External Shock Model for the Prompt Phase of Gamma Ray Bursts: Implications for GRB Source Models

Charles D. Dermer

E. O. Hulburt Center for Space Research, Code 7653, Naval Research Laboratory, Washington, DC 20375-5352

Kurt E. Mitman

University of Virginia, Charlottesville, VA, and Pembroke College, University of Cambridge, Cambridge, England CB2 1RF

Abstract. An external shock model for the prompt gamma-ray luminous phase of gamma-ray bursts (GRBs) is treated both analytically and numerically. A widely cited derivation claiming that an external shock model for rapidly variable GRBs must be very inefficient employs an incorrect expression for the angular timescale. Numerical results show that variable GRBs can be formed with > 10% efficiency to transform the directed kinetic energy of the relativistic fireball to gamma-rays. Successes of the external shock model and difficulties with an internal wind/colliding shell model are summarized. An impulsive external shock model is consistent with the supranova model.

1. Introduction

The prompt gamma-ray luminous phase of GRBs lasts from seconds to minutes after the start of a burst and provides our best probe of the processes that take place in the vicinity of the GRB central engine. Within the framework of the relativistic blast-wave/fireball scenario, a central problem concerns the nature of the prompt radiation. In the internal shock model, an active central engine is assumed to eject waves of relativistic plasma that collide with each other to form shocks that accelerate nonthermal particles and radiate high-energy photons. In the impulsive external shock model, a single relativistic wave of plasma interacts with inhomogeneities in the surrounding medium to form external shocks that accelerate particles which radiate the prompt gamma rays.

The resolution of this problem has important implications for theories of the central engine. In the collapsar model (e.g., MacFadyen, Woosley, and Heger 2001), the core of a massive rotating star collapses directly to a black hole, forming a disk that is assumed to accrete onto the black hole over timescales of seconds to minutes. This active central engine drives a jet of baryon-dilute relativistic ejecta that penetrates the surrounding stellar envelope to form colliding relativistic shells. If the collapsar model is correct, than an impulsive external shock model is ruled out, because a single explosive event would be quenched by
the massive envelope surrounding the accreting black hole. No highly relativistic shock could emerge to form either the prompt or afterglow emission.

By contrast, if an impulsive external shock model is correct, then the collapsar model is ruled out, because the collapsar model requires an active central engine and the formation of a jet that persists on the timescale of the prompt phase.

An impulsive external shock model is, however, compatible with the supernova model for GRBs (as is an internal shell model). In the supernova model (Vietri and Stella 1998), a massive star undergoes a two-step collapse to a black hole. In the first step, a supernova ejects a remnant, leaving behind a neutron star which is stabilized against direct collapse to a black hole by its rapid rotation. The loss of angular momentum support by gravitational and electromagnetic dipole radiation leads to the collapse of the neutron star to a black hole some weeks to years after the initial supernova. The process of black-hole formation drives a baryon-dilute outflow that interacts with the surrounding supernova remnant material through an external shock to form GRB radiation.

The purpose of this paper is to show that an impulsive external shock model can account for the highly variable GRB light curves.

2. The External Shock Model for GRBs

Three major criticisms have been directed at an external shock model for GRBs during the prompt phase. These are:

1. Highly variable light curves cannot be made with high efficiency;
2. Pulse widths should spread with time; and
3. Gaps in light curves cannot be formed.

We answer each criticism below.

2.1. Short Timescale Variability

Consider an explosion that produces a spherical shell of relativistic particles moving with Lorentz factor $\Gamma_0 \gg 1$. Fenimore, Madras, and Nayakshin (1996) showed that if the shell was instantaneously illuminated over all parts of its surface within the Doppler beaming cone on angular scales $\theta \lesssim 1/\Gamma_0$, then a characteristic emission profile is formed with mean duration $t_{FWHM} \approx 0.2R/\Gamma_0^2c$, due to light-travel time delays from different portions of the surface of the shell. Here $R$ is the distance of the shell from the explosion center. For a single relativistic shell moving to larger radii, successive instantaneous illuminations would form pulses with successively larger durations, contrary to observations. These authors noted that the conclusion that a single expanding shell cannot produce a variable GRB could be avoided if the condition of local spherical symmetry was broken on size scales $\ll R/\Gamma_0$, for example, by density inhomogeneities. This was considered unlikely because of the required large number of such density enhancements.

