

GRBs as ultra-high energy cosmic ray sources: clues from *Fermi*

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Abstract

If gamma-ray bursts are sources of ultra-high energy cosmic rays, then radiative signatures of hadronic acceleration are expected in GRB data. Observations with the *Fermi Gamma-ray Space Telescope* (*Fermi*) offer the best means to search for evidence of UHECRs in GRBs through electromagnetic channels. Various issues related to UHECR acceleration in GRBs are reviewed, with a focus on the question of energetics.

1 Introduction

Fermi observations of GRBs provide a new probe of particle acceleration in the relativistic outflows of GRBs. Some generic features of the high-energy behavior of 10 Large Area Telescope (LAT) GRBs consisting of 8 long-soft and 2 short-hard GRBs at the time of this conference have been identified, as summarized by Omodei [1]. These are:

1. A delayed onset of the $\gtrsim 100$ MeV radiation observed with the LAT compared with the start of the keV/MeV GBM radiation;
2. Long-lived LAT emission extending well after the Gamma ray Burst Monitor (GBM) radiation has fallen below background, as known previously for long duration GRBs from EGRET [2];

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3. Existence of a distinct hard spectral component in addition to a component described by the Band function in both long and short GRBs, confirming the discovery of such a component from joint BATSE/EGRET TASC analyses [3].

In this contribution, the possibility that these features can be explained by UHECRs in GRBs is considered. Because protons and ions are weakly radiative compared to electrons, even with escaping energies $E \approx 10^{20}$ eV needed to explain UHECRs, large amounts of nonthermal hadronic energy are required. We consider energetics arguments to constrain models for UHECRs from GRBs.

2 Maximum energy release in GRBs

Bohdan Paczyński, in his seminal article on hypernovae [4], proposed an explanation for the large apparent isotropic energies of GRBs by appealing to the enormous energy available in the process whereby the core of a massive star collapses to form a long GRB. He noted that the $\sim 10 M_{\odot}$ core of a Type II supernovae carries $\approx 5 \times 10^{54}$ erg of rotational energy, which could be tapped through Blandford-Znajek processes if surrounded by a highly magnetized torus formed during the stellar collapse event. Paczyński's arguments suggest that the maximum energy available from core collapse supernovae is therefore

$$\mathcal{E}_{max} \lesssim 10^{54} \text{ erg} , \quad (1)$$

with perhaps an order-of-magnitude less in the coalescence events thought to form the short hard GRBs.

The association of long-duration GRBs with Type Ib/c rather than Type II supernovae does not alter his energetics argument, but the recognition that GRBs are jetted greatly reduces the absolute energy requirements. Energy extracted through Blandford-Znajek processes is likely beamed in view of the rapid rotation of the newly formed black hole. Even so, we can still apply the energy bound given by eq. (1) to determine the plausibility of models with large energy requirements.

3 Energetics of UHECRs from GRBs

The idea that GRBs could accelerate UHECRs was proposed by Waxman [5] and Vietri [6] in 1995, and subject to criticism on energetics grounds [7], though here related to whether GRBs within the GZK radius have the

requisite volume- and time-averaged luminosity density. We can reformulate their argument in light of new data. The Auger results show that the differential energy density of UHECRs at 10^{20} eV is $\approx 2 \times 10^{-22}$ erg cm $^{-3}$. The horizon distance for 10^{20} eV UHECR protons is ≈ 50 Mpc (shorter than the mean-free-path of ≈ 140 Mpc, because this is the distance from which protons with measured energy E originally had energy $\approx 2.7E$), so that the required emissivity to power $\gtrsim 10^{20}$ eV UHECRs is $\dot{\epsilon}_{CR} \approx c \times 2 \times 10^{-22}$ erg cm $^{-3}$ /50 Mpc $\approx 4 \times 10^{43}$ erg Mpc $^{-3}$ yr $^{-1}$. If UHECRs are protons, then $\dot{\epsilon}_{CR} \approx 10^{44} \dot{\epsilon}_{44}$ erg Mpc $^{-3}$ yr $^{-1}$, with $\dot{\epsilon}_{44} \simeq 1$, is required to power $\gtrsim 10^{19}$ eV UHECRs, noting that the exponentially decreasing horizon distance with energy approximately cancels the $\propto E^{-2}$ decrease in UHECR energy density over this energy range.

