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A COMPACT BINARY MERGER MODEL FOR THE SHORT, HARD GRB 050509b

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ABSTRACT

The first X-ray afterglow for a short (∼30 ms), hard gamma-ray burst (GRB) was detected by *Swift* on 2005 May 9 (GRB 050509b). No optical or radio counterpart was identified in follow-up observations. The tentative association of the GRB with a nearby giant elliptical galaxy at redshift $z = 0.2248$ would imply a total energy release $E_{\gamma,\,\rm iso} \approx 3 \times 10^{48}$ ergs and that the progenitor had traveled several tens of kiloparsecs from its point of origin, in agreement with expectations linking these events to the final merger of compact binaries driven by gravitational wave emission. We model the dynamical merger of such a system and the time-dependent evolution of the accretion tori thus created. The resulting energetics, variability, and expected durations are consistent with GRB 050509b originating from the tidal disruption of a neutron star by a stellar mass black hole, or of the merger of two neutron stars followed by prompt gravitational collapse of the massive remnant. We discuss how the available γ-ray and X-ray data provide a probe for the nature of the relativistic ejecta and the surrounding medium.

Subject headings: binaries: close — gamma rays: bursts — stars: neutron

1. INTRODUCTION

Classical gamma-ray bursts (GRBs) naturally divide into two classes based on their duration and spectral properties (Kouveliotou et al. 1993): short/hard ($t < 2$ s) and long/soft ($t > 2$ s) bursts. Through the impetus of the *BeppoSAX* satellite, it became clear that those of the long variety signal the catastrophic collapse of massive, rapidly rotating stars (Woosley 1993) at high redshift (Metzger et al. 1997). The nature of short events (about one-third of the total), is still undetermined, but the merger of two compact objects in a tight binary, as will occur in PSR 1913+16 (Hulse & Taylor 1975) and PSR J0737−3039 (Burgay et al. 2005) in 300 and 85 Myr respectively, has long been considered a prime candidate for a progenitor (Paczyński 1986; Eichler et al. 1989). The short duration of the prompt γ-ray emission, however, precluded the determination of accurate positions and follow-up observations, until now.

A breakthrough came on 2005 May 9, when *Swift* succeeded in promptly localizing GRB 050509b, a short burst lasting only $t_{50} \sim 30$ ms (Gehrels et al. 2005; Bloom et al. 2005). The fast response allowed for an accurate position determination, and a rapidly fading X-ray source was located, falling below detection within ∼300 s. For the next few days, several multiwavelength observations were made, but unfortunately no optical or radio afterglow was detected. Although the issue of a host and its implications for the distance scale remain to be resolved, initial reports of a giant elliptical galaxy at redshift $z = 0.2248$, lying only 10″ away from the burst position[4] appear consistent with model expectations of compact binary mergers. This is because a compact object binary could take hundreds of millions of years to spiral together, and could by then have traveled several tens of kiloparsecs away from its point of origin if given a substantial kick velocity upon formation (see, e.g., Bloom et al. 1999 and Ivanova et al. 2003 for population synthesis estimates). The detection of GRB 050509b thus presents us with the unique opportunity, to which this Letter is devoted, to constrain this scenario, both from the prompt γ-ray emission and the afterglow. In § 2 we address the energetics and timescales that can be expected for the merger of two compact objects based on recent calculations, and we compare them with the data for GRB 050509b. In § 3 we constrain the properties of the ejecta and the external medium by using the information available to us from both the afterglow and prompt emission, considering both the distance scale of the tentative host galaxy and a higher redshift. Our findings are summarized in § 4.

2. ENERGETICS AND INTRINSIC TIMESCALES OF THE TRIGGER

It has long been assumed (Lattimer & Schramm 1974) that the merger of a black hole–neutron star (BH-NS) or double neutron star (NS-NS) binary would result in the formation of an accretion disk with enough mass and internal energy to account for the energetics of a typical GRB, through the tidal disruption of the neutron star in the former or the postmerger collapse of the central core in the latter. Calculations supporting this view have been carried out in the Newtonian regime, resulting in disks with $m_d \approx 0.3\ M_\odot$, $kT \approx 10$ MeV, and $\rho \approx 10^{11}$ g cm^{-3}, which could power a GRB (Ruffert et al. 1996; Kluźniak & Lee 1998; Rosswog et al. 2002). General relativity (GR) is certain to play a role, but gauging its effects is not an easy task. The star could plunge directly into the black hole and be accreted whole in a matter of a millisecond (Miller 2005), precluding the production of a GRB 10–100 times longer. Pseudo-Newtonian simulations (Rosswog 2005) and post-Newtonian orbital evolution estimates (Prakash et al. 2004), however, reveal that the star is frequently distorted enough by tidal forces that disklike structures and long, partially unbound tidal tails can form. The outcome is sensitive to the mass ratio $q = M_{\rm NS}/M_{\rm BH}$, and it appears that rotating BHs favor the creation of disks (Taniguchi et al. 2005). For mass ratios $q \simeq 0.25$, it is possible to form a disk,[5] although of lower mass than previously thought, $m_d \approx 10^{-2}\ M_\odot$.