Dermer and Mitman (1999; hereafter DM99) confirmed by direct numerical simulation that if clouds with radii $r \ll R/\Gamma_0$ existed near GRBs, short timescale
variability (STV) in GRB light curves could indeed be formed. For $\Gamma_0 \approx 300$, comparison with GRB pulse properties implied that density inhomogeneities located $\approx 10^{16}$ cm from the sites of GRBs with sizes $\approx 10^{12}$-$10^{13}$ cm are required. The discovery of the evolving prompt absorption feature in GRB 990705 (Amati et al. 2000) provides unexpected support for this model. The variable absorption can be explained within the context of either resonance scattering (Lazzati et al. 2001) or photoelectric absorption (Böttcher, Fryer, and Dermer 2002) models if small dense clouds of sizes $\approx 10^{13}$ cm are found $\approx 10^{17}$ cm from the sites of GRBs, consistent with the numerical expectations for STV. Explanation of X-ray lines in GRB 011211 (Reeves et al. 2002) also require small, high density clouds to account for the features detected with XMM.

Sari and Piran (1997) proposed an analytic argument to demonstrate that an external shock model could produce STV only if it was very inefficient. Because this argument has been widely cited as a refutation of the external shock model, we carefully review it and point out the error contained within the argument.

Consider a blast wave passing through a spherical density inhomogeneity (or cloud) with size $r < R/\Gamma_0$ that is located at an angle $\theta$ with respect to the line-of-sight to the observer. The duration of the received pulse of radiation depends on the light travel-time delays from different portions of the blast wave as it interacts with the cloud. Photons which are emitted when the blast wave passes through the near and far sides of the cloud are received over a radial timescale

$$t_r = \frac{2r}{\beta_0 \Gamma_0 D c} \approx \frac{r}{\Gamma_0^2 c},$$

where the Doppler factor $D = [\Gamma_0 (1 - \beta_0 \cos \theta)]^{-1}$, and $\beta_0 = \sqrt{1 - \Gamma_0^{-2}}$. The radial timescale varies by a factor $\approx 2$, depending on whether the cloud is located on-axis or at an angle $\theta \approx 1/\Gamma_0$.

Photons emitted from points defining the greatest angular extent of the cloud are received over an angular timescale

$$t_{\text{ang}} \approx \frac{r \theta}{c}.$$

Eq. 2 can easily be derived from special relativity. Note that if $r \to R/\Gamma_0$ and $\theta \to 1/\Gamma_0$, then $t_{\text{ang}} \to R/\Gamma_0^2 c$, as expected. When $\theta \approx 1/\Gamma_0$, $t_{\text{ang}} \approx \Gamma_0 t_r \gg t_r$. Except for those few clouds with $\theta \lesssim 1/\Gamma_0$ lying almost exactly along the line-of-sight to the observer, $t_{\text{ang}} \gg t_r$.

Sari and Piran (1997) argue that a highly variable light curve is only possible in an external shock model if the radiative efficiency is very low. They define a variability index $\mathcal{V}$, roughly corresponding to the number of distinct pulses in a GRB light curve, given by $\mathcal{V} = T/\Delta T$, where $T$ is the GRB duration and $\Delta T$ is a typical pulse width. A highly variable GRB can have $\mathcal{V} \gg 100$. The efficiency $\eta$ to extract energy from a GRB blast wave is given by the ratio of the total area $A_c \approx N_c \pi r^2 \approx V \pi r^2$ subtended by the $N_c$ clouds within the Doppler beaming cone $\theta \lesssim 1/\Gamma_0$, to the area $A_{bw} = \pi R^2/\Gamma_0^2$ of the blast wave within the Doppler beaming cone. Thus $\eta = \mathcal{V} \pi r^2/(\pi R^2/\Gamma_0^2)$.

