Delayed GeV Emission from Ultra-High Energy Cosmic Ray Acceleration and Radiation in GRB 080916C

Soebur Razzaque*† **Charles D. Dermer*** **and Justin D. Finke***†

**U.S. Naval Research Laboratory Washington, D.C., USA*
†*National Research Council Research Associate*

Abstract. **Gamma Ray Burst GRB 080916C was detected on September 16, 2008 by the Gamma-ray Burst Monitor (GBM) and Large Area Telescope (LAT) on the Fermi Gamma Ray Space Telescope. At redshift 4.35, its apparent energy release is $\approx 9 \times 10^{54}$ erg, making it the most energetic GRB yet observed. An intriguing feature of this GRB, which appears to be common to all GRBs detected with the Fermi LAT, is that $\gtrsim 100$ MeV photons arrived later than the onset of keV–MeV emission detected with the GBM. We present a hadronic model where the protons are accelerated to ultra-high energies in relativistic shocks of GRBs and make gamma rays through synchrotron radiation, with the delay due to the proton synchrotron cooling time scale. Neutrons escaping from GRB blast waves can be a source of ultra-high energy cosmic rays if photopion cooling for protons is imporant.**

Keywords: **gamma ray, gamma-ray burst**

I. INTRODUCTION

Fermi GBM and LAT collected a combined fluence of 2.4×10^{-4} erg cm^{-2} in 10 keV – 10 GeV γ rays from GRB 080916C [1] at a redshift $z = 4.35 \pm 0.15$ [2]. The LAT collected a total of ≈ 145 photons with energy $\gtrsim 100$ MeV which comprise a third of the GBM fluence in the 20 keV – 2 MeV range. An intriguing feature of this GRB is the delayed arrival, by ≈ 4.5 s, of the $\gtrsim 100$ MeV γ rays detected with the LAT as compared to the ≈ 8 keV – 5 MeV γ rays detected with the GBM. The highest energy photon at $13.22^{+0.70}_{-1.54}$ GeV was detected 16.5 s after the trigger, allowing a test for the quantum gravity models that lead to violation of Lorentz invariance [1].

Broadband spectral modelling with the Band function [3] (two power-laws with photon indices α and β connected smoothly below and above the peak photon energy $\varepsilon_{\rm pk}$ in the νF_ν spectrum) fits data well at different time intervals: 0–3.6, 3.6–7.7, 7.7–16, 16–55, 55–100 s with varying parameters [1]. The observed rapid variability, $t_v \approx 0.1$–1 s, and non-thermal spectra extending to $>$ GeV imply that the emission region moves with a bulk Lorentz factor $\Gamma \gtrsim 900$ towards us [1]. The high-energy photon index β however becomes harder in time, from -2.6 in the first 3.6 s to -2.2 at later times.

Protons and ions, if present in the GRB jet, can reach ultra-high energies by a Fermi shock-acceleration mechanism that also accelerate electrons which radiate keV–MeV synchrotron photons (see Refs. [4], [5] for reviews on electron synchrotron radiation from the GRB fireball shock model). Here we report on our recent work [6] where we model synchrotron radiation by shock-accelerated protons in the GRB jet [7], [8] giving rise to a hard spectral component that can account for the delayed emission of $\gtrsim 100$ MeV photons as well as soft-to-hard evolution of the Band parameter β in the first ≈ 8 s.

II. SHOCK ACCELERATION AND COOLING

The γ-ray flux detected from GRB 080916C in the first ≈ 8 s is $\Phi_\gamma = 10^{-5}\Phi_{\gamma,-5}$ erg cm^{-2} s^{-1}, with $\Phi_{\gamma,-5} \approx 1$. Assuming this flux comes from a shocked region of size scale $R \simeq \Gamma^2 ct_v/(1+z)$, we calculate the radiation energy density in the shocked plasma as $u'_\gamma \simeq 4\pi d_L^2 \Phi_\gamma / 4\pi R^2 c\Gamma^2$ in the fast-cooling scenario and in the comoving fireball frame.[1] The energy density in baryons is $u'_b = u'_\gamma / \epsilon_e$, and we assume it to be a factor $1/\epsilon_e = 250\epsilon_{e,-2.4}^{-1}$ times higher. We also assume that a fraction $\epsilon_B = 0.1\epsilon_{B,-1}$ of u'_b is converted to the magnetic-field energy density $u'_B = B'^2/8\pi$ in the shock, resulting in a magnetic field