To better estimate the mass of the disk (which will crucially

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[4] The projected distance is ≈40 kpc.

[5] For the 18 galactic BH binaries, an absolute lower bound is $M_{\rm BH} \geq 3.2\ M_\odot$, and for eight of them (44%), average values yield $6.5 < M_{\rm BH}/M_\odot < 7.5$ (McClintock & Remillard 2006).

TABLE 1
Disk Formation in BH-NS Mergers

M_{NS} (M_{BH})	Γ	m_d ($M_\odot$)	m_{tail} ($M_\odot$)
0.3 ……	5/3	0.03	0.05
0.2 ……	5/3	0.03	0.05
0.1 ……	5/3	…	0.01
0.3 ……	2.0	0.04	0.1
0.2 ……	2.0	0.03	0.1
0.1 ……	2.0	…	0.02

affect the energetics) and the circumstances under which it may form, we have extended our study of merging BH-NS pairs using a pseudo-Newtonian potential in three dimensions (Lee & Kluźniak 1999) and summarize our new results in Table 1. A relatively narrow but not unlikely range of parameters allows for the formation of a small disk, with $m_d \approx 3 \times 10^{-2}\ M_\odot$. Mass ratios higher than $\frac{1}{3}$ are unlikely to occur, and if $q \leq 0.1$ only a wide, relatively cold arclike structure is formed. The densities and temperatures in the resulting disks are $\rho \approx 10^{10}$–10^{11} g cm^{-3} and $kT \approx 2$–5 MeV. We have considered the stiffness of the nuclear equation of state as a parameter by using polytropes with various indices in the range $5/3 \leq \Gamma \leq 2$. The standard mass for the neutron star is 1.4 $M_\odot$.

In the case of merging neutron stars (Shibata et al. 2005), a low-mass disk (with ≈1% of the total mass) may survive once the supramassive remnant collapses because of gravitational wave emission on a timescale shorter than ≈100 ms, and it may release up to 10^{50} ergs in neutrinos. In addition, the merger process and the collapse itself would likely produce a signal of their own (Rosswog & Ramirez-Ruiz 2002).

Once a disk is formed, the energy output depends on its initial mass, m_d, and temperature. We have recently calculated (Lee et al. 2005) a realistic set of time-dependent models for their dynamical evolution, covering the typical duration timescales of short GRBs (up to 1 s). These two-dimensional models make use of a smooth particle hydrodynamics (SPH) code in azimuthal symmetry and include an accurate equation of state that considers photodisintegration, neutronization, and a relativistic Fermi gas of arbitrary degeneracy, as well as neutrino cooling and finite optical depths to neutrinos. From the resulting neutrino luminosities, we have computed the total energy deposition that could drive a relativistic outflow through $\nu\bar{\nu}$-annihilation, assuming a 1% efficiency at $L_\nu = 10^{53}$ ergs s^{-1} (Popham et al. 1999) and its duration. The results for various disk masses and effective α-disk viscosities are shown in Figure 1 (*the connected squares*), along with the energy-duration curve for GRB 050509b constrained by the redshift. The total output, $E_{\nu\bar{\nu}} \simeq 10^{49}(m_d/0.03\ M_\odot)^2$ ergs, is roughly independent of the inferred duration, which increases with decreasing disk viscosity since the overall evolution is slower (see Lee et al. 2005). The strong dependence on disk mass reflects the sensitivity of the neutrino emission rates on temperature ($e^\pm$ capture on free nucleons dominates the cooling rate, with emissivity $\dot{q} \propto \rho T^6$).