They then claim that $\eta \lesssim 1/4\mathcal{V} \ll 1$, so that a highly variable light curve with $\mathcal{V} \gg 1$ must be very inefficient. As can easily be seen, this expression
Dermer & Mitman

makes use of the relation $V < (R/\Gamma_0)/2r$, which would follow by assuming that the characteristic duration of a GRB is $T \approx t_{\text{dur}} \approx R/\Gamma_0^2 c$, and that the variability timescale $\Delta t \approx r/\Gamma_0 c$. This last approximation makes use of an expression for $t_{\text{ang}}$ (see eq. [2]) that is only correct at $\theta \approx 1/\Gamma_0$.

As was shown by DM99, the clouds located at angles $\theta \ll 1/\Gamma_0$ with respect to the line-of-sight make a disproportionate contribution to the variability of GRB light curves precisely because $t_{\text{ang}}$ becomes so small — and therefore the peak flux of a pulse becomes so large — for such clouds. The peak pulse flux

$$\phi_{\text{pk}} \propto \frac{\mathcal{D}^{3+\alpha}}{\max(t_r, t_{\text{ang}})} \rightarrow \frac{c\mathcal{D}^{3+\alpha}}{\nu_0 r \theta},$$

(3)

where $\alpha$ is the energy spectral index, and the last expression holds for clouds with $\theta \gtrsim 1/\Gamma_0^2$. Here we have used a beaming factor appropriate to isotropic synchrotron radiation in the comoving frame. Specifically,

$$\frac{\phi_{\text{pk}}(\theta = 1/10\Gamma_0)}{\phi_{\text{pk}}(\theta = 1/\Gamma_0)} \approx 10 : 2^{3+\alpha} \approx 80 - 160.$$  

(4)

Hence 1% of clouds, at $\theta = 1/10\Gamma_0$, produce 8-16% of the fluence in very narrow pulses that are $\approx 100\times$ brighter than clouds at $\theta \approx 1/\Gamma_0$. This produces highly variable light curves with reasonable ($\gtrsim 10\%$) efficiency.

Fig. 1 shows new calculations of GRB light curves in an external shock scenario. We assume that a GRB explodes with apparent isotropic energy release of $10^{53}$ ergs and $\Gamma_0 = 300$. Clouds, with a partial covering factor of 10%, are assumed to radiate 10% of their intercepted energy in the form of a Band-type spectrum (if the clouds are even more radiative, then the pulses will be even brighter). Clouds are “uniformly randomly” distributed between $10^{16}$ and $10^{17}$ cm, that is, the location of the cloud is randomly selected throughout the volume of the shell by Monte Carlo methods, provided that the volume of each cloud does not overlap the volume of another cloud. The underlying assumption is that no spatial correlations exist between cloud locations. In Fig. 1a, all clouds have the same radius $r = 10^{13}$ cm, and Gaussian noise is added to the simulation at a level typical of BATSE GRBs. Fig. 1b shows a simulation where clouds are chosen with equal partial covering factor per logarithmic interval for clouds with sizes between $10^{12}$ and $3 \times 10^{13}$ cm. No noise is added in Fig. 1b. As can be seen, there is no difficulty in making highly variable light curves in an external shock model, even with a 10% (or larger) partial covering factor.

