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The nature of the outflow in gamma-ray bursts

P. Kumar,[1] E. McMahon,[1★] A. Panaitescu,[2] R. Willingale,[3] P. O'Brien,[3] D. Burrows,[4] J. Cummings,[5] N. Gehrels,[5] S. Holland,[5] S. B. Pandey,[6] D. Vanden Berk[4] and S. Zane[6]

[1]*Astronomy Department, University of Texas, Austin, TX 78712*
[2]*Space Science and Applications, MS D466, Los Alamos National Laboratory, Los Alamos, NM 87545*
[3]*Department of Physics and Astronomy, University of Leicester, Leicester LE 1 7RH*
[4]*Department of Astronomy and Astrophysics, Pennsylvania State University, 525 Davey Lab, University Park, PA 16802*
[5]*NASA Goddard Space Flight Centre, Greenbelt, MD 20771*
[6]*Mullard Space Science Laboratory, University College of London, Holmbury St Mary, Dorking, Surrey RH5 6NT*

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ABSTRACT

The *Swift* satellite has enabled us to follow the evolution of gamma-ray burst (GRB) fireballs from the prompt γ-ray emission to the afterglow phase. The early-time X-ray and optical data for GRBs obtained by telescopes aboard the *Swift* satellite show that the source for prompt γ-ray emission, the emission that heralds these bursts, is short lived, and is distinct from the source for the long-lived afterglow emission that follows the initial burst. Using these data we determine the distance of the γ-ray source from the centre of the explosion. We find this distance to be 10^{15}–10^{16} cm for most bursts, and show that this is within a factor of about 10 of the radius of the shock heated circumstellar medium (CSM) producing the X-ray photons. Furthermore, using the early γ-ray, X-ray and optical data we show that the prompt gamma-ray emission cannot be produced in internal shocks nor can it be produced in the external shock; in a more general sense γ-ray generation mechanisms based on shock physics have problems explaining the GRB data for ten *Swift* bursts analyzed in this work. A magnetic field dominated outflow model for GRBs has a number of attractive features, although evidence in its favour is inconclusive. Finally, the X-ray and optical data allow us to provide an upper limit on the density of the CSM of about 10 protons cm^{-3} at a distance of $\sim 5 \times 10^{16}$ cm from the centre of explosion.

Key words: gamma-rays: bursts – gamma-rays: theory.

1 INTRODUCTION

A large fraction of bursts detected by *Swift* show the early X-ray flux rapidly declining with time as $\sim t^{-3}$ or faster for about 10 min (Tagliaferri et al. 2005; Nousek et al. 2006; O'Brien et al. 2006). This is often followed by a rather shallow declining light-curve (LC) that can last for a few hours where the flux falls off as $\sim t^{-1/2}$. The extrapolation of the fast declining X-ray LC backwards in time matches the LC during the burst, which suggests that the early X-ray and late γ-ray emissions are produced by the same source (O'Brien et al. 2006).

The fastest decline of LC for a relativistic source of angular size $\theta_{\rm j} > \Gamma_0^{-1}$ arises when the source switches off quickly in the comoving frame due to, for instance, a rapid adiabatic cooling at the end of the heating episode of the ejecta; the observed flux declines as $t^{-2-\beta}$ in this case (Kumar & Panaitescu 2000) – where Γ_0 is the Lorentz factor (LF) of the source and β is the spectral index, i.e. $f_\nu \propto \nu^{-\beta}$. The observed rate of decline of the early X-ray LC is often at this theoretical limit (O'Brien et al. 2006). This provides a compelling argument that the γ-ray source had a finite, short life, and by implication must be distinct from the much longer-lived afterglow source.

In this paper we determine some properties of the γ-ray source and its distance from the centre of the explosion using early time data obtained by instruments aboard *Swift*.

