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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 γ–ray burst was detected by *Swift* on 9 May 2005 (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 the progenitor had traveled several tens of kpc 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 provides a probe for the nature of the relativistic ejecta and the surrounding medium.

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

1. INTRODUCTION

Classical γ-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 the short events (about 1/3 of the total), is still undetermined, but the merger of two compact objects in a tight binary, as will occur in PSR1913+16 (Hulse & Taylor 1975) and PSRJ0737-3039 (Burgay et al. 2005) in 300 Myr 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 9 May 2005, when *Swift* succeeded in promptly localizing GRB 050509b, a short burst lasting only ~ 30 ms (Gehrels et al. 2005; Bloom et al. 2005). The rapid response allowed for an accurate position determination and a rapidly fading X-ray source was quickly located onboard, falling below detection within ~ 300 s. For the next few days several multiwavelength observations were made, but unfortunately the afterglow vanished too soon to permit detection. 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[1] 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 — if given a substantial kick velocity upon formation — have traveled several tens of kiloparsecs away from its point of origin (see e.g., Bloom et al. 1999; 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 place constraints on this scenario, both from the prompt γ-ray emission and the afterglow. In § 2 we address the energetics and timescales which can be expected for the merger of two compact objects based on recent calculations, and 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 TIME SCALES OF THE TRIGGER

It has long been assumed (Lattimer & Schramm 1974) that the merger of 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 energy budget of a typical GRB, either through the tidal disruption of the neutron star in the former, or post–merger collapse of most of the central core in the latter. Calculations supporting this view have been carried out in the Newtonian regime, and indeed result in disks with $m_{\rm d} \approx 0.3 M_{\odot}$, $kT \approx 10$ MeV, and $\rho \approx 10^{11}$ g cm^{-3}, which could probably power a GRB (Ruffert et al. 1996; Kluźniak & Lee 1998; Rosswog et al. 2002).

General Relativity (GR) is certain to play a key role, but gauging its effect is not an easy task. Analytical calculations of the location of the innermost stable orbit in such systems indicate that tidal disruption may be avoided completely, with the star plunging directly into the black hole, being accreted whole in a matter of a millisecond (Miller 2005). This would preclude the formation of a GRB lasting 10 to 100 times longer. While a determination of the location of the innermost stable orbit is certainly a useful guide, it cannot accurately describe the dynamical behavior of the system once mass transfer begins. Pseudo–Newtonian numerical simulations (Rosswog 2005) and post-Newtonian orbital evolution estimates (Prakash et al. 2004) reveal that the star is frequently distorted enough by tidal forces that long tidal tails and disk–like structures can form. The outcome is particularly sensitive to the mass ratio $q = M_{\rm NS}/M_{\rm BH}$ and pre-

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[1] The projected distance is ≈ 40 kpc.

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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

liminary GR calculations show that the spin of the black hole is also important, with rotating BHs favoring the creation of disks (Taniguchi et al. 2005). Dynamical calculations of BH-NS systems in pseudo–Newtonian potentials that mimic GR effects typically show that for mass ratios $q \simeq 0.25$ it is possible to form a disk[2], although of lower mass than previously thought, $m_d \approx 10^{-2} M_\odot$. Large, partially unbound one–armed tidal tails are also frequently formed.

To better estimate the mass of the disk (which will crucially 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 results in Table 1. There is a relatively narrow, but not unlikely range of parameters which allows for the formation of a small disk, with $m_d \approx 3 \times 10^{-2} M_\odot$. Mass ratios higher that 1/3 are unlikely to occur, and if $q \leq 0.1$ only a wide, relatively cold arc–like 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 $1.4 M_\odot$.

For merging neutron star pairs, GR calculations (Shibata et al. 2005) show that a low–mass disk (containing about 1% of the total mass) may remain in orbit once the supra–massive remnant collapses because of gravitational wave emission on a time scale shorter than ≈ 100 ms. The leftover disk may release up to 10^{50} erg in neutrinos. Additionally, 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 time scales of short GRBs (a few tenths of a second). From the resulting neutrino luminosities we have computed the total energy deposition that could drive a relativistic outflow through $\nu\overline{\nu}$ annihilation, assuming a 1% efficiency at $L_\nu = 10^{53}$ erg 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 (joined square symbols), along with the luminosity–duration curve for GRB 050509b constrained by the redshift. The total output $E_{\nu\overline{\nu}} \simeq 10^{49}[m_d/0.03 M_\odot]^2$ erg, is very 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 is simply a reflection of the sensitivity of the neutrino emission rates on temperature ($e^\pm$ capture on free nucleons dominates the cooling rate, with emissivity $\dot{q} \propto \rho T^6$).