2.2. Pulse Width Spreading

Another objection to the external shock model is that the pulse widths should spread with time (Fenimore, Ramirez-Ruiz, and Wu 1999; Ramirez-Ruiz and Fenimore 2000). One aspect of this criticism consists of noting that emission from off-axis clouds would arrive later at the detector, and these would have larger values of $t_{\text{ang}}$ than clouds located along the line-of-sight. This effect is weakly apparent in Fig. 2 of DM99, where a highly idealized scenario is simulated. No background noise was included, and clouds with identical radii were uniformly randomly distributed within a shell with discrete inner and outer boundaries. Figs. 1a and 1b separately relax the first two of these assumptions,
Figure 1. Model GRB light curves formed through external shocks with clouds in the circumburst medium. (a) All clouds have radii $r = 10^{13}$ cm. (b) Clouds are chosen with equal partial covering factor per logarithmic interval in cloud size between $10^{12}$ and $3 \times 10^{13}$ cm.

with the effect of reducing the tendency of pulses to spread with time. The more important assumption of a uniform random distribution has not yet been relaxed. The density inhomogeneities formed by the interaction of an intense pulsar wind with a supernova shell would produce Rayleigh-Taylor instabilities and complex cloud distributions (e.g., Jun 1998) with correlations among their locations. The uniform random assumption is clearly oversimplified, and a realistic cloud geometry would further ameliorate the pulse-width spreading problem (which is in any case minor, as shown by our simulations). One might furthermore speculate that the $-5/3$ slope found in the power density spectrum of GRB light curves (Beloborodov, Stern, and Svensson 1998) is related to the development of a Kolmogorov spectrum of cloud sizes through hydrodynamic turbulence.

A second aspect of this objection is that the pulse widths will spread with time as a result of blast wave deceleration, inasmuch as the blast wave will progressively slow as it sweeps up material from the external medium. This is not a problem in a highly structured medium, however, because whenever the blast wave encounters a cloud with a sufficiently large column density to produce a bright pulse, that portion of the blast wave is so strongly decelerated that any further interactions would produce undetectable emission. The remaining parts of the blast wave continue to travel with their original speed until encountering a density inhomogeneity with a “thick column” that would produce a bright pulse while only decelerating the intercepted portion of the blast wave.

2.3. Gaps in Light Curves

It has also been argued (Fenimore and Ramirez-Ruiz 1999) that gaps in GRB light curves are better explained with an active central engine that falls dormant for some period of time than with an external shock model. Active regions at different portions of the shell were argued to have to “conspire” in an external shock model to form a gap, since the arrival time to the observer of the different emitting regions on the shell would depend on the unknown direction to the observer. This argument does not take into account the strong dependence of pulse intensity on angle θ of the cloud, eq. (3), which favors those clouds nearly
Dermer & Mitman

along the line-of-sight to the observer. Nor does it consider possible gaps and clustering in cloud distributions. Because of the strong sensitivity of $\phi_{pk}$ on $\theta$, gaps in light curves would simply reflect layers of clouds, to reveal a tomographic image of the circumburster medium, as noted in the conclusion of DM99.

3. External vs. Internal Shocks

3.1. External Shock Model Successes

Explanations of the prompt GRB emission in terms of an external shock model offers many advantages over the colliding shell model. First is a simple understanding of the typical duration timescales of GRBs, which range from fractions of a second to hundreds of seconds. As originally pointed out by Rees and Mészáros (1992, 1993), the duration of the luminous prompt emission is on the deceleration timescale $t_d \approx 10(E_{52}/n_0\Gamma_{300}^8)^{1/3}$ s for explosions occurring in a uniform circumburster medium with density $n_0$. Here the apparent isotropic explosion energy is $10^{52} E_{52}$ ergs, and $\Gamma_{300} = \Gamma_0/300$. Deceleration in clumpy media will take place on a timescale $\Delta R/\Gamma_0^2 c \approx 4R_{16}/\Gamma_{300}^2$ s, where $R_{16} = \Delta R/(10^{16}$ cm) is the width of density inhomogeneities.

