\gamma\theta)^2 K_{1/3}^2(\xi)/[1 + (\gamma\theta)^2]$  are factors for radiation polarized parallel and perpendicular to the projection of the magnetic field direction on the plane of the sky defined by the observer's direction (Jackson 1975). The factor  $\xi = \epsilon/\hat{\epsilon}$ , where  $\hat{\epsilon} = 3\epsilon_B \gamma^2 / (1 + \gamma^2 \theta^2)^{3/2}$ , and  $K_n(x)$  is a modified Bessel function of the second kind, with asymptotes  $K_n(x) \rightarrow \frac{1}{2}\Gamma(n)(2/x)^n$  in the limit  $x \ll 1$ , and  $K_n(x) \rightarrow \sqrt{\pi/2x} \exp(-x)$  in the limit  $x \gg 1$ . The condition  $\xi \ll 1$  corresponds to  $\epsilon \ll \hat{\epsilon}$  where  $K_n(\xi)$  are in their power-law asymptotes, and  $\xi \gtrsim 1$  or  $\epsilon \gtrsim \hat{\epsilon}$  is where  $K_n(\xi)$  are in exponential decline. The characteristic energy  $\hat{\epsilon}$  approaches  $3\epsilon_B \gamma^2$  when  $\gamma\theta \ll 1$ , and  $\hat{\epsilon}$  declines with  $\theta$  according to the relation  $\hat{\epsilon} \approx 3\epsilon_B \gamma^2 / (\gamma\theta)^3$  when  $\gamma\theta \gg 1$ . When  $\epsilon \ll \hat{\epsilon}$ , then  $\Lambda_{\parallel} \gg \Lambda_{\perp}$  and  $dE/d\epsilon d\Omega \approx 3^{1/3} (1.07e/\pi)^2 (\gamma\epsilon/\epsilon_B)^{2/3} / \bar{\lambda}_C \propto \epsilon^{2/3}$ . For a fixed value of  $\epsilon$ , this emissivity exponentially cuts off when  $\epsilon \gtrsim 3\epsilon_B / \gamma\theta^3$ , or when  $\theta \gtrsim \theta_{\text{max}} = (3\epsilon_B / \gamma\epsilon)^{1/3}$ .

The synchrotron emission spectrum at energies  $E_\gamma \ll E_j$ , integrated over solid angle, is thus

$$\frac{dE}{d\epsilon} \approx 2\pi \int_0^{(3\epsilon_B/\gamma\epsilon)^{1/3}} d\theta \theta \left( \frac{dE}{d\epsilon d\Omega} \right) \approx \frac{3e^2}{\pi \bar{\lambda}_C} \propto \epsilon^0. \quad (3)$$

This differs from the energy index  $+1/3$  for synchrotron radiation radiated by electrons in the classical regime, because in this case one integrates over a complete orbit of an electron (Rybicki & Lightman 1979). In this case, the solid angle element  $d\Omega \rightarrow d\theta \sin \theta \rightarrow d\theta \sin \psi$  in the integration in Eq. (3).

### 3. Neutron beams from GRBs

In our model, ultrarelativistic protons undergo photomeson interactions with internal and external radiation photons, producing a beam of outflowing neutrons. Subsequent interactions of

these neutrons with photons of the external radiation field generate a beam of hyper-relativistic electrons. The  $\gtrsim 1$  MeV emission during the prompt phase is mainly cascade radiation produced within the GRB shell, while the emission induced by the neutron beam is formed at later times. This interpretation requires that the fluence of photohadronic cascade radiation within the shell exceed by a factor of order unity the cascade fluence induced by the neutral beam radiation, consistent with observations. At later times, as shown above, synchrotron radiation from the hyper-relativistic electrons has a low-energy cutoff at  $E_\gamma < E_j \sim 0.5$  GeV, with a specific characteristic power-law number spectral index equal to  $-1$ , as observed for GRB 941017 (González et al. 2003).

The  $\approx 200$  s decay time of the anomalous emission can be explained by the projected thickness  $\approx R(1 - \cos \theta_j)$  of the emitting region from the front to the edges of a jet blastwave at distances  $R \approx 6 \times 10^{14} (\theta_j/0.1)^{-2} [(1+z)/2]^{-1}$  cm from the central source, implying significant opacity to photomeson processes due to external photons at these distances. Note that hyper-relativistic electrons can make a substantial contribution to emission at  $\theta \approx \theta_j \gg 1/\Gamma$ , where  $\Gamma$  is the GRB blastwave Lorentz factor.