2 γ-RAY SOURCE DISTANCE

The early X-ray LC can be used to determine the distance of the γ-ray source (R_γ) from the central explosion as suggested by Lazzati & Begelman (2006) and Lyutikov (2006). However, instead of using the unknown gamma-ray burst (GRB) jet angle to determine R_γ, as in previous works, we determine the source radius in terms of

★E-mail: pk@astro.as.utexas.edu (PK); emcmahon@astro.as.utexas.edu (EM)

Table 1. GRB sample, showing α, β_γ (BAT spectral index averaged over the duration of the burst), β_x [X-ray Telescope (XRT) spectral index at the beginning of the steep decline phase], source redshift z where available (where unavailable, z is set to 2.5, the median z for *Swift* bursts), the isotropic equivalent energy released in the BAT band (15–150 keV), the T_{90} duration, the time t_2 when the steep decline of the X-ray LC ends, optical V-band observations and the time $t_{\rm opt}$ in seconds from the GRB peak at which these observations were carried out.

GRB	FRED?	α	β_γ	β_x	z	$E_{\rm iso,52}$	T_{90}[a]	t_2[b]	V[c]	$t_{\rm opt}$
050315	yes	4.3 ± 0.36	1.2 ± 0.09	1.6 ± 0.25	1.949	8.9	96	405.4	>18.5	138
050713b	yes	3.1 ± 0.32	0.53 ± 0.15	0.70 ± 0.11		23	120	719.9	>19.5	187
050714b	no	4.8 ± 1.2	1.7 ± 0.41	1.7 ± 0.41		3.0	70	545.9	>18.7	170
050814	yes	3.0 ± 0.17	0.98 ± 0.19	1.1 ± 0.08	5.3	67	65	1314.2	>18.7	211
050819	no	3.0 ± 0.40	1.6 ± 0.21	1.2 ± 0.23		2.2	36	914.3	>18.1	133
051016a	no	2.93 ± 1.03	0.95 ± 0.16	1.2 ± 0.73		4.5	22	529.5	>20.3	214
060108	yes	2.3 ± 0.31	0.94 ± 0.11	0.98 ± 0.25	2.03	1.1	14	358.3	>19.1	190
060211a	no	3.7 ± 0.36	0.83 ± 0.08	0.99 ± 0.08		7.7	126	978.5	>18	253
060219	no	2.7 ± 0.75	1.7 ± 0.28	2.15 ± 1.06		2.2	62	543.1	>18.6	218
060223a	no	3.82 ± 4.84	0.77 ± 0.08	0.90 ± 0.23	4.41	13	11	85.3	17.8	187

Notes. [a]In units of seconds. We note that $t_1 \sim T_{90}$ in most cases. [b]In units of s from t_0 as defined in O'Brien et al. (2006). [c]V-band magnitudes.

the FS radius that has the advantage that it has a very weak dependence on the only unknown parameter in the problem – the density of the circumstellar medium. In order to exploit this method and determine where and how γ-rays are generated, we synthesize γ-ray, X-ray and optical data within ~10 min of the burst, for 10 *Swift* bursts, where we can establish that the steeply falling portion of the LC is due to the large-angle emission. For these cases we can determine the source distance and derive other properties of the γ-ray source.

Some conditions need to be satisfied for the rapidly falling early X-ray afterglow LC in order that it can be considered as the large-angle emission from the γ-ray source. These conditions are: the temporal decay index of the X-ray LC during the steep decline phase (α) should be equal to $(2 + \beta)$ – where β is the spectral index ($f_\nu \propto \nu^{-\beta}$); the spectral index during early X-ray afterglow should be the same as at the end of the GRB; the X-ray afterglow flux extrapolated to the end of the prompt γ-ray emission should be same as the γ-ray flux at the end of the burst extrapolated to the X-ray band. We apply an additional condition that $t_2/t_1 > 3$ to ensure that we have a sufficiently long baseline for an accurate determination of α that is not too sensitive to the uncertainty in the origin of time; t_1 and t_2 are the time at the beginning and end of the steep X-ray decline phase, respectively.

10 bursts detected by *Swift* between 2005 January and 2006 May met these four conditions. Four of these 10 bursts had a single-peaked LC or were FRED (fast rise exponential decline) shaped, and the remaining six bursts in the sample contained multiple peaks. The relevant data for the 10 GRBs are shown in Table 1.