$$
\begin{aligned}
B' &\simeq (1+z)\sqrt{8\pi \frac{\epsilon_B}{\epsilon_e} \frac{d_L^2 \Phi_\gamma}{\Gamma^6 c^3 t_v^2}} \\
&\approx \frac{10^5}{\Gamma_3^3 t_{v,-1}}\sqrt{\frac{\epsilon_{B,-1}\Phi_{\gamma,-5}}{\epsilon_{e,-2.4}}} \text{ G.} \quad (1)
\end{aligned}
$$

Here we used $\Gamma = 10^3\Gamma_3$ and $t_v = 0.1t_{v,-1}$ s, and the standard ΛCDM cosmology to calculate the luminosity distance d_L. From here on we use $B' = 10^5 B'_5$ G in our calculation unless otherwise specified.

The acceleration time scale for protons to gain energy $E'_p = 10^9 E'_{p,9}$ GeV by a Fermi mechanism in the electric field induced by B' is proportional to the Larmor time, E'_p/eB', and is given by

$$
t'_{acc,p} \simeq \frac{\phi E'_p}{ecB'} \approx 11 \frac{\phi_1 E'_{p,9}}{B'_5} \text{ s.} \quad (2)
$$

Here $\phi = 10\phi_1$ is the number of gyro-radii required to increase a particle energy by a factor of 2.7. The synchrotron cooling time for protons in the same magnetic field is

$$
t'_{syn,p} \simeq \frac{3}{4}\left(\frac{m_p}{m_e}\right)^2 \frac{m_p^2 c^3}{\sigma_T u'_B E'_p} \approx \frac{0.45}{B'^2_5 E'_{p,9}} \text{ s.} \quad (3)
$$

---

[1]All variables are primed in the comoving frame.

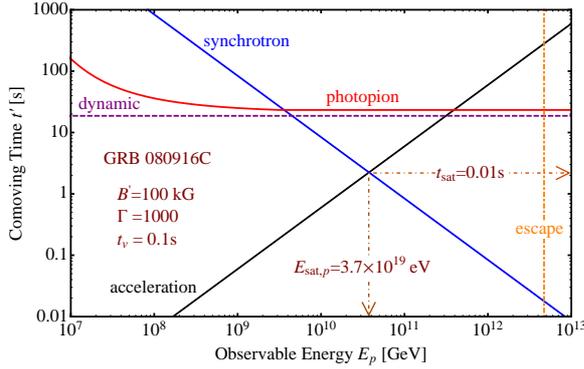Fig. 1. The acceleration, cooling, escape and dynamical time scales for protons in the fireball of GRB 080916C assuming $t_{v,-1} = 1$, $\Gamma_3 = 1$, $\phi_1 = 1$ and $B'_5 = 1$. The proton energy is saturated to an energy $E_{sat,p} = E'_{sat,p}\Gamma/(1+z)$ when $t'_{acc,p} = t'_{syn,p}$ from Eq. (5). The saturation time in Eq. (6) is $t_{sat} = t'_{sat}(1+z)/\Gamma$ in the observer's frame. The photopion cooling time scale is longer than the dynamical time scale and is not an important cooling channel for the parameters of GRB 080916C.

The photohadronic cooling time scale depends on the observed keV–MeV γ-ray source density $n'_\gamma(\varepsilon')$ and the inverse of it is given by

$$t'^{-1}_{p\gamma} \simeq c\sigma_0 \int_{\varepsilon'_{th}m_pc^2/2E'_p}^{\infty} d\varepsilon' n'_\gamma(\varepsilon'), \qquad (4)$$

for a single $p\gamma$ scattering. Here we approximated a $p\gamma$ cross-section times the mean energy loss factor by protons as $\sigma_0 \equiv \sigma_{p\gamma}f_{p\gamma} \approx 68 \ \mu$b and we take $\varepsilon'_{th} \simeq 0.2$ GeV as the threshold photon energy for pion production in the rest frame of the proton [7], [9].