The external radiation field could be due to plerionic emission in the supernova model (Königl & Granot 2002), or to GRB synchrotron photons that are backscattered by stellar wind electrons in the collapsar model (Beloborodov 2002). We estimate the effective photomeson energy-loss scattering depth  $\tau_{ny}$  for neutrons in the collapsar-model case, and show that it implies a size scale of the back-scattering material in accord with the radius inferred from the duration of the anomalous component. Above the photopion threshold for backscattered radiation, which applies to  $\gtrsim$  several hundred GeV protons,  $\tau_{ny} \approx K_{ny} \sigma_{ny} \Phi_\gamma(R) \tau_T$ , where the product of the inelasticity  $K_{ny}$  and cross section  $\sigma_{ny} \approx 70 \mu\text{barns}$  (Atoyan & Dermer 2003),  $\Phi_\gamma(R) \approx d_L^2 \varphi / [\langle \epsilon \rangle m_e c^2 R^2]$  is the photon fluence of the prompt GRB emission at radius  $R$ , and  $\tau_T \approx \sigma_T R n_w(R)$  is the Thomson depth for scattering photons with observed energies  $\langle \epsilon \rangle m_e c^2$  at radius  $R = 10^{14} R_{14}$  cm in the frame of the stellar wind. The expression for photon fluence is written in terms of the energy fluence  $\varphi = 10^{-4} \varphi_{-4}$  erg cm $^{-2}$  from a GRB at luminosity distance  $d_L = 10^{28} d_{28}$  cm.

The stellar wind outflow rate  $\dot{M} = 10^{-4} \dot{M}_{-4} M_\odot/\text{yr}$  and wind speed  $v = 2000 v_{2000}$  km s $^{-1}$  are scaled to the properties of the winds of Wolf-Rayet stars (Lozinskaya 1992), which are likely GRB progenitors. This implies a Thomson depth  $\tau_T \approx 0.01 \dot{M}_{-4} / R_{14} v_{2000}$ , so that  $\tau_{ny} \approx d_{28}^2 \varphi_{-4} \dot{M}_{-4} / [\langle \epsilon \rangle (1+z) R_{14}^3 v_{2000}]$  at scales  $R$ . Equating the restriction on radius following from the requirement  $\tau_{ny} \gtrsim 1$  with the relation on  $R$  from duration for  $z = 1$  and  $d_{28} = 2.2$  implies  $\theta_j \approx 0.14 [(\langle \epsilon \rangle / 0.1) v_{2000} / \varphi_{-4} \dot{M}_{-4}]^{1/6}$ , which is a typical jet opening angle. The differing GRB external radiation and density environments which determine the intensity of target photons could account for the unusual spectrum of GRB 941017.

The fluence in the anomalous MeV component of GRB 941017 is  $\gtrsim 3\times$  larger than the prompt emission fluence. If the anomalous fluence is assumed to originate from photopion processes from nonthermal protons, then  $\gtrsim 1$  order of magnitude more energy should be available in hadrons than electrons

to produce these fluence ratios, when account is taken of losses to neutrinos and inefficient extraction of proton energy. The neutral beam model interpretation therefore requires that the accelerated particles in, at least, GRB 941017 are hadronically dominated by  $\geq 1$  order of magnitude, consistent with predictions linking cosmic rays to GRB sources (Wick et al. 2003).

The neutron beam can take up to  $\approx 30\text{--}50\%$  of the accelerated proton energy, with an equal amount of power going into neutrinos, gamma rays and electrons. At later stages when the internal photon field disappears, the cascade induced by electrons in the blast wave is suppressed as a consequence of the strong Klein-Nishina effects on  $\gamma\gamma$  photo-absorption for the external radiation, which is contributed mostly by backscattered prompt X-rays and MeV  $\gamma$  rays. But the backscattered radiation field still remains effective for photohadronic processes with UHE protons that continue to be accelerated in the GRB blast wave after the decline of the prompt emission. Note that such an environment satisfies requirements for acceleration by external shocks (Vietri et al. 2003), and for acceleration through the converter mechanism (Derishev et al. 2003). Because the opacity to  $\gamma\gamma$  absorption is small for UHE  $\gamma$  rays from  $\pi^0$  decay, these  $\gamma$  rays will escape from the blast wave and contribute to the neutral beam power at later stages directly.

In conjunction with the neutral beam power is the prediction of a very significant fluence of UHE neutrinos. From GRBs with anomalous  $\gamma$ -ray components and large fluences (the fluence of GRB 941017, including the anomalous component, is  $\geq 6.5 \times 10^{-4}$  erg cm $^{-2}$ ), we predict several  $\nu_\mu$  events detectable with an IceCube-class km-scale telescope from this type of event, in agreement with phenomenological inferences by Alvarez-Muñiz et al. (2003).

In summary, we have proposed a hadronic model for the anomalous radiation component in GRB 941017. During the prompt phase, this emission originates from cascade radiation within the GRB blast wave. The anomalous component in the extended phase is synchrotron radiation from hyper-relativistic electrons formed by the associated neutron beam escaping from

the blast wave. The radiation components are well-suited for observations with the GBM and LAT on *GLAST*. GRBs with anomalous  $\gamma$ -ray emission components should also be bright neutrino sources detectable with *IceCube*.

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