With long-duration GRBs taking place about twice per day over the full sky for BATSE-type detection capabilities [8], and are found at a typical redshift of unity, implying a local space density for unbeamed sources of $\sim 2 \times 365 \text{ yr}^{-1} \zeta / [4\pi(4 \text{ Gpc})^3/3] \approx 0.3(\zeta/0.1) \text{ Gpc}^{-3} \text{ yr}^{-1}$, consistent with the value of $\approx 0.5 \text{ Gpc}^{-3} \text{ yr}^{-1}$ found in more detailed treatments [9]. Here ζ accounts for the smaller star-formation activity occurring at $z \approx 1$ than at the present epoch [10]. If each GRB releases an amount of energy $\mathcal{E}_{CR}$ in UHECRs, then the local volume- and time-averaged cosmic-ray emissivity is $\dot{\epsilon}_{CR} \simeq 5 \times 10^{-10} \mathcal{E}_{CR}(\zeta/0.1) \text{ Mpc}^{-3} \text{ yr}^{-1}$. Equating this with the emissivity required to power the UHECRs implies that each GRB must release $\mathcal{E}_{CR} \approx 2 \times 10^{53} \dot{\epsilon}_{44}(\zeta/0.1)$ erg in UHECRs. This can be compared with the typical electromagnetic energy release per GRB of $4\pi(4 \text{ Gpc})^2 10^{-5} \mathcal{F}_{-5} \text{ erg cm}^{-2} \approx 2 \times 10^{52} \mathcal{F}_{-5}$ erg, where $\mathcal{F} = 10^{-5} \mathcal{F}_{-5} \text{ erg cm}^{-2}$ is the average BATSE long-duration GRB fluence. Thus the energy released in UHECRs has to be $\gtrsim 10\times$ the energy measured from electromagnetic processes, independent of beaming.

The need for large baryon loads in GRB blast waves is confirmed by detailed fits to the UHECR energy spectrum, which imply a factor $\approx 10 - 100$ times more energy in UHECRs than observed in electromagnetic radiation [11]. An explanation for the rapid declines in *Swift* X-ray light curves in terms of escaping UHECR neutrons from photohadronic production also requires highly baryon-loaded GRB outflows [12].

4 Minimum bulk Lorentz factor

A δ -function approximation for the $\gamma\gamma$ opacity constraint, given the detection of a γ -ray photon with energy $m_e c^2 \epsilon_1$ and variability time t_v , implies a

minimum bulk Lorentz factor

$$\Gamma_{\min} \approx \left[\frac{\sigma_T d_L^2 (1+z)^2 f_{\epsilon} \epsilon_1}{4t_v m_e c^4} \right]^{1/6}, \quad \hat{\epsilon} = \frac{2\Gamma^2}{(1+z)^2 \epsilon_1}. \quad (2)$$

where f_{ϵ} is the νF_{ν} flux at photon energy $m_e c^2 \epsilon$. Thus $\Gamma_{\min} \approx 916 [f_{-6} \epsilon_1 (3 \text{ GeV}) / t_v (\text{s})]^{1/6}$, where the νF_{ν} flux is $10^{-6} f_{-6} \text{ erg cm}^{-2} \text{ s}^{-1}$, using values corresponding to time bin b for GRB 080916C [13]. This GRB, at redshift $z \approx 4.35 \pm 0.15$ and luminosity distance $d_L = 1.25 \times 10^{29} \text{ cm}$, had a total 10 keV – 10 GeV energy fluence $\mathcal{F} = 2.4 \times 10^{-4} \text{ erg cm}^{-2}$, implying a total γ -ray energy release $\mathcal{E}_{\gamma, iso} \cong 8.8 \times 10^{54} \text{ erg}$.