Magnetically dominated outflows may alternatively tap the disk energy through the Blandford-Znajek mechanism. Our estimates are shown in Figure 1 (*circles*), assuming equipartition of the magnetic field energy density and the internal energy of the fluid in the inner disk. The energy flux is sensitive primarily to the equatorial flow density. It is thus initially roughly constant and then drops on an accretion (i.e., viscous) timescale. This explains the energy-duration correlation in Figure 1. Since the observed flux sets the threshold for burst detection, neutrino-powered events will enhance the relative importance of shorter events (since $E_{\nu\bar{\nu}} \sim$ const, then $L_{\nu\bar{\nu}} \propto t^{-1}$), while magnetically dominated short GRBs more truthfully reflect the underlying intrinsic distribution (since $L_{BZ} \sim$ const, then $E_{\nu\bar{\nu}} \propto t$). Relaxing the assumption of full equipartition will lower the total energy budget accordingly. The dependence on disk mass is different, with $E_{BZ} \simeq 5 \times 10^{50}(m_d/0.03\ M_\odot)(\alpha/10^{-1})^{-0.55}$ ergs. Our estimates assume that whatever seed field was present has been amplified to the correspondingly high values extremely rapidly. Whether or not this will actually occur is unclear, particularly for the shortest events, as the field can grow only on a timescale associated with the convection or differential rotation of a proto–neutron star in the case of the magnetorotational instability.

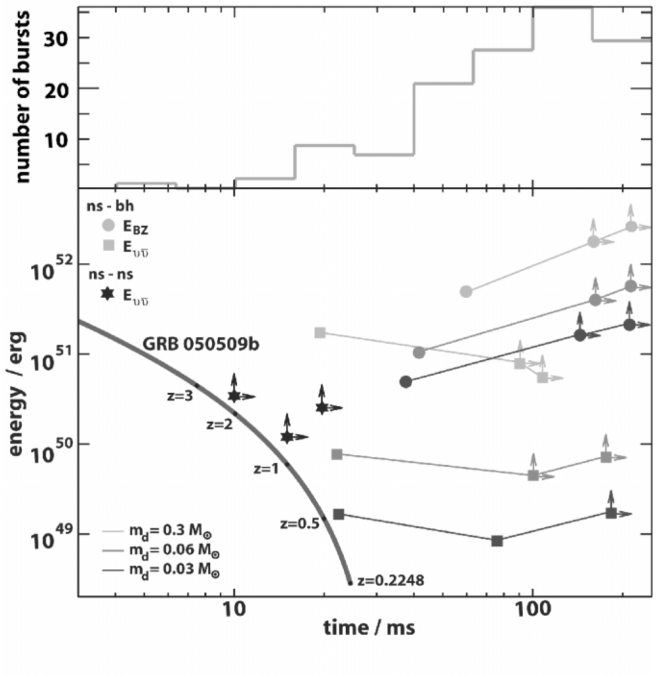

Fig. 1.—*Top:* Histogram of observed short-hard burst durations taken from Paciesas et al. (1999). *Bottom*: Comparison of the energy-duration relation as a function of redshift for GRB 050509b (*black line*) with estimates from compact binary mergers. The connected squares and circles show the total isotropic energy release (assuming collimation of the outflow into $\Omega_b = 4\pi/10$) and duration (t_{50}) for $\nu\bar{\nu}$-annihilation–powered and Blandford-Znajek–powered bursts, respectively, as computed from our two-dimensional disk evolution models. The range in initial disk mass covers 1 order of magnitude, and the effective disk viscosities are $\alpha = 10^{-1}$, 10^{-2}, and 10^{-3} (*from left to right*). Many of the estimates are lower limits because at the end of our calculations, not enough mass had drained from the disk for the luminosity to drop appreciably. The stars correspond to $\nu\bar{\nu}$-driven outflows in NS-NS mergers, computed by Rosswog & Liebendorfer (2003).