Consider a γ-ray source moving with LF Γ_0 that turns off at radius R_γ. A rapidly falling X-ray LC will be seen following this turn-off when the X-ray flux we receive is dominated by emission from the part of the γ-ray source that moves at an angle larger than Γ_0^{-1} with respect to the line of sight (Kumar & Panaitescu 2000) – this will be referred to as the large-angle emission (LAE). Photons originating from part of this source that lies at angle θ with respect to the line of sight, as seen at the centre of the explosion, will arrive at the observer at time $t = (1 + z)R_\gamma\theta^2/2c$ and will have specific intensity smaller than that for $\theta = 0$ by factor of $(1 + \theta^2\Gamma_0^2)^3$. The LAE, corresponding to $\theta > \Gamma_0^{-1}$, starts at the end of the prompt phase at time t_1 and dominates the LC until some time t_2 when emission from the forward shock (FS) overtakes the rapidly decreasing flux from the γ-ray source. The gamma-ray source radius at the time the source dies can be determined using the equation $R_\gamma = 2ct_2/[\theta(t_2)^2(1 + z)] = 2ct_\gamma\Gamma_0^2/(1 + z)$, where t_γ is approximately equal to the burst duration in the observer frame.

Table 2. Calculated quantities. The first optical data for GRB 060223a was obtained at 187s after the BAT trigger whereas the steep decline of the X-ray LC ended at 85s (t_2 = 85 s). The extrapolation of the X-ray flux at 85s to the optical band gives a V-band magnitude of 16.3 whereas the observed flux at 187 s was 17.8 mag. For all other bursts, UV/Optical Telescope (UVOT) measurements were between t_1 and t_2.

GRB	LAE fluence[a]	Optical flux ratio[b]	$\Gamma_{\rm FS}(t_2)$	$R_{\rm FS}(t_2)$[c]	R_γ[d]
050315	0.08	2.1×10^4	84.1	5.8	1.4
050713b	0.08	1.8×10^2	81.6	8.2	1.4
050714b	0.8	7.2×10^4	70.0	4.6	0.59
050814	0.17	9.2×10^2	92.7	10.7	0.53
050819	0.66	5.0×10^2	55.4	4.8	0.19
051016a	0.47	4.9×10^2	74.6	5.0	0.21
060108	0.29	1.9×10^1	68.9	3.4	0.13
060211a	0.23	2.9×10^2	63.4	6.7	0.86
060219	0.4	2.8×10^4	67.4	4.2	0.48
060223a	0.17		200	3.8	0.49

Notes. [a]Ratio of fluence from the end of GRB to time t_2 in 0.1–10 keV band and the fluence in 15–150 keV band during the burst. [b]The ratio of the expected to observed optical flux (or upper limit) at the time of UVOT observation. The expected flux is the extrapolation of the X-ray flux to the optical band using the XRT spectral index. [c]In units of 10^{16} cm. [d]In units of 10^{16} cm.

The 0.1–10 keV fluence of the early rapidly declining X-ray LC, starting from the end of the GRB prompt emission to time t_2 is greater than ~15 per cent of the GRB fluence for most of the bursts (see Table 2). Therefore, the source for the steep X-ray LC is not some minor pulse in the explosion but it is responsible for producing a good fraction of the prompt γ-ray energy radiated (both FRED and non-FRED bursts); for this reason t_γ appearing in the equation $R_\gamma = 2ct_\gamma\ \Gamma_0^2/(1 + z)$ should be roughly equal to the burst duration otherwise the fluence during the LAE would be much less than the observed value [FRED bursts have the smallest ratio of LAE and GRB fluence (Table 2), and for these bursts t_γ is equal to the burst duration].