Provided the target photon number spectrum has an index softer than -1 , eq. (2) gives a result within $\sim 10\%$ of a numerical integration over spectral parameters. Issues in the evaluation of the uncertainty, $\Delta\Gamma_{\min}$, in the value of $\Gamma_{\min}$ include (1) uncertainties in redshift and νF_{ν} spectral flux; (2) the definition of variability time t_v ; (3) the cospatial assumption that the target photons are made in the same region as the high-energy photon; (4) the assumed geometry and dynamical state [14] of the emission region, giving the escape probability of a high-energy photon; (5) statistical fluctuations for the detection of a high-energy photon that furthermore depend on the actual high-energy photon spectrum.

Writing the GRB blast wave Lorentz factor $\Gamma = q\Gamma_{\min}$, a consideration of these various issues show that $q \gtrsim 0.5$ represents a reasonably conservative expectation for the actual value of Γ . The energetics of a given model can depend strongly on Γ .

5 Emission radius: internal or external shocks?

The total apparent energy release of GRB 080916C is $\mathcal{E}_{iso} = 10^{55} \mathcal{E}_{55} \text{ erg}$, with $\mathcal{E}_{55} \gtrsim 1$. The corresponding deceleration length is $r_{dec} = 1.2 \times 10^{17} \mathcal{E}_{55}^{1/3} / n \Gamma_3^{2/3} \text{ cm}$, where $10^3 \Gamma_3$ is the coasting Lorentz factor and $n (\text{cm}^{-3})$ is the external medium density. The implied radius for internal shock emission is $r \cong \Gamma^2 c t_v / (1+z) \cong 6 \times 10^{15} \Gamma_3^2 t_v (\text{s})^2 \text{ cm}$. The unexpectedly large emission radius, close to the deceleration radius when $q \approx 2$, has led a number of researchers to argue that the LAT radiation originates from leptonic synchrotron radiation at an external forward shock [15, 16]. Another possibility is that the delayed LAT emission results from upscattered cocoon radiation [17].

6 γ rays from UHECRs in GRB blast waves

We can make some simple estimates to deduce the total energy needed to obtain bright hadronic γ -ray emission from GRBs through proton synchrotron and photopion processes [18, 19, 20]. Here we consider only UHECR proton acceleration, using parameters appropriate to GRB 080916C.

The internal photon energy density $u'_\gamma \cong d_L^2 \Phi / R^2 \Gamma^2 c$, where $\Phi = 10^{-5} \Phi_{-5}$ erg cm $^{-2}$ s $^{-1}$ is the measured energy flux, $R \cong \Gamma^2 \hat{c} \hat{t} / (1+z)$ is the shock radius, and $\hat{t}$ is a fiducial timescale (corresponding to t_v for internal shocks, or the GRB duration for an external shock). Writing the magnetic-field energy density $u'_B = \epsilon_B u'_\gamma$, where $u'_B = B^2 / 8\pi$, then the magnetic field in the emission region of GRB 080916C is $B(\text{kG}) \cong 2.0 \sqrt{\epsilon_B \Phi_{-5}} / \Gamma_3^3 \hat{t}(\text{s})$. The Hillas criterion whereby the Larmor radius $r'_L = m_p c^2 \gamma'_p / eB < \Delta R' \cong R / \Gamma$, where $\Delta R'$ is the comoving shell width, implies that the escaping UHECR proton Lorentz factor $\gamma_p \cong \Gamma \gamma'_p \lesssim c e B \Gamma^2 \hat{t} / (1+z) m_p c^2$. For GRB 080916C, this relation implies that UHECRs can be accelerated to $\gamma_p \lesssim (2 d_L e / \Gamma m_p c^2) \sqrt{2 \pi \epsilon_B \Phi} / c \cong 4 \times 10^{12} \sqrt{\epsilon_B \Phi_{-5}} / \Gamma_3$, independent of time (note that $B \propto t^{-1}$, with the divergence at $t \rightarrow 0$ prevented due to the time dependence of Φ), or to energy $E_p \lesssim 2 \times 10^{21} B(\text{kG}) \Gamma_3^2 \hat{t}(\text{s})$ eV.