3. CONSTRAINTS ON THE PROPERTIES OF THE EJECTA AND THE EXTERNAL MEDIUM

The afterglow of GRB 050509b was detected by the *Swift* X-Ray Telescope (XRT) during an observation that started 62 s after the burst and lasted 1.6 ks (Bloom et al. 2005) with a flux of $F_X \approx 7 \times 10^{-13}$ ergs cm^{-2} s^{-1} in the 0.2–10 keV range at $t = 200$ s and a temporal decay index $\alpha \approx 1.3^{+0.4}_{-0.3}$, where $F_\nu \propto t^{-\alpha}$. The numerous upper limits in the optical and the few upper limits in the radio are not very constraining for the theoretical models (see Bloom et al. 2005). The fact that the X-ray flux was already decaying at $t \gtrsim 60$ s implies $t_{dec} < 60$ s, where

$$t_{dec} = (1+z)\frac{R_{dec}}{2c\Gamma_0^2} = 42(1+z)\left(\frac{E_{51}}{n_0}\right)^{1/3}\left(\frac{\Gamma_0}{100}\right)^{-8/3}\ \text{s} \quad (1)$$

and $R_{\rm dec} = (3E_{k,\,\rm iso}/4\pi n m_p c^2\Gamma_0^2)^{1/3}$ are the observed time and radius at which the outflow decelerates significantly, Γ_0 is the initial Lorentz factor, $n = n_0$ cm^{-3} is the external density, and $E_{k,\,\rm iso} = 10^{51}E_{51}$ ergs is the isotropic equivalent kinetic energy. That is, $\Gamma_0 = 87[t_{\rm dec}/(1+z)60\ {\rm s}]^{-3/8}(E_{51}/n_0)^{1/8}$.

3.1. *Prompt Emission from Internal Shocks*

Internal shocks typically occur at a radius $R_{\rm IS} \approx 2\Gamma_0^2 c t_v$, where t_v is the variability time. Since GRB 050509b had a single-peaked light curve (Gehrels et al. 2005), $t_v \approx T_{\rm GRB}/(1+z)$, where $T_{\rm GRB} \approx 30$ ms is the observed burst duration. The Thompson optical depth is $\tau_{\rm T} = E_{k,\,\rm iso}\sigma_{\rm T}/4\pi R^2 m_p c^2\Gamma_0$. To see the prompt emission, we need $\tau_{\rm T}(R_{\rm IS}) < 1$, implying

$$\Gamma_0 > 100 E_{51}^{1/5}\left(\frac{t_v}{30\ {\rm ms}}\right)^{-2/5}. \qquad (2)$$

For internal shocks, the νF_ν spectrum peaks at

$$E_p = h\nu_m = \frac{1.3g^2}{\sqrt{1+z}}\epsilon_{B,\,-2}^{1/2}\epsilon_{e,\,-1}^{2}E_{51}^{1/2}\frac{(30\ {\rm ms})^{3/2}}{t_v T_{\rm GRB}^{1/2}}\left(\frac{\Gamma_0}{100}\right)^{-2}\ {\rm keV}, \qquad (3)$$

where $\epsilon_B = 10^{-2}\epsilon_{B,\,-2}$ and $\epsilon_e = 0.1\epsilon_{e,\,-1}$ are the fractions of the internal energy behind the shock in the magnetic field and in relativistic electrons, respectively, and $g = 3(p-2)/(p-1)$; here p is the power-law index for the electron energy distribution. Equations (2) and (3) imply

$$E_p < \frac{1.3g^2}{\sqrt{1+z}}\epsilon_{B,\,-2}^{1/2}\epsilon_{e,\,-1}^{2}E_{51}^{1/10}\left(\frac{t_v}{30\ {\rm ms}}\right)^{-1/5}\left(\frac{T_{\rm GRB}}{30\ {\rm ms}}\right)^{-1/2}\ {\rm keV}. \qquad (4)$$

The *Swift* Burst Alert Telescope (BAT) spectrum is $\nu F_\nu \propto \nu^{0.5\pm0.4}$ in the 15–350 keV range (Barthelmy et al. 2005), implying $E_p \gtrsim 300$ keV, which is hard to achieve for internal shocks (see eq. [4]). Possible ways of increasing E_p are if (1) the internal shocks are highly relativistic, rather than mildly relativistic as assumed above, or (2) only a small fraction of the electrons are accelerated to relativistic energies (e.g., Ramirez-Ruiz & Lloyd-Ronning 2002). It is not clear how likely either of these options is. The constraints on the physical parameters in the internal shock model are summarized in Figure 2.