The radius ($R_{\rm FS}$) and the LF ($\Gamma_{\rm FS}$) of the shock front in the CSM are related by: $R_{\rm FS}(t_2) \approx 2ct_2\Gamma_{\rm FS}^2(t_2)/(1 + z)$. Since the energy of the LAE source is a significant fraction of the total GRB energy, it must have provided a good part of the kinetic energy deposited in the CSM, and so the LF of the LAE source, Γ_0, should be larger than Γ_{FS}. Thus, using the expression for the LAE radius, $R_\gamma = 2ct_\gamma\Gamma_0^2/(1+z) > R_{FS}(t_2)(t_\gamma/t_2)$, we find that $R_{FS}(t_2)/R_\gamma < t_2/t_\gamma$. For the 10 bursts in our sample, t_2/t_γ is between 5 and 25; the average value of t_2/t_γ for the four FREDs is 14.0 and the six non-FREDs is 13.5. If the deceleration time for CSM shock, t_d, is less than t_2 (as expected because the X-ray flux is decreasing monotonically with time) then the initial LF of the CSM shock, $\sim\Gamma_0$, is larger than the LF at deceleration by a factor of 2, and $R_{FS}(t_d)/R_\gamma$ is smaller than t_2/t_γ by a factor of $\sim$4. Therefore, we conclude that γ-rays are produced within a factor of $\sim$4 of the deceleration radius, on average, for our sample of bursts.

We now calculate $R_{FS}(t_2)$ and estimate R_γ. The FS radius at time t_2 can be calculated from the dynamics of adiabatic blast waves, which yields $R_{FS}(t_2) = [3ct_2E_{iso}/2\pi m_p c^2(1+z)n_0]^{1/4}$, where E_{iso} is the isotropic equivalent of energy in the FS and n_0 is the mean density of the CSM within a sphere of radius $R_{FS}(t_2)$. The former is obtained from the GRB fluence, and n_0 (or an upper limit for n_0) is calculated from the X-ray and optical flux at t_2. For the bursts in our sample we find $n_0 \lesssim 10$ cm^{-3} provided that X-rays are produced via the synchrotron process (no conditions were imposed on microphysics parameters ϵ_e and ϵ_B in this calculation); the constraint on n_0 is weaker if X-rays are produced via synchrotron-self-Compton (SSC) process. [1] Using GRB fluence and $n_0 = 10$ cm^{-3} we calculate the FS radius $R_{FS}(t_2)$ and the LF, $\Gamma_{FS}(t_2) = [R_{FS}(t_2)(1+z)/2ct_2]^{1/2}$. The result for the 10 GRBs is shown in Table 2;[2] from $R_{FS}(t_2)$ we calculate the lower bound on the γ-ray source distance from the centre of explosion and find it to be between 10^{15} and 10^{16} cm. Note that R_{FS} and Γ_{FS} have a very weak dependence on E_{iso} and n_0, and therefore any error in E_{iso} or n_0 has little effect on these quantities.

3 γ-RAY GENERATION MODELS

3.1 Forward shock

Although we find that the burst and early afterglow data are not incompatible with $R_\gamma \sim R_{FS}(t_2)$, the FS model for γ-ray generation (according to which the prompt γ-ray emission is generated in shock-heated CSM) can be ruled out. This is because the γ-ray production mechanism is short-lived, and the early X-ray and optical observations show, as discussed below, that the synchrotron self-absorption frequency for the γ-ray source is greater than 2 eV, which cannot be satisfied in the FS model.[3]

All 10 bursts in our sample have excellent optical upper limits or detections a few minutes after the burst – typically at the beginning of the steeply declining X-ray LC – provided by the UV-optical telescope aboard *Swift*. From the flux and the spectrum in the X-ray at the time of the optical observation we estimate the expected flux in the optical band and find it to exceed the observed value or upper limit by two orders of magnitude or more (see Table 2). This means that the X-ray spectrum must turn over at lower energies and become steeper than $\nu^{1/3}$. Another possibility, that there is large extinction in the optical *V*-band, can be ruled out because late-time optical data shows extinction of less than a factor of 2. Moreover, in those cases where we have optical detection, the spectrum in the optical band is consistent with ν^{-1} – similar to the spectrum in the X-ray band. These results suggest that the optical band lies below the synchrotron self-absorption frequency (ν_a) for the early X-ray/γ-ray emission, or $\nu_a > 2$eV; it also implies that the optical flux detected at early times in a few cases must come from a source different from the X-ray/γ-ray source.