A further restriction on the maximum proton energy is obtained by balancing the acceleration rate, given by $c / (\phi r'_L)$, with $\phi \gg 1$, with the synchrotron loss rate. This gives $\gamma_{\text{sat},p} \cong 2 \times 10^{12} \Gamma_3 / \sqrt{(\phi/10) B(\text{kG})}$, comparable to the value obtained above from the Hillas condition for the chosen parameters.

6.1 Proton synchrotron energy requirements

The proton synchrotron energy loss timescale, as measured by an observer, is $t_{\text{syn}} \cong 3 m_e c^2 (1+z) / [4 \Gamma \mu^3 c \sigma_T u'_B \gamma'_p]$, where $\mu \equiv m_e / m_p$. The typical photon energy (in $m_e c^2$ units) of the measured proton synchrotron emission is $\epsilon_{p,\text{syn}} \cong \Gamma \mu B \gamma_p'^2 / [(1+z) B_{\text{cr}}]$, where $B_{\text{cr}} = 4.414 \times 10^{13}$ G is the critical magnetic field. From this, one obtains the jet power associated with the magnetic field, given by

$$L_B \cong \frac{R^2 c \Gamma^2 B^2}{2} \cong \frac{2 \times 10^{58} \Gamma_3^{16/3} t_{\text{syn}}^{2/3}(\text{s})}{E_\gamma (100 \text{ MeV})^{2/3}} \text{ erg s}^{-1} \quad (3)$$

[19]. The absolute energy requirements are $\mathcal{E}_{\text{abs}} \cong L_B t_{\text{syn}} f_b / (1+z) \cong 1.6 \times 10^{59} \Gamma_3^{16/3} f_b^{5/3} t_{\text{syn}}(10 \text{ s}) / E_\gamma (100 \text{ MeV})^{2/3}$ erg, where f_b is a beaming factor. In the scenario of Ref. [18], the delayed onset corresponds to the time

for protons to accumulate and cool such that they are radiating most of the proton-synchrotron photons near energy E_γ .

Such large energies disfavor this interpretation for the LAT radiation. To salvage the proton synchrotron model [18], a narrow jet opening angle of order 1° along with a value of $q \cong 0.5$ gives $\mathcal{E}_{abs} \cong 4 \times 10^{53} (\Gamma_3/0.5)^{16/3} (f_b/10^{-4}) t_{syn}^{5/3} (10 \text{ s})/E(100 \text{ MeV})^{2/3} \text{ erg}$, within acceptable ranges. Another way to avoid the large energy losses is to suppose that the UHECR protons are accelerated to their allowed maximum energy and radiate proton synchrotron photons that cascade to energies $\lesssim 100 \text{ MeV}$. This possibility seemed unlikely given that the spectrum of GRB 080916C is consistent with a single Band function [13]. The detection of distinct components in GRB spectra suggests that a cascading interpretation be more carefully considered [20, 21].

6.2 Photohadronic energy requirements

Proton-photon interactions making secondary pions, γ rays, and neutrinos represents another likely channel for making a γ -ray component identifiable in the *Fermi* data. The efficiency for extracting the energy of a proton with escaping energy E_p from photohadronic processes can be written as $\eta_{p\gamma}(E_p) = t_{dyn}/t_{p\gamma}(E_p) \cong (R/\Gamma c)t_{p\gamma}^{-1}(E_p)$, where t_{dyn} is the dynamical time scale, the rate for photohadronic energy losses is $t_{p\gamma}^{-1}(E_p) \cong c(K_{p\gamma}\sigma_{p\gamma}) \int_{\epsilon'_{thr}}^{\infty} d\epsilon' n'(\epsilon')$, and the comoving photon spectrum $n'(\epsilon') \cong d_L^2 f_\epsilon / (m_e c^3 \epsilon'^2 R^2 \Gamma^2)$, with $\epsilon' \cong (1+z)\epsilon/\Gamma$. Here $K_{p\gamma}\sigma_{p\gamma} \cong 70\mu\text{b}$ above threshold photon energy defined by $\gamma'\epsilon' \cong 400$ [11]. Defining protons with energy E_p^{pk} which interact at threshold with photons with energy ϵ_{pk} at the peak $f_{\epsilon_{pk}}$ of the νF_ν spectrum, then $E_p^{pk} \cong 400m_p c^2 \Gamma^2 / [(1+z)\epsilon_{pk}] \cong 7 \times 10^{16} \Gamma_3^2 / \epsilon_{pk} \text{ eV}$. One obtains

