External Shocks, UHECRs, and the Early Afterglow of GRBs

CHARLES D. DERMER

E. O. Hulburt Center for Space Research, Code 7653, Naval Research Laboratory, Washington, D.C. 20375-5352; dermer@gamma.nrl.navy.mil

Summary. — Highly variable γ-ray pulses and X-ray flares in GRB light curves can result from external shocks rather than central engine activity under the assumption that the GRB blast-wave shell does not spread. Acceleration of cosmic rays to \( \gtrsim 10^{20} \) eV energies can take place in the external shocks of GRBs. Escape of hadronic energy in the form of UHECRs leads to a rapidly decelerating GRB blast wave, which may account for the rapid X-ray declines observed in Swift GRBs.

PACS 95.85.Ry – 98.70.Rz.

1. – Introduction

GRB light curves measured with Swift consist of a BAT light curve in the 15 – 150 keV range followed, after slewing within \( \approx 100 \) s, by a detailed 0.3 – 10 keV XRT X-ray light curve \(^{1}\). This information supplements our knowledge of the highly variable hard X-ray and γ-ray light curves measured from many GRBs with BATSE and other GRB detectors. About one-half of Swift GRBs show X-ray flares or short timescale structure, sometimes hours or later after the onset of the GRB. Approximately 30% of the Swift GRBs display rapid X-ray declines, and an additional \( \approx 30\% \) display features unlike simple blast wave model predictions \(^{2}\).

We make three points in this paper:

1. Highly variable light curves can be produced by an external shock under the assumption that the GRB blast wave does not spread, or spreads much more slowly than assumed from gas-dynamic or relativistic hydrodynamic models that do not take into account magnetic effects in GRB blast waves. If this assumption is valid, then it is wrong to conclude that highly variable γ-ray emissions, X-ray flares with \( \Delta t/t \ll 1 \), or late time X-ray flares require delayed central engine activity or colliding shells.

2. External shocks in GRB blast waves can accelerate cosmic ray protons and ions to \( \gtrsim 10^{20} \) eV, making GRBs a logical candidate to accelerate the highest energy cosmic rays.
3. Escape of ultra-high energy cosmic rays (UHECRs) takes place from an external shock formed by an expanding GRB blast wave on time scales of a few hundred seconds for the observer. Blast-wave deceleration due to the loss of the internal hadronic energy is proposed \[3\] to be the cause of X-ray declines in GRB light curves observed with Swift.

2. — X-ray flares and $\gamma$-ray pulses from external shocks

We have performed a detailed analysis of the interaction between a GRB blast-wave shell and an external stationary cloud \[4\]. The analysis is performed under the assumption that the cloud width $\Delta_{cl} \ll x$, where $x$ is the distance of the cloud from the GRB explosion. The interaction is divided into three phases: (1) a collision phase with both a forward and reverse shock; (2) a penetration phase where either the reverse shock has crossed the shell while the forward shock continues to cross the cloud, or vice versa; and (3) an expansion phase, where both shocks have crossed the cloud and shell, and the shocked fluid expands. The shell width is written as

$$\Delta(x) \cong \Delta_0 + \eta \frac{x}{\Gamma_0},$$

and the proper number density of the relativistic shell is given by

$$n(x) = \frac{E_0}{4\pi x^2 \Gamma_0^4 m_p c^2 \Delta(x)},$$

where $\Gamma_0$ is the coasting Lorentz factor of the GRB blast wave, and $E_0$ is the apparent isotropic energy release.

Short timescale flaring requires (a) a strong forward shock, which from the relativistic shock jump conditions \[5\] imply a maximum cloud density given by

$$n_{cl} \lesssim \frac{E_0}{16\pi x^2 \Gamma_0^4 m_p c^2 \Delta(x)},$$

and (b) significant blast-wave deceleration to provide efficient energy extraction, which occurs in clouds with thick columns \[6\], that is, with densities

$$n_{cl} \lesssim \frac{E_0}{4\pi x^2 \Gamma_0^2 m_p c^2 \Delta_{cl}}.$$

These two conditions translate into the requirement that

$$\Delta_{cl} \gtrsim 4\Gamma_0^2 \Delta(x)$$

in order to produce short timescale variability. The short timescale variability condition \[6\] for quasi-spherical clouds is

$$\Delta_{cl} \lesssim \frac{x}{\Gamma_0}.$$
Using eq. (1) for the shell width, eqs. (5) and (6) imply the requirement that