We have plotted in Fig. 1 the acceleration and cooling time scales for protons using the Band function fit paramters in Ref. [1], the assumed magnetic field $10^5 B'_5$ G from Eq. (1), with $B'_5 = 1$, and the parameter $10\phi_1$. The dynamical time scale is $t'_{dyn} \simeq t_v\Gamma/(1+z) \approx 18.7t_{v,-1}\Gamma_3$ s. Note that the photohadronic cooling of proton is inefficient within the dynamical time scale and that the synchrotron cooling limits the maximum proton energy. The proton escape time scale $t'_{esc} \simeq (3/2)(ceB'/E'_p)t'^2_{dyn}$ in the Bohm diffusion limit, plotted with vertical line for the proton energy at which $t'_{esc} = t'_{dyn}$ indicates that the protons are effectively trapped in the GRB fireball and lose energy by radiating synchrotron photons. Protons can, however, escape the GRB fireball as ultra-high energy cosmic rays (UHECRs) by converting to neutrons via $p\gamma \to n\pi^+$ process if $t'_{p\gamma} \lesssim t'_{dyn}$ or $t_v < 0.01$ s for GRB 080916C [6], or if there is a larger soft ($\ll$ keV) flux than the extrapolation of the Band function implies.

III. PROTON SYNCHROTRON AND e^+e^- PAIR SYNCHROTRON RADIATION SPECTRA

The maximum shock-accelerated proton energy increases $\propto t'$ initially and saturates to a maximum value

$$E'_{sat,p} \simeq \frac{m_p}{m_e}\sqrt{\frac{6\pi em_p^2c^4}{\sigma_T\phi B'}} \approx \frac{2 \times 10^8}{\sqrt{\phi_1 B'_5}} \text{ GeV} \qquad (5)$$

when $t'_{acc,p} = t'_{syn,p}$ (see Fig. 1). The time scale to reach the saturation energy is

$$t'_{sat} \simeq \frac{m_p}{m_e}\sqrt{\frac{6\pi\phi m_p^2c^2}{e\sigma_TB'^3}} \approx 2.2\sqrt{\frac{\phi_1}{B'^3_5}} \text{ s.} \qquad (6)$$

For $t' \geq t'_{sat}$ the maximum proton energy remains constant at $E'_{sat,p}$. The synchrotron cooling however becomes more efficient with increasing time. The characteristic synchrotron cooling-break energy for protons, from the condition $t'_{syn,p} = t'$, is given by $E'_{c,p} = E'_{sat,p}(t'_{sat}/t')$. Protons above this energy cool efficiently down to $E'_{sat,p}$ within t'. As a result the proton spectrum can be approximated by a broken power law with the spectral index softened by unity for $E'_p > E'_{sat,p}$ (see Ref. [10], e.g.) as illustrated in Fig. 2 (*Left panel*). The injected proton number spectrum is $\propto E'^{-k}_p$.

The characteristic synchrotron photon energy corresponding to the proton saturation energy $E'_{sat,p}$ is

$$\varepsilon_{sat,p} \simeq \frac{\Gamma}{1+z}\frac{3e\hbar B'}{2m_p^3c^5}E'^2_{sat,p} \approx 8 \ \frac{\Gamma_3}{\phi_1} \text{ TeV}, \qquad (7)$$

and that correspnding to the cooling proton energy $E'_{c,p}$ is given by

$$\varepsilon_{c,p}(t) = \varepsilon_{sat,p}(t_{sat}/t)^2. \qquad (8)$$

The proton synchrotron νF_ν flux from a slow-cooling proton spectrum without any $\gamma\gamma$ absorption is given by