$$\eta_{p\gamma}(E_p^{pk}) = \frac{K_{p\gamma}\sigma_{p\gamma} d_L^2 f_{\epsilon_{pk}}}{\Gamma^4 m_e c^4 t_v (1-b)\epsilon_{pk}} \cong 0.015 \frac{f_{-6}}{\Gamma_3^4 t_v(s)\epsilon_{pk}} \quad (4)$$

[5, 22, 23]. Here $b(< 0)$ is the νF_ν index above ϵ_{pk} , so that $f_\epsilon = f_{\epsilon_{pk}} (\epsilon/\epsilon_{pk})^b$ when $\epsilon > \epsilon_{pk}$, and $\eta_{p\gamma}(E_p) \cong \eta_{p\gamma}(E_p^{pk}) (E_p/E_p^{pk})^{1-b}$. Likewise in the asymptotic limit $\epsilon \ll \epsilon_{pk}$, $\eta_{p\gamma}(E_p) \cong \eta_{p\gamma}(E_p^{pk}) (E_p/E_p^{pk})^{1-a}$, where a is the νF_ν index at energies below the peak energy (provided $a > 1$).

The total efficiency for photohadronic production depends on the spectrum of accelerated protons and ions. If an E_p^{-2} spectrum is assumed, then the efficiency is reduced in proportion to the number of decades of weakly radiating low-energy protons. This might not be too severe if the lowest

energy protons have escaping energy $E_p \approx \Gamma^2 m_p c^2 \approx \Gamma_3^2$ PeV. Furthermore, nonlinear shock acceleration in colliding shells, and second-order processes in the shocked fluid can give harder cosmic-ray spectra, though consistency when fitting the measured UHECR spectrum would constrain the assumed accelerated cosmic-ray spectrum.

The final expression in eq. (4), specific to parameters of GRB 080916C, shows that $\sim 1 - 10\%$ of the energy can be extracted via photohadronic processes by protons with energy $E_p \approx E_p^{pk}$, with more than half of this energy released in the form of leptons and photons which generates an electromagnetic cascade emerging in the form of γ rays when the system becomes optically thin to $\gamma\gamma$ processes. At $E_p \gg E_p^{pk}$, a larger fraction is extracted. Consequently, the energy of baryons must be ≈ 10 to $100 \times$ greater than the nonthermal lepton content if a comparable amount of electromagnetic radiation is to be emitted from hadronic as leptonic processes. Note the sensitive Γ -dependence of the photohadronic efficiency, $\eta_{p\gamma}(E_p^{pk}) \propto \Gamma^{-4}$, by comparison with $\tau_{\gamma\gamma}(\epsilon) \propto \Gamma^{-6}$. The implications for neutrino and γ -ray production are considered in [24].

7 Summary

In this contribution, we have sketched the energy requirements for GRBs to be sources of UHECRs, and for electromagnetic signatures of ultrarelativistic hadrons to be found in the *Fermi* data. The large amounts of energy needed has been noted many times in the past, whether from proton synchrotron [25, 26] or photohadronic processes. Although the large energy requirements make uncomfortable demands on γ -ray emission models, an internal consistency is found insofar as the baryon load in long GRBs must be large given their relative rarity within the GZK radius, and that enormous energies are available from the rotational and accretion energy in the newly forming black holes. Future *Fermi* observations and the possibility of detecting PeV neutrinos from GRBs with IceCube could establish whether GRBs are the sources of UHECRs.

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