A straightforward calculation of FS emission shows that if X-rays at time t_1 are produced via the synchrotron process then $\nu_a \ll 2$ eV; this result holds even when we allow for the possibility that the external medium might be enriched with $e^\pm$ pairs, with up to 10^3 pairs per proton. Therefore, the FS model violates the requirement of $\nu_a > 2$ eV that is needed to reconcile the optical and X-ray data at early times. If X-rays arise from SSC process then the spectrum below 0.3 keV can be as steep as $f_\nu \propto \nu$; however, the optical flux associated with the underlying synchrotron radiation in this case exceeds the observed limit.

3.2 Internal shock

We now consider the internal shock model for prompt γ-ray generation. According to this model a fluctuation in the LF of the relativistic outflow from the central explosion leads to collision between faster and slower ejecta that produces internal shocks and γ-ray radiation. No relationship is expected, in general, between where these collisions take place and the deceleration radius, whereas we find the average $R_{FS}(t_d)/R_\gamma \lesssim 4$. We also found that the average value for $R_{FS}(t_2)/R_\gamma$ is the same for GRBs with multiple spikes in the prompt γ-ray LC and FRED bursts; this suggests that γ-rays are produced at a radius that is not set by the variability time-scale of the central engine, contrary to what one expects in the internal shock model.

The GRB ejecta should consist of baryonic material and/or $e^\pm$ in order to have internal shocks. The interaction of such ejecta with the CSM would launch a reverse shock which would move into the ejecta that would heat it, producing synchrotron radiation that peaks in the optical band and that declines with time as t^{-2} (Panaitescu & Meszaros 1998; Sari & Piran 1999). It is widely believed that such an emission from shocked ejecta was seen in GRB 990123 and 021211.

We show the early optical LC for these two bursts in Fig. 1 after subtracting the extrapolation of the late-time optical emission, which arises in the FS. This extrapolation is justified because the optical LCs for a number of *Swift* bursts shows a single power-law decline from 300 s to hours, unlike the more complex X-ray LC (Panaitescu et al. 2006; Fan & Piran 2006). We find that, after subtracting the FS contribution, the early LCs for GRB 990123 and 021211 decline as $\sim t^{-2.5}$. This decline is steeper than expected for reverse-shock optical emission, and is similar to that of the early X-ray LCs. Therefore, it is likely that the steeply falling early optical LCs in these bursts are produced via the same mechanism as the early X-ray, i.e. the large-angle emission from the γ-ray source (Panaitescu et al. 2006). This interpretation is supported by the fact that the spectrum below the peak for both these bursts during the prompt phase was $\sim\nu^{1/3}$.

[1] If the density of the CSM is set by the mass loss from the GRB progenitor star, then this small mean density of $\sim$10 cm^{-3} along the jet axis, within the radius $R_{FS}(t_2) \sim 5 \times 10^{16}$ cm, means that the mass-loss rate divided by the wind speed from the progenitor star in the polar region, in the last $\sim$100 yr of its life, was smaller than for typical Wolf–Rayet stars by at least a factor of a few tens.

[2] A lower limit to the GRB jet angle (θ_j) can be determined using $\Gamma_{FS}(t_2)$, $\theta_j > (t_2/t_\gamma)^{1/2}/\Gamma_{FS}(t_2)$. We find a θ_j that would produce a jet-break in the afterglow LC at less than one day. The jet-break is observed in one case, 050315a, at 3.4 d (Vaughan et al. 2006), suggesting that we are not seeing the edge of the jet at t_2.

[3] Ramirez-Ruiz & Granot (2006) point out that the observed data for GRB prompt emission do not satisfy the relation between the spectral peak, flux and burst duration, expected if γ-rays are produced in the FS.