$$f_\varepsilon^{p,syn} \simeq f_{\varepsilon_{pk}}^{p,syn} \times$$
$$\begin{cases} \left(\frac{\varepsilon_{c,p}}{\varepsilon_{sat,p}}\right)^{\frac{2-k}{2}}\left(\frac{\varepsilon_{min,p}}{\varepsilon_{c,p}}\right)^{\frac{3-k}{2}}\left(\frac{\varepsilon}{\varepsilon_{min,p}}\right)^{\frac{4}{3}}; \varepsilon \leq \varepsilon_{min,p} \\ \left(\frac{\varepsilon_{c,p}}{\varepsilon_{sat,p}}\right)^{\frac{2-k}{2}}\left(\frac{\varepsilon}{\varepsilon_{c,p}}\right)^{\frac{3-k}{2}}; \varepsilon_{min,p} < \varepsilon < \varepsilon_{c,p}(t) \ (9) \\ \left(\frac{\varepsilon}{\varepsilon_{sat,p}}\right)^{\frac{2-k}{2}}; \varepsilon_{c,p}(t) \leq \varepsilon \leq \varepsilon_{sat,p} \end{cases}$$

and the flux at the peak is

$$f_{\varepsilon_{pk}}^{p,syn} \simeq \frac{k-2}{2}\frac{\Phi_\gamma}{\epsilon_e}\frac{1 - (\varepsilon_{min,p}/\varepsilon_{sat,p})^{\frac{3-k}{2}}}{(\varepsilon_{min,p}/\varepsilon_{sat,p})^{\frac{2-k}{2}} - 1}. \qquad (10)$$

Here $\varepsilon_{min,p}$ is the characteristic synchrotron photon energy corresponding to the minimum proton energy $\Gamma_{rel}m_pc^2$, Γ_{rel} being the relative Lorentz factor between two colliding shells, or a shell and wind or external medium. Figure 2 (*Right panel*) shows the time evolution of the proton synchrotron spectrum in Eq. (9).

Photons with energies above $\varepsilon_{\gamma\gamma} \sim 10$ GeV are strongly attenuated due to $\gamma\gamma \to e^+e^-$ pair production process in the GRB fireball [11], resulting in an injection of high-energy e^+e^- pairs which cool efficiently and make a second-generation electron synchrotron component. We assume for simplicity that a high-energy photon give its energy ε' equally to an e^+ and an e^-, each receiving an energy $E'_e \simeq \varepsilon'/2$. Thus the characteristic synchrotron photon energy radiated by the e^+e^- pairs created from photons of energy $\varepsilon_{sat,p}$ is

$$\varepsilon_{sat,e} \simeq \frac{\Gamma}{1+z}\frac{3e\hbar B'}{2m_e^3c^5}\frac{\varepsilon'^2_{sat,p}}{4} \approx 600 \ \frac{\Gamma_3 B'_5}{\phi_1^2} \text{ MeV.} \qquad (11)$$
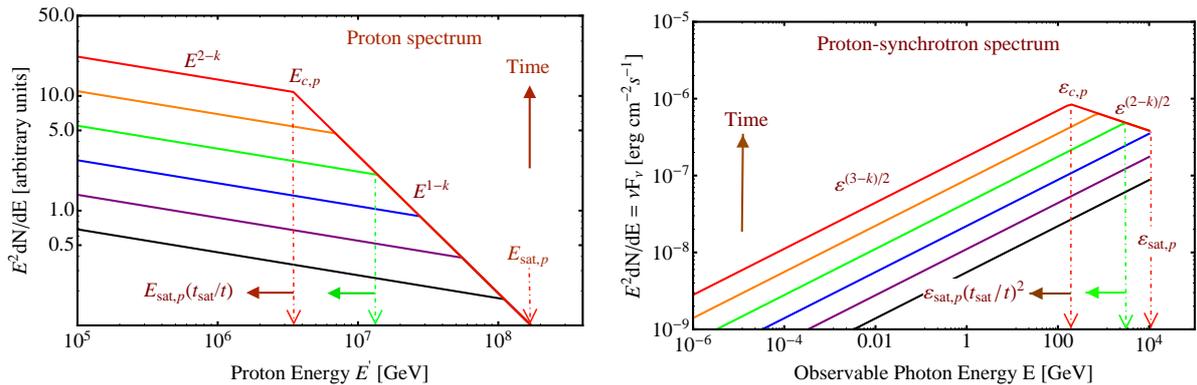
Fig. 2.   *Left panel:* Graph of the shock-accelerated proton energy spectrum with synchrotron cooling break $E'_{c,p}$ evolving with time. The injected number spectrum is $\propto E'^{-k}$. *Right panel:* Graph of the proton synchrotron radiation spectrum from the proton spectrum in the left panel. For a given photon energy below the synchrotron cooling energy $\varepsilon_{c,p}$ in Eq. (8), the flux increases $\propto t$. For both panels, $B'_5 = 1$, $\phi_1 = 1$ and $z = 4.35$ were used.