Another advantage of an external shock model is that it provides a simple explanation for the tendency of the $\nu F_\nu$, $E_{pk}$ distribution to appear in a narrow energy range near the peak energy of the effective area of the detector. This effect is understood (Dermer, Chiang, and Böttcher 1999) by considering both the triggering properties of GRB detectors and the emission properties of blast waves with different amounts of baryon loading. Dirty fireballs with large baryon loading and small $\Gamma_0$ produce extended GRB emissions with small peak fluxes $\phi_{pk}$, and with $E_{pk}$ values at low energies. These emissions are unlikely to trigger BATSE as a result of the smaller peak fluxes and larger backgrounds over the longer timescales. Clean fireballs produce the bulk of their brief luminous emission at energies well above the energy range where BATSE is most sensitive. The result is that BATSE is most sensitive to GRBs with $E_{pk}$ in the BATSE triggering range.

A model that simultaneously explains the BATSE $t_{50}$ duration distribution, the $E_{pk}$ distribution, and the peak-flux size distribution was constructed by Böttcher and Dermer (2000). The resulting model predicts a GRB redshift distribution that can be used to improve the parameters of the model when compared against the measured GRB redshift distribution. To avoid fine tuning of $\Gamma_0$, the external shock model predicts that a class of dirty fireballs must exist (Dermer, Böttcher, and Chiang 1999) with properties similar to the X-ray rich GRBs discovered with Beppo-SAX (Heise et al. 2001).

Qualitative considerations also suggest a simple explanation for the GRB variability-luminosity correlation (Fenimore and Ramirez-Ruiz 2000; Reichart et al. 2001). Blast waves which interact with small dense clouds along the line-of-sight produce intense bright peaks with total fluence that would, had the GRB occurred in a uniform circumburster medium, be radiated over a much longer timescale and at a smaller peak flux level. Consequently, the peak fluxes of highly variable GRB light curves would reach much larger values than smooth light curves.
3.2. Internal Shock Model Difficulties

When two shells collide to form a spherical radiating surface, light-travel time effects imply a unique temporal relation between the shell intensity and $E_{pk}$, that depends only on the (measurable) spectral indices of the GRB pulse (Soderberg and Fenimore 2001). The evolution of GRB pulses do not follow the predicted trend, implying that the simplest version of colliding shell physics is incomplete or incorrect.

The efficiency of colliding shells is of order $\sim 1\%$ (Kumar 2000) unless the contrast between the $\Gamma_0$ factors of the shells is very large (Beloborodov 2000). If the $\Gamma_0$ contrast is small, a narrow range of $E_{pk}$ may be possible, but if large, $E_{pk}$ will range over orders of magnitude, thus reducing the $\gamma$-ray detection efficiency. In either case, therefore, a colliding shell model is very inefficient. This makes it difficult to understand the constant-energy reservoir result of Frail et al. (2001). In contrast, the interactions of a single relativistic blast wave with stationary material will always have the same relative Lorentz factor $\Gamma_0$, which can account for the rough similarity between $E_{pk}$ values in different pulses of a GRB light curve (e.g., Crider et al. 1999).

In models involving colliding shells, no first principles understanding for the GRB duration distribution has been proposed, as the temporal variation in a wind model reflects the period of activity of the central engine, which is arbitrarily assigned. Consequently, no explanation for the statistical properties of GRBs, namely the $E_{pk}$, $t_{dur}$, and $\phi_{pk}$ distributions, has been proposed within the context of this model.

4. Implications for Source Models

If an impulsive external shock model is correct, then, as argued earlier, the collapsar model is ruled out. As shown by analytic arguments and numerical simulations, highly variable GRBs can be formed through interactions of a single blast wave with density inhomogeneities in the surrounding medium. The existence of such inhomogeneities may be associated with the material from an earlier supernova explosion. An impulsive external shock model is consistent with the supranova model, which provides several advantages to explain GRB afterglow behavior using the standard blast wave physics approach (Königl and Granot 2002).