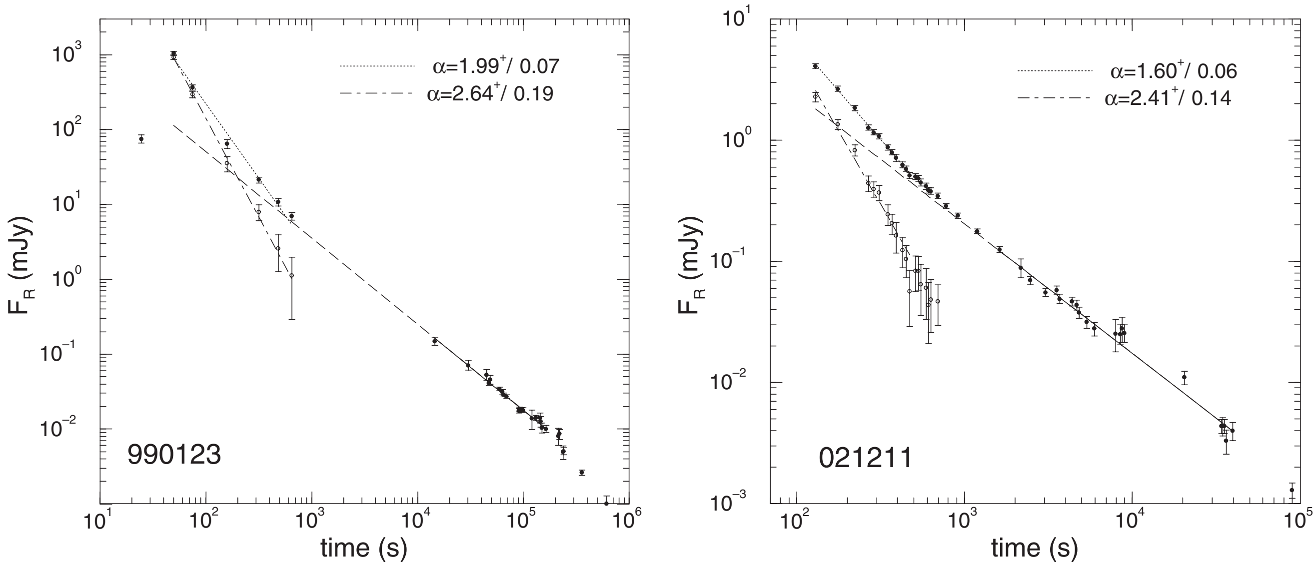

Figure 1. Left-hand panel: power-law fits to the early and late optical afterglow of GRB 990123. The dotted line shows the fit ($\chi^2 = 17$ for 4 d.o.f.) to the Rebotic Optical Transient Search Experiment (ROTSE) data (50–10^3 s after trigger), the solid line is the fit ($t^{-\alpha}$ with $\alpha = 1.15 \pm 0.07$) to the FS emission at 10^4–2×10^5 s which is back-extrapolated (dashed line) to the epoch of the ROTSE measurements. The dot–dashed line shows the fit ($\chi^2 = 1.2$ for 4 d.o.f.) to the ROTSE emission with the FS subtracted – the residual flux declines as $t^{-2.64\pm0.19}$. Right-hand panel: power-law fits to the early and late optical afterglow of GRB 021211. The dotted line shows the fit to the Katzman Automatic Imaging Telescope (KAIT) data at 100–500 s, the solid line is the fit ($\alpha = 1.07 \pm 0.04$) to the FS emission at 1.5×10^4–4×10^4 s which is back-extrapolated (dashed line) to the epoch of the early KAIT measurements. The dot–dashed line shows the fit to the KAIT emission with the FS subtracted – the residual flux decays as $t^{-2.41\pm0.14}$.

Furthermore, a good fraction of *Swift* bursts have been followed in the optical starting at a few minutes after the burst and most of these have either weak optical flux or very stringent upper limits on the flux (Roming et al. 2006). We, therefore, lack evidence for the expected reverse-shock emission from a baryonic/leptonic ejecta. There are a number of possibilities for this lack of reverse-shock emission, including an obvious one that there is no reverse shock because the baryonic/leptonic component in GRB outflows is small and the bulk of the explosion energy is carried outwards by magnetic fields.