3.2. *Prompt Emission from the External Shock*

In this case $t_{\rm dec} \approx T_{\rm GRB} \approx 30$ ms, implying a very high $\Gamma_0 \approx 1500(1+z)^{3/8}(E_{51}/n_0)^{1/8}$. Also, $E_p = \max\,(h\nu_m, h\nu_c)$, where

$$h\nu_m = 8.8(1+z)^{1/2}g^2\epsilon_{B,\,-2}^{1/2}\epsilon_{e,\,-1}^{2}E_{51}^{1/2}(t_{\rm dec}/30\ {\rm ms})^{-3/2}\ {\rm MeV}, \qquad (5)$$

$$h\nu_c = 25(1+z)^{-1/2}(1+Y)^{-2}\epsilon_{B,\,-2}^{-3/2}n_0^{-1}E_{51}^{-1/2} \times (t_{\rm dec}/30\ {\rm ms})^{-1/2}\ {\rm keV}, \qquad (6)$$

and Y is the Compton Y-parameter. The value of E_p is reasonable and independent of n for $\nu_c < \nu_m$. This requires, however, sufficiently high values of n and $E_{k,\,\rm iso}$.

In the external shock model, the prompt emission and the afterglow are produced in the same physical region. It is thus instructive to check whether or not the extrapolation of the flux in the prompt emission to the XRT observation at $t \approx 200$ s reproduces the observed flux. The prompt fluence was $f \approx (2.3 \pm 0.9) \times 10^{-8}$ ergs cm^{-2} in the 15–350 keV BAT range (Barthelmy et al. 2005), implying a γ-ray flux of $F_\gamma(20\ {\rm ms}) \approx 10^{-6}$ ergs cm^{-2} s^{-1}. The spectral slope of $\nu F_\nu \propto \nu^{0.5\pm0.4}$ implies an X-ray flux of $F_{\rm X}(20\ {\rm ms}) \approx 2 \times 10^{-7}$ ergs cm^{-2} s^{-1} in the 0.3–10 keV XRT range. This, in turn, implies an average temporal decay index of $\langle\alpha\rangle \approx 1.3$–$1.4$ between 20 ms and 200 s. One might expect $\langle\alpha\rangle$ to be somewhat smaller, as the maximal value of α is $(3p-2)/4$ (i.e., 1.375 for $p = 2.5$)[6] at $\nu > \max\,(\nu_m, \nu_c)$, which is above 300 keV at 20 ms. This results in overproducing the flux at 200 s by a factor of ~10–20 for $p = 2.5$. The observed flux is reproduced for $p \approx 2.8$. Lower values of p might still be possible if, e.g., there are significant radiative losses or a much higher ϵ_B in the very early afterglow.