$$\eta < \sim \frac{1}{4\Gamma_0}$$

in order to produce rapid variability from an external shock. Hence the production of $\gamma$-ray pulses and X-ray flares from external shocks depends on whether the GRB blast-wave width spreads in the coasting phase according to eq. (1), with $\eta \approx 1$, as is generally argued. In the gas-dynamical study of [7], inhomogeneities in the GRB fireball produce a spread in particle velocities of order $|v - c|/c \sim \Gamma_0^{-2}$, so that $\Delta(x) \sim x/\Gamma_0^2$ when $x > \Gamma_0^2 \Delta_0$. This dependence is also obtained in a hydrodynamical analysis [8].

Two points can be made about these relations. First, the spread in $\Delta$ considered for a spherical fireball is averaged over all directions. As the fireball expands and becomes transparent, the variation in fluid motions or gas particle directions over a small solid angle $\sim \frac{1}{\Gamma_0^2}$ of the full sky becomes substantially less. Second, the particles within a magnetized blast-wave shell will expand and adiabatically cool so that the fluid will spread with thermal speed $v_{th} = \beta_{th} c$. The comoving width of the blast wave is $\Gamma_0 \Delta_0 + \beta_{th} c \Delta' \approx \Gamma_0 \Delta_0 + \beta_{th} x/\Gamma_0$, so that the spreading radius $x_{spr} \approx \Gamma_0^2 \Delta_0/\beta_{th}$. Adiabatic expansion of nonrelativistic particles can produce a very cold shell with $\beta_0 \lesssim 10^{-3}$, leading to very small shell widths.

The requirement on the thinness of $\Delta(x)$ does not apply to the adiabatic self-similar phase, where the width is necessarily $\sim x/\Gamma_0^2$, as implied by the relativistic shock hydrodynamic equations [5]. Even in this case, however, $\Delta \ll x/\Gamma_0^2$ if the blast wave is highly radiative [9]. Under the assumption of a strong forward shock and small clouds in the vicinity of a GRB, highly variable GRB light curves are formed with reasonable efficiency ($\gtrsim 10\%$) to transform blast wave energy into $\gamma$ rays [6, 10].

### 3. Cosmic ray acceleration in GRB blast waves

The maximum particle energy for a cosmic ray proton accelerated by an external shock in a GRB blast wave is derived. Consider a GRB blast wave with apparent isotropic energy release $E_0 = 10^{54} E_{54}$ ergs, (initial) coasting Lorentz factor $\Gamma_0 = 300 \Gamma_{300}$, and external medium density $n_0 = 100 n_{2} \text{ cm}^{-3}$. The comoving blast wave volume for the assumed spherically symmetric explosion, after reaching distance $x$ from the center of the explosion, is

$$V' = 4\pi x^2 \Delta',$$

where the shell width $\Delta' = x/12\Gamma$ (the factor $1/12\Gamma$ is the product of the geometrical factor $1/3$ and the factor $1/4\Gamma$ from the continuity equations of relativistic hydrodynamics; $\Gamma$ is the evolving GRB blast wave Lorentz factor).

The Hillas condition [11] for maximum particle energy $E'_{max}$ is that the particle Larmor radius is less than the size scale of the system; $E_{max}$ in the stationary frame (primes refer to the comoving frame) is given by

$$r'_L = \frac{E'_{max}}{eB'} = \frac{E_{max}}{\Gamma eB} < \Delta'.$$

The largest particle energy is reached at the deceleration radius $x = x_d$ when $\Gamma \approx \Gamma_0$. 

Thus, the deceleration radius

\[ x_d \equiv \left( \frac{3E_0}{4\pi \Gamma_0^2 m_p n_0} \right)^{1/3} \approx 2.6 \times 10^{16} \left( \frac{E_{54}}{\Gamma_{300}^2} \right)^{1/3} \text{cm}. \]

Hence \( E_{\text{max}} \approx Z e B' x_d / 12 \).