An impulsive external shock model, if correct, implies that GRB explosions are due to compact objects that collapse directly to denser configurations, without the intermediate formation of an accretion disk. This implication is in accord with numerical simulations (e.g., Saijo et al. 2002) showing that the collapse of a rotating core of a supermassive star does not leave sufficient material to form an accretion disk that could power a GRB. Models for the formation of an impulsive GRB include the pair electromagnetic pulse during black hole formation (Ruffini et al. 2001), or pair production through neutrino/antineutrino annihilation processes during compact object coalescence (Janka et al. 1999). Extension of neutrino calculations to the collapse of rotating supramassive neutron stars is important to determine whether such models provide sufficient energy to explain GRB observations.
Acknowledgments. This work is supported by the Office of Naval Research.

References

Amati, L. et al. 2000, Science, 290, 953
Beloborodov, A. M., Stern, B. E., & Svensson, R. 1998, ApJ, 508, L25
Beloborodov, A. M. 2000, ApJ, 539, L25
Böttcher, M., Fryer, C. L., & Dermer, C. D. 2002, ApJ, 567, 441
Böttcher, M. & Dermer, C. D. 2000, ApJ, 529, 635
Crider, A., et al. 1999, ApJ, 519, 206
Dermer, C. D. & Mitman, K. E. 1999, ApJ, 513, L5 (DM99)
Dermer, C. D., Chiang, J., & Böttcher, M. 1999, ApJ, 513, 656
Dermer, C. D., Böttcher, M., & Chiang, J. 1999, ApJ, 515, L49
Fenimore, E. E., Madras, C. D., & Nayakshin, S. 1996, ApJ, 473, 998
Fenimore, E. E., Ramirez-Ruiz, E., & Wu, B. 1999, ApJ, 518, L73
Fenimore E. E., Ramirez-Ruiz E., 1999, in PASP Conf. Proc. Gamma Ray Bursts: The First Three Minutes, astro-ph/9906125
Fenimore, E. E., & Ramirez-Ruiz, E. 2000, astro-ph/0004176
Frail, D. A. et al. 2001, ApJ, 562, L55
Heise, J., in’t Zand, J., Kippen, R. M., & Woods, P. M. 2001, Gamma Ray Bursts in the Afterglow Era, 16
Janka, H.-T., Eberl, T., Ruffert, M., & Fryer, C. L. 1999, ApJ, 527, L39
Jun, B. 1998, ApJ, 499, 282
Königl, A. & Granot, J. 2002, ApJ, 574, 134
Kumar, P. 1999, ApJ, 523, L113
Lazzati, D., Ghisellini, G., Amati, L., Frontera, F., Vietri, M., & Stella, L. 2001, ApJ, 556, 471
MacFadyen, A. I., Woosley, S. E., & Heger, A. 2001, ApJ, 550, 410
Mészáros, P. & Rees, M. J. 1993, ApJ, 405, 278
Ramirez-Ruiz, E. & Fenimore, E. E. 2000, ApJ, 539, 712
Rees, M. J. & Mészáros, P. 1992, MNRAS, 258, 41P
Reeves, J. N. et al. 2002, Nature, 416, 512
Reichart, D., Lamb, D., Fenimore, E. E., Ramirez-Ruiz, E., Cline, T., & Hurley, K. 2001, ApJ, 552, 57
Ruffini, R., Bianco, C. L., Fraschetti, F., Xue, S., & Chardonn et, P. 2001, ApJ, 555, L117
Saijo, M., Baumgarte, T. W., Shapiro, S. L., & Shibata, M. 2002, ApJ, 569, 349
Sari, R. & Piran, T. 1997, ApJ, 485, 270
Soderberg, A. M. & Fenimore, E. E. 2001, Gamma Ray Bursts in the Afterglow Era, 87
Vietri, M. & Stella, L. 1998, ApJ, 507, L45