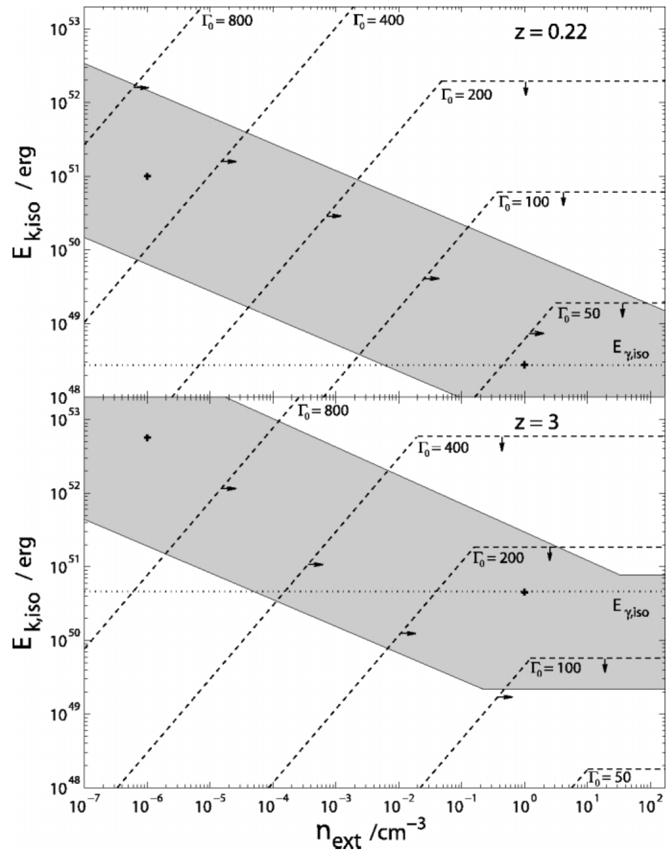

FIG. 2.—Constraints on the isotropic equivalent kinetic energy, $E_{k,\,\rm iso}$, and the external density, n, for the redshift of the tentative host galaxy ($z = 0.2248$; *upper panel*) and for $z = 3$ (*lower panel*). Dashed lines labeled by the value of the initial Lorentz factor, Γ_0, bound the regions of allowed parameter space (in the direction of the arrows). These limits apply only if the prompt emission is from internal shocks, and they are derived from the requirements that $t_{\rm dec} < 60$ s and $\tau_{\rm T}(R_{\rm IS}) < 1$. The shaded region is that allowed from the X-ray flux at the *Swift* XRT observation ($t \approx 200$ s) for a reasonable range of values for the microphysical parameters: $2.2 < p < 2.5$, $0.03 < \epsilon_e < 0.3$, and $10^{-3} < \epsilon_B < 0.1$ (this is independent of the model for the prompt emission). The plus signs show the location of the exemplary models given in Table 3 of Bloom et al. (2005).

4. DISCUSSION AND PROSPECTS

From the inferred energy per solid angle, simple blast wave models seem able to accommodate the data on the afterglow of GRB 050509b. Constraints on the angle-integrated γ-ray energy are not very stringent: the outflow could be concentrated

[6] This is valid before the jet break time (Granot & Sari 2002), which most likely occurs significantly later than 200 s.

in a high Lorentz factor beam only a few degrees across, or it could actually be wider. Standard arguments concerning the opacity of a relativistically expanding fireball (Paczyński 1986) indicate that Lorentz factors $\Gamma \gtrsim 10^2$ are required, with a baryon loading no larger than $\sim 10^{-4}\ M_{\odot}$. As we have argued in § 3.1, for GRB 050509b internal shocks face the problem of explaining the observed peak energy. With an external shock, the required Lorentz factor is high by usual standards, and such accelerations would accordingly require a remarkably low baryon loading close to the central engine.

Only detailed simulations in full GR will provide us with the details of the merger process in a compact binary. However, an approximate treatment using variable compressibility in the equation of state and a range of mass ratios leads to similar outcomes, suggesting that the creation of a dense torus is a robust result. If the central engine involves such a configuration, is it possible to discriminate between the alternate modes for its formation: compact merger or collapsar? Accurate localizations of further events should help us to confirm or reject the latter option, since a collapsar would occur in or near a region of recent star formation, contrary to the expectations concerning compact object mergers (see § 1). A more direct test would obviously be a detection, or lack thereof, of a supernova-like signature[7] (Bloom et al. 2005; Hjorth et al. 2005). Definitive and spectacular confirmation could come from the detection of a coincident gravitational wave signal in the 0.1–1 kHz range, since mass determinations in X-ray binaries and the binary pulsars indicate that in NS-NS systems, mass ratios should be close to unity, whereas in BH-NS binaries, they should be smaller than $\frac{1}{3}$. An accurate measurement of the in-spiral waveform in the LIGO band would allow simultaneous determination of the ratio of reduced to total system mass, μ/M_T, and of the "chirp" mass, $M_c = (m_1 m_2)^{3/5}/(M_T)^{1/5}$, from which the mass ratio can be derived.

[7] It is important to note that the natural timescale for a collapsing envelope to produce a GRB is given by the fallback time, which is longer than a few seconds.

GRB 050509b is the first event in the short class of bursts for which we have an accurate localization and a tentative distance indicator, based on an association with an elliptical galaxy at $z = 0.2248$. At the inferred distance of $\simeq$1 Gpc, we have shown here that the energetics and duration can be accounted for by small, dense disks around stellar mass black holes, based on dynamical modeling of such systems. The lack of a supernova-like signature in the optical at that distance (Hjorth et al. 2005) argues against a collapsar/hypernova progenitor. Putting GRB 050509b at a significantly higher redshift places more serious constraints that are not only due to the energetics but particularly to the short duration: at $z = 3$, $E_{\gamma,\,\mathrm{iso}} \approx 4.6 \times 10^{50}$ ergs, and $t_{50} \approx 8$ ms (see Figs. 1 and 2). This is hard to reconcile with the current models and makes it unlikely that a collapsing stellar core is the origin of GRB 050509b. The observed duration distribution of bursts may be affected by the mechanism responsible for the production of the relativistic outflow, with magnetically powered events more faithfully reflecting the intrinsic population. GRB 050509b is in many respects an unusual event, being so short and apparently subenergetic.

Much progress has been made in understanding how γ-rays arise from the sudden deposition of energy in a small volume and in deriving the properties of the afterglows that follow. The identity of short-burst progenitors remains a standing mystery, which further observations of events similar to GRB 050509b will hopefully help elucidate.

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