The flux level however is below the LAT sensitivity because only the photons with energy $\varepsilon_{sat,p}$ creates e^+e^- pairs with energy $\varepsilon_{sat,p}/2$ that contribute to the emission at $\varepsilon_{sat,e}$ and the number of such photons is small for a steep injection proton spectrum. The νF_ν flux of e^+e^- pair synchrotron radiation peaks at the cooling break energy

$$\varepsilon_{c,e}(t) = \varepsilon_{sat,e}(t_{sat}/t)^4. \qquad (12)$$

The second generation e^+e^- pair synchrotron radiation spectrum has the same form as Eq. (9) with modified spectral indices $(3-k)/2 \rightarrow (3-k)/4$ and $(2-k)/2 \rightarrow (2-k)/4$, $f_{\varepsilon_{pk}}^{e,syn} = f_{\varepsilon_{pk}}^{p,syn}/2$, and cuts off at an energy corresponding to $\varepsilon_{\gamma\gamma}$.

IV. RESULTS AND DISCUSSION

Figure 3 shows the time evolution of the proton-synchrotron and the second generation e^+e^- pair synchrotron radiation spectrum for the parameters of GRB 080916C, assuming constant injection of protons. In this simple picture of the GRB jet model, the protons are accelerated to the saturation energy within ~ 10 ms, making a prompt second-generation electron synchrotron spectrum too weak to be detected, followed after a few seconds by strong direct proton synchrotron emission that sweeps into the LAT band from high energies. Also shown in Fig. 3 is the Band function fit to the time-averaged data from Ref. [1]. Synchrotron radiation by shock-accelerated primary electrons in the fireball explain keV–MeV data.

GRBs are one of the leading candidate sources of UHECRs [12], [13]. A nearby GRB with parameters of GRB 080916C can accelerate protons up to $2 \times 10^{20}\Gamma_3/\sqrt{\phi_1 B'_5}$ eV and become a source of UHECRs if protons can escape either by diffusion or by converting to neutrons via photopion production. As shown in Fig. 1, the escape time scale for the highest energy proton $E_{sat,p}$ is longer than the dynamical time in the Bohm diffusion limit. Photopion cooling for GRB 080916C

parameters with the shortest variability time 0.1 s [2] is also not important. However for GRBs with much smaller variability time scale, photopion cooling can become important [7]. A suppression of the 100 MeV – GeV emission originating from $\gamma\gamma$ absorption due to low bulk Lorentz factor may indicate efficient photopion production [14]. High energy, $\gtrsim$ TeV, neutrinos will accompany neutrons that escape the GRB fireball as UHECRs [15], [16]. Detection of these neutrinos by neutrino telescopes such as IceCube [17] can firmly establish the sources of UHECRs.

We can estimate the rate of long-duration GRBs as energetic as GRB 080916C within the ≈ 100 Mpc clustering/GZK radius for UHECRs observed with Auger [18]. For a maximum total energy release of 10^{54} erg, the GRB 080916C jet opening angle $\theta_j < 100/\Gamma = 0.1/\Gamma_3$. The beaming-corrected GRB rate, which is shown to follow the star formation rate [19], of $\approx 2f_b$ Gpc^{-3} yr^{-1} at the typical redshift $z \approx 1$–2 is a factor $1/10$ smaller in the local universe due to a decrease in the star formation rate and a factor $f_b \gtrsim 200$ larger due to the beaming factor. An UHECR of energy $E = 60E_{60}$ EeV is deflected by an angle