[2] For the 18 galactic BH binaries, an absolute lower bound is $M_{BH} \geq 3.2 M_\odot$, and for 8 of them (44%), average values yield $6.5 < M_{BH}/M_\odot < 7.5$ (McClintock & Remillard 2004).

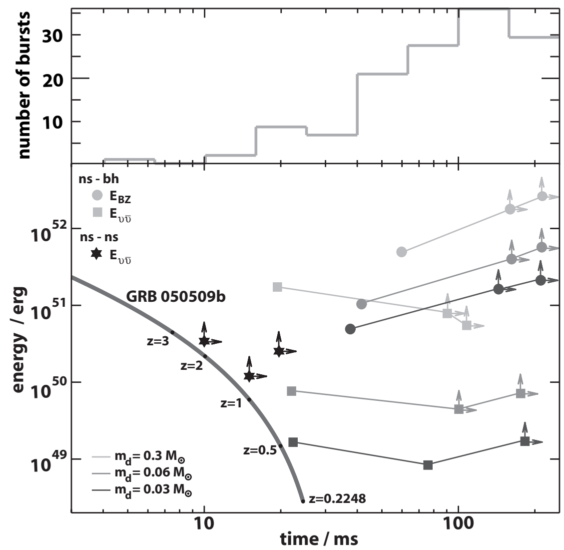

FIG. 1.— *Top:* Histogram of observed short burst durations taken from Paciesas et al. (1999). *Bottom*: Energy–duration relation as a function of redshift for GRB 050509b (black line). The square (round) joined symbols show the total isotropic energy release (assuming collimation of the outflow into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

An alternative way to tap the energy in the disk is through magnetically dominated outflows via the Blandford–Znajek mechanism. Assuming full equipartition of the magnetic field energy density with the internal energy in the fluid in the inner disk gives the estimates shown in Figure 1 (round symbols). The energy flux is sensitive primarily to the equatorial density in the accretion flow. 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 $E_{BZ} \simeq 5 \times 10^{50}[m_d/0.03 M_\odot][\alpha/10^{-1}]^{-0.55}$ erg. Our estimates assume that whatever seed field was present has been amplified to the correspondingly high values extremely rapidly. Whether this will actually occur is unclear, particularly for the shortest events, as the field can grow only in a time scale associated with proto–neutron star–like convection or differential rotation in the case of the MRI.

Fast (ms) variability in the accretion disk due to instabilities and flaring may give rise to enough irregularities to produce internal shocks in the relativistic outflow. Gradual interaction of the ejecta with the external medium tends to produce a smoother, perhaps single–peaked light curve (see § 3). Our computed time-dependent luminosities (for $\nu\bar{\nu}$ annihilation as well as magnetically powered outflows) show both features to varying degrees. The relative importance of each in particular bursts may account for the large difference in observed light curves between various events.

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

The afterglow data for GRB 050509b are rather sparse. It was detected by the *Swift* XRT during an observation which started 62 s after the burst and lasted 1.6 ks (Bloom et al. 2005) with a flux of $F_X \approx 7\times10^{-13}$ erg 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 $F_\nu \propto t^{-\alpha}$. There are also numerous upper limits in the optical, and a few upper limits in the radio. These limits are, however, 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 $t_{\rm dec} < 60$ s, where

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

and $R_{\rm dec} = (3E_{\rm k,iso}/4\pi n m_p c^2\Gamma_0^2)^{1/3}$ are the observed time and radius where the outflow decelerates significantly, Γ_0 is the initial Lorentz factor of the outflow, $n = n_0$ cm^{-3} is the external density and $E_{\rm k,iso} = 10^{51}E_{51}$ erg 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 duration of the GRB. The Thompson optical depth is $\tau_T = E_{\rm k,iso}\sigma_T/4\pi R^2 m_p c^2\Gamma_0$. In order to see the prompt emission we need $\tau_T(R_{\rm IS}) < 1$ which implies

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

For internal shocks, the νF_ν spectrum peaks at

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

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, $g = 3(p-2)/(p-1)$ and p is the index for the energy distribution of electrons. Eqs. 2 and 3 imply

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

The *Swift* BAT spectrum is $\nu F_\nu \propto \nu^{0.5\pm0.4}$ in the $15-350$ keV range (Barthelmy et al. 2005), implying $E_{\rm p} \gtrsim 300$ keV, which is hard to achieve for internal shocks (see Eq. 4). Possible ways of increasing $E_{\rm p}$ are if (i) the internal shocks are highly relativistic, rather than mildly relativistic as assumed above, or (ii) 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 shocks model are summarized in Fig. 2.