3.3 Modelling GRB prompt emission

We can obtain further insights to γ-ray sources by modelling the average properties of the prompt emission in our set of GRBs. The basic procedure is to calculate the synchrotron and IC radiations for a relativistic, shock-heated medium and compare this to the average burst spectrum and variability time-scale. This synchrotron and IC radiation is completely described by five parameters: B, τ_e, Γ_0, N_e and γ_i, which are, respectively, magnetic field strength, optical depth of the source to Thompson scattering, the LF of the source, the total number of shocked electrons, and the lowest LF of electrons in the source comoving frame just behind the shock front; the electron distribution just behind the shock front is a power-law function of index p which is constrained by the observed high energy spectra. The distribution in the source as a whole has a more complicated shape due to radiative losses, which we calculate using the five parameters. We determine which part of the 5D parameter space produces radiation that matches the observed low-energy spectral index, peak energy, flux at the peak and average pulse duration of the GRBs in our sample. The solutions we find apply to any relativistic-shock heated medium – internal or external shocks.

We first attempt to describe the prompt emission of these 10 bursts with synchrotron radiation. The low-energy (20–150 keV) spectral index for six of the 10 bursts is $0.5 < \beta_\gamma < 1$, and therefore the synchrotron cooling frequency (ν_c) should be larger than about 150 keV and the injection frequency ν_i below 20 keV. This constraint, along with peak flux of 0.2 mJy and pulse duration of 10 s, produces a 5D solution space with $\Gamma_0 > 600$ and $R_\gamma = (N_e\sigma_T/4\pi\tau_e)^{1/2} \gtrsim 10^{17}$ cm (Fig. 2a). This is in contradiction to what we found using the steep X-ray LC decay – $R_\gamma \lesssim 10^{16}$ cm and bulk LF of <100 (Table 2). This discrepancy suggests that synchrotron radiation from a relativistically shock-heated medium (internal or external shocks) cannot describe the prompt γ-ray emission properties of the GRBs in our sample. For the remaining four GRBs, $1.2 < \beta_\gamma < 1.8$ and both ν_i and ν_c should be below 20 keV. The synchrotron solutions for this case, for the most part, are very similar to the previous synchrotron case. There are a few intriguing solutions consistent with the R_γ and Γ_0 found in the LAE calculation, but the prompt optical flux is very bright, and can also be ruled out. Therefore, we rule out synchrotron emission in shock-heated medium as the mechanism for GRB prompt emission.[4]

Is it possible that the γ-rays were produced via SSC process in a relativistic shock? We perform the 5D parameter space search for SSC radiation for both of the β_γ cases described above and find that (for either β_γ) the source radius R_γ and Γ_0 for the allowed 5D parameter space are consistent with the values we obtained for our sample in Table 2 (see Fig. 2b). The problem, however, is that the prompt optical flux with SSC is many orders of magnitude larger

[4] Three assumptions were made in these calculations: electron pitch angle distribution is uniform; electrons are not continuously energized as they move downstream from the shock front; and B does not vary by a large factor across the source.