$$\theta \simeq \frac{d}{2R_L\sqrt{d/\lambda}} \approx 4.4° Z \frac{B_{nG}}{E_{60}}\sqrt{d_{100}\lambda_1} \qquad (13)$$

in intergalactic magnetic field with mean strength $B = 1B_{nG}$ nG over a distance $d = 100d_{100}$ Mpc and coherence length of $\lambda = 1\lambda_1$ Mpc. The Larmor radius $R_L = E/ZeB$. Deflection causes dispersion in time of arrival of UHECRs and increases the apparent rate [20]. The corresponding number of GRB sources within ≈ 100 Mpc with jets pointing within $4°$ of our line-of-sight is

$$N_{GRB} \approx 30 \left(\frac{f_b}{200}\right)\left(\frac{B_{nG}}{E_{60}}\right)^2 \sqrt{\lambda_1^3}. \qquad (14)$$

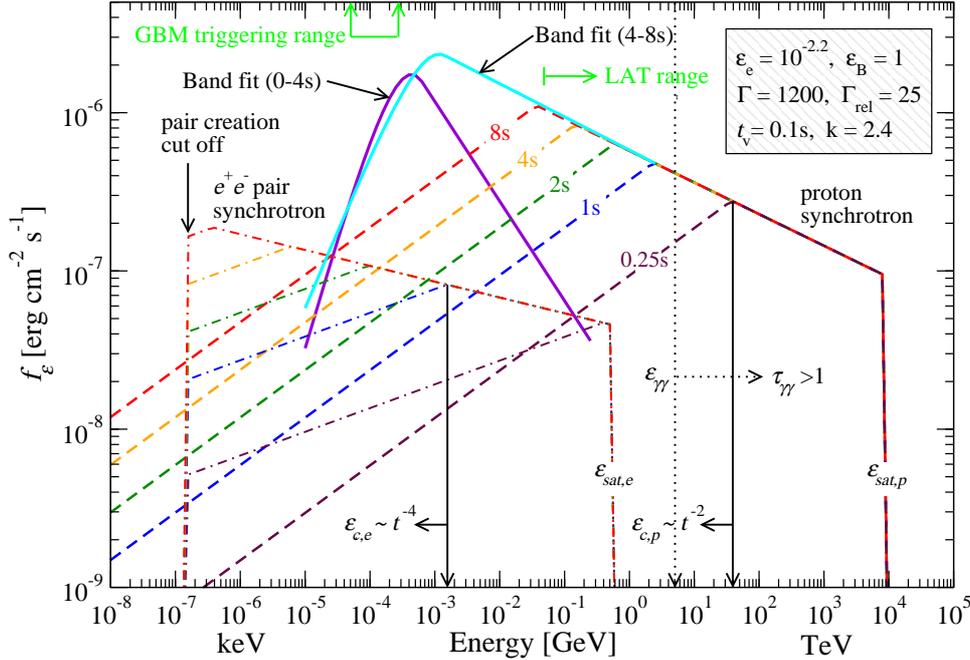Thus if typical long duration GRBs have a narrow, highly relativistic core accelerating UHECRs, then they

Fig. 3. Spectral modeling of GRB 080916C in the $\gtrsim 100$ MeV range by proton synchrotron (dashed lines) and secondary e^+e^- synchrotron (dashed-dot lines) radiation. Proton synchrotron photons above $\varepsilon_{\gamma\gamma}$ produce e^+e^- pairs by interacting with soft target photons. The pairs lose energy efficiently by radiating synchrotron photons, forming a weak spectral component. The maximum photon energies for proton-synchrotron radiation ($\varepsilon_{sat,p}$) and e^+e^- pair-synchrotron radiation ($\varepsilon_{sat,e}$) remains fixed in time while the νF_ν peak energies scale as $\varepsilon_{c,p} = \varepsilon_{sat,p}(t_{sat}/t)^2$ and $\varepsilon_{c,e} = \varepsilon_{sat,e}(t_{sat}/t)^4$. Also shown by solid lines for comparision are the fitted Band spectra of time-averaged data in the 0 s – 3.6 s and 3.6 s – 7.7 s time intervals [1]. Proton-synchrotron radiation initially dominates at high energy and sweeps into the LAT band after several seconds, causing a delay in $\gtrsim 100$ MeV emission, as well as hardening the spectrum. At a fixed photon energy below the cooling energy, the νF_ν flux increases $\propto t$. We assumed a uniform injection of shocked protons over 8 s, although a variable injection gives similar time delay in the high-energy γ-ray flux.

could account for the Auger events within the GZK radius.