The mean magnetic field \( B' \) in the GRB blast wave is assigned in terms of a magnetic field parameter \( \epsilon_B \) that gives the magnetic field energy density in terms of the energy density of the downstream shocked fluid, so

\[ B' = (32\pi n_0 \epsilon_B m_p c^2)^{1/2} \sqrt{\Gamma (\Gamma - 1)} \approx 0.4 (\epsilon_B n_0)^{1/2} \Gamma \approx 1200 \epsilon_B n_2 \Gamma_{300} \text{Gauss} \]

Thus

\[ E_{\text{max}} \approx 8 \times 10^{20} Z n_2^{1/6} \epsilon_B^{1/2} \Gamma_{300}^{-1/3} \epsilon_{54}^{1/3} \text{eV}. \]

\[ \phi \pi \]

so that external shocks of GRBs can accelerate particles to ultra-high and, indeed, super-GZK energies. Implicit in this result is that acceleration occurs within the GRB blast wave through, for example, second-order Fermi acceleration \[13\]. Acceleration to ultra-high energy through first-order relativistic shock acceleration requires a highly magnetized surrounding medium \[14\].

4. – Rapid X-ray declines from UHECR escape

If UHECRs are accelerated by GRB blast waves, then blast-wave dynamics will be affected by the loss of internal energy when the UHECRs escape. This effect is proposed to explain the rapid X-ray declines in the Swift GRB light curves \[3\]. Photohadronic processes become important when the threshold condition \( \epsilon' \gamma' > m_\pi/m_e c^2 \approx 400 \), where \( \epsilon = h\nu/m_e c^2 \) is the dimensionless photon energy, \( m_p c^2 \gamma \) is the proton energy, and \( \gamma \) is the proton Lorentz factor. For protons interacting with photons at the peak proton energy \( \epsilon_{pk} \equiv 2 \epsilon_{ph}/(1+z) \) of the \( \nu F_\nu \) spectrum,

\[ E_{pk} \approx \frac{3 \times 10^{16} (\Gamma/300)^2}{(1+z) \epsilon_{pk}} \text{eV}. \]

The comoving timescale for a proton to lose a significant fraction of its energy through photohadronic processes is given by \( t'_{\phi \pi} (\gamma) \), where \( t'_{\phi \pi}^{-1} (\gamma) \approx (K_{\phi \pi} \sigma_{\phi \pi}) [\epsilon' u'_{ph}(\epsilon')] c, K_{\phi \pi} \sigma_{\phi \pi} \approx 70 \mu b \) is the product of the photohadronic cross section and inelasticity, and the comoving energy density of photons with energy \( \approx \epsilon' \) is \( u'_{\nu} \equiv m_e c^2 \gamma^2 n'_{ph}(\epsilon') \).

The relation between the measured \( \nu F_\nu \) flux \( f_\nu \) and internal energy density is \( u'_{\nu} \equiv d_L^2 f_\nu/(c\gamma^2) \), where \( d_L = 10^{28} d_{28} \text{cm} \) is the luminosity distance of the GRB. For protons interacting with photons with energy \( \epsilon'_{pk} \), we therefore find that the comoving time required for a proton with energy \( E_{pk} \) (as measured by an observer outside the blast wave) to lose a significant fraction of its energy through photohadronic processes is

\[ t'_{\phi \pi} (E_{pk}) \approx \frac{m_e c^2 \gamma^2 \epsilon_{pk}}{K_{\phi \pi} \sigma_{\phi \pi} d_L^2 f_{\epsilon_{pk}}} \approx 2 \times 10^6 \frac{x_{16} (\Gamma/300)(1+z) \epsilon_{pk}}{d_{28}^2 f_{-6} s} \]

where \( x = 10^{16} x_{16} \text{ cm} \) and \( f_{\epsilon_{pk}} = 10^{-6} f_{-6} \text{ ergs cm}^{-2} \text{ s}^{-1} \) is the \( \nu F_\nu \) flux measured at \( \epsilon_{pk} \); the relation between \( E_{pk} \) and \( \epsilon_{pk} \) is given by eq. \[12\].
The dependence of the terms $x(t)$, $f_{pk}(t)$, $\Gamma(t)$, and $\epsilon_{pk}(t)$ on observer time in eq. (14) can be analytically expressed for the external shock model in terms of the GRB blast wave properties $E_0$, $\Gamma_0$, environmental parameters, e.g., $n_0$, and microphysical blast wave parameters $\epsilon_B$ and $\epsilon_e$. This can also be done for other important timescales, for example, the (available) comoving time $t'_{\text{ava}}$ since the start of the GRB explosion, the comoving acceleration time $t'_{\text{acc}} = \zeta_{\text{acc}} m_p c^2 / eBc$, written as a factor $\zeta_{\text{acc}} \gg 1$ times the Larmor timescale $[15]$, the escape timescale $t'_{\text{esc}}$ in the Bohm diffusion approximation, and the proton synchrotron energy loss timescale $t'_{\text{syn}}$.