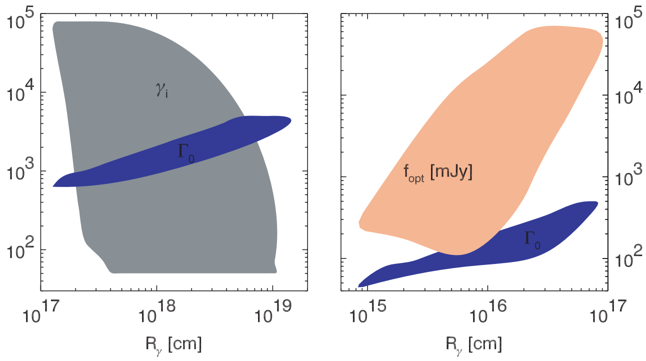

Figure 2. Left-hand panel: the allowed range of value for R_γ, Γ_0 (the LF of the γ-ray source – shown by the blue band) and γ_i, the minimum LF of shocked electrons close to the shock front, for the case when the prompt GRB emission is produced via the synchrotron process. These results were obtained for a GRB pulse duration of 10 s, a flux at 100 kev of 0.2 mJy, a cooling frequency (ν_c) greater than 150 keV and the synchrotron frequency corresponding to γ_i, ν_m, less than 20 keV so that the spectrum in the Burst Alert Telescope (BAT) band corresponds to $f_\nu \propto \nu^{-(p-1)/2}$; for GRB pulse duration of 1 s the minimum R_γ decreases by a factor of $\sim$4 and the minimum Γ_0 increases by a factor of $\sim$2. The allowed parameter space for synchrotron solution is found not to be very sensitive to the peak flux and ν_c and ν_m; the allowed range for R_γ and Γ_0 is very similar to what is shown in the left-hand panel for the entire range of observed γ-ray flux for the 10 bursts in our sample and their spectral properties including when $\nu_m < \nu_c < 20$ keV or $f_\nu \propto \nu^{-p/2}$; there are, however, some intriguing solutions consistent with burst parameters found in Table 2 when $\nu_c < \nu_m < 20$ keV, although these have bright optical flux. The large allowed range for γ_i encompasses internal and external shock 'solutions'. Right-hand panel: the allowed range of values for R_γ, Γ_0 for SSC solutions for the same observed parameters for the prompt γ-ray emission as in the synchrotron solution of the left-hand panel. Also shown is the optical flux in mJy for the SSC solutions; 1 mJy $\sim$16.2 R-magnitude, and the observed upper limit on optical flux for nine of the 10 GRBs in our sample is $\lesssim$0.1 mJy.

than the observational upper limits (Fig. 2b). It is very unlikely that this large flux has gone undetected because of dust extinction or bursts going off at very high redshifts (Roming et al. 2006). Therefore, we conclude that GRB prompt emission is not due to the SSC process in relativistic shocks either. This means that synchrotron or SSC from any shock model has problems describing the γ-ray emission in any of the bursts in our sample – and that internal and external shocks can be ruled out as possible γ-ray emission mechanisms.

We have described a number of problems for the external and internal shock models and more generally for any model based on shock physics. These, together with the lack of evidence for baryonic outflow (no firm detection of reverse-shock emission in GRBs), suggest that GRB prompt emission is produced by some very different process. It either involves a very different kind of shock physics than we see during GRB afterglows, which seems unlikely, or because γ-ray generation does not involve shocks, such as, for instance, would be the case when magnetic field transports the energy in GRB outflows and its dissipation produces the radiation we see; cf. Usov (1992, 1994), Thompson (1994), Katz (1997), Meszaros & Rees (1997), Lyutikov & Blandford (2003), Wheeler et al. (2000), Vlahakis & Konigl (2001), Spruit, Daigne & Drenkhahn (2001). The Poynting model has a number of attractive features, such as high radiative efficiency, no reverse shock, large radius for γ-ray source (Lyutikov & Blandford 2003), and low baryon loading which comes for free. The Poynting outflow, however, might have difficulty explaining the observed variability of the GRB prompt light curve (Piran, personal communication).

4 SUMMARY

The early X-ray data show that the γ-ray source is short-lived and turns off at a distance of a $\sim 5 \times 10^{15}$ cm from the central explosion – which is found to be within a factor of $\sim$10 of the FS radius at early times for all 10 bursts in our sample. We have presented arguments that the prompt γ-ray emission is unlikely to be produced in the external or internal shocks or any mechanism based on shock-heating of electrons. In their electromagnetic model Lyutikov & Blandford (2003) find that γ-rays are generated at a distance of $\sim 3 \times 10^{16}$ cm from the central explosion, which is of order the value we find. This could just be a coincidence, but considering the problems with shock-based models, the lack of reverse-shock optical detection and very high efficiency for γ-ray generation, we find the Poynting outflow model for GRBs to be an attractive possibility.

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