Other astrophysical objects with relativistic outflows such as low luminosity GRBs [21] and radio galaxies [22], including Cen A [23], could accelerate UHE-CRs as well. Fermi γ-ray space telescope and ground-based Cherenkov telescopes can search for UHECR signature in magnetically dominated black-hole jet systems [24], [25] as in the case of GRB 080916C.

We found that UHECR protons, if accelerated in GRB jets, would produce synchrotron radiation that is delayed with respect to lower energy keV – MeV radiation made by shock accelerated electrons [6]. The delay of the proton synchrotron radiation is due to the time required to accelerate and accumulate cosmic-ray protons, and this radiation is emitted at energies where the Fermi LAT is sensitive. We also found that long duration GRBs represent a viable source class of UHECRs.

REFERENCES

[1] Fermi Collaboration, A. Abdo et al., *Science* **323**, 1688 (2009).
[2] J. Greiner et al., *Astron. Astrophys.*, **498**, L89 (2009).
[3] D. Band et al., *Astrophys. J.*, **413**, 281 (1993).
[4] T. Piran, *Rev. Mod. Phys.*, **76**, 1143 (2005).
[5] P. Meszaros, *Rep. Prog. Phys.*, **69**, 2259 (2006).
[6] S. Razzaque, C. D. Dermer and J. D. Finke, *Nature Physics* (submitted).
[7] S. Razzaque, C. D. Dermer, J. D. Finke, A. Atoyan, in Huntsville GRB Symposeum, 2008, http://arxiv.org/abs/0901.4973.
[8] B. Zhang and P. Meszaros, *Astrophys. J.*, **559**, 110 (2001).
[9] C. D. Dermer, *Astrophys. J.*, **664**, 384 (2007).
[10] R. Sari, T. Piran and R. Narayan, *Astrophys. J.*, **497**, L17 (1998).
[11] S. Razzaque, P. Meszaros and B. Zhang, *Astrophys. J.*, **613**, 1072 (2004).
[12] E. Waxman, *Phys. Rev. Lett.*, **75**, 386 (1995).
[13] M. Vietri, *Astrophys. J.*, **453**, 883 (1995).
[14] C. D. Dermer, E. Ramirez-Ruiz and T. Le, *Astrophys. J.*, **664**, L67 (2007).
[15] C. D. Dermer, A. Atoyan, *Phys. Rev. Lett.*, **91**, 071102 (2003).
[16] S. Razzaque, P. Meszaros and E. Waxman, *Phys. Rev. D*, **69**, 023001 (2004).
[17] IceCube Collaboration, J. Ahrens et al., *Astropart. Phys.*, **20**, 507 (2004).
[18] The Pierre Auger Collaboration, J. Abraham et al., *Science*, **318**, 938 (2007).
[19] D. Guetta, T. Piran and E. Waxman, *Astrophys. J.*, **619**, 412 (2005).
[20] E. Waxman and P. Coppi, *Astrophys. J. Lett.*, **464**, L75 (1996).
[21] X.-Y. Wang, S. Razzaque, P. Meszaros and Z.-G. Dai, *Phys. Rev. D* **76**, 083009 (2007).
[22] T. Stanev, P. L. Biermann, J. Lloyd-Evans, J. P. Rachen and A.A. Watson, *Phys. Rev. Lett.*, **75**, 3056 (1995).
[23] C. D. Dermer, S. Razzaque, J. Finke and A. Atoyan *New Journal of Physics*, (in press) http://arxiv.org/abs/0811.1160.
[24] A. Reimer, R.J. Protheroe and A.-C. Donea, *Astron. and Astrophys.*, **419**, 89 (2004).
[25] F. A. Aharonian, *New Astronomy*, **5**, 377 (2000).