Fig. 1 shows the rates (or the inverse of the timescales) for $10^{20}$ eV protons in the case of an adiabatic blast wave that decelerates in a uniform surrounding medium. The left-hand panel of Fig. 1 uses the parameter set $z = 1$, $\Gamma_0 = 300$, $E_{54} = 1$, $n_0 = 1000 \text{ cm}^{-3}$, $\epsilon_e = 0.3$, $\epsilon_B = 0.3$, and the right-hand panel uses the parameter set $z = 1$, $\Gamma_0 = 150$, $E_{54} = 10$, $n_0 = 1000 \text{ cm}^{-3}$, $\epsilon_e = 0.1$, $\epsilon_B = 0.3$.

The characteristic deceleration timescale in the left and right cases, given by $t_d \cong 9.6(1 + z)(E_{54}/n_2 \Gamma_{500}^8)^{1/3}$ s, is $\approx 9$ s and $\approx 120$ s, respectively.

For these parameters, it takes a few hundred seconds to accelerate protons to energies $\approx 10^{20}$ eV, at which time photohadronic losses and escape start to be important. Photohadronic losses inject electrons and photons into the GRB blast wave. The electromagnetic cascade emission, in addition to hyperrelativistic electron synchrotron radiation from neutron escape followed by subsequent photohadronic interactions [16], makes a delayed anomalous $\gamma$-ray emission component as observed in some GRBs [17, 18]. Ultra-high energy neutrino secondaries are produced by the photohadronic processes. Detection of high-energy neutrinos from GRBs would confirm the importance of hadronic processes in GRB blast waves. The ultra-high energy neutrons and escaping protons form the UHECRs with energies $\gtrsim 10^{20}$ eV.

Fig. 1. – Rates and inverse timescales as a function of observer time for $10^{20}$ eV cosmic ray protons as measured by a stationary external observer. Left and right panels are results for parameter sets 1 and 2, respectively.
The GRB blast wave rapidly loses internal energy due to the photohadronic processes and particle escape. The blast wave will then rapidly decelerate, producing a rapidly decaying X-ray flux. As argued in more detail elsewhere [3], the rapidly decaying fluxes in Swift GRBs are signatures of UHECR acceleration by GRBs. If this scenario is correct, GLAST will detect anomalous $\gamma$-ray components, particularly in those GRBs that undergo rapid X-ray declines in their X-ray light curves.

* * *

This work is supported by the Office of Naval Research, by NASA GLAST Science Investigation No. DPR-S-1563-Y, and NASA Swift Guest Investigator Grant No. DPR-NNG05ED41I. Thanks also to Guido Chincarini for the kind invitation.

REFERENCES
[1] Gehrels N. et al., Astrophys. J., 611 (2004) 1005
[2] O’Brien P. et al., Astrophys. J., 647 (2006) 1213
[3] Dermer C., Astrophys. J., (2006) submitted (astro-ph/0606320)
[4] Dermer C., (2006) preprint
[5] Blandford R. and McKee C., Phys. Fluids, 19 (1976) 1130
[6] Dermer C. and Mitman K., Astrophys. J. Lett., 513 (1999) L5
[7] Mészáros P., Laguna, P., and Rees, M., Astrophys. J., 415 (1993) 181
[8] Piran T., Shemi A., and Narayan, R., MNRAS, 263 (1993) 861
[9] Cohen E., Piran T., and Sari, R., Astrophys. J., 509 (1998) 717
[10] Dermer C. and Mitman K., Astron. Soc. Pac. Conf. Ser., 312 (1999) 301
[11] Hillas A., Ann. Rev. Astron. Astrophys., 22 (1984) 425
[12] Vietri M., Astrophys. J., 507 (1998) 40
[13] Dermer C. and Humi, M., Astrophys. J., 479 (2001) 493
[14] Gallant Y. and Achterberg, A., MNRAS, 305 (1999) L6
[15] Rachen J. and Mészáros P., Phys. Rev. D, 58 (1998) 123005
[16] Dermer C. and Atoyan, A., Astron. Astrophys., 418 (2004) L5
[17] Hurley K. et al., Nature, 372 (1994) 652
[18] González M. et al., Nature, 424 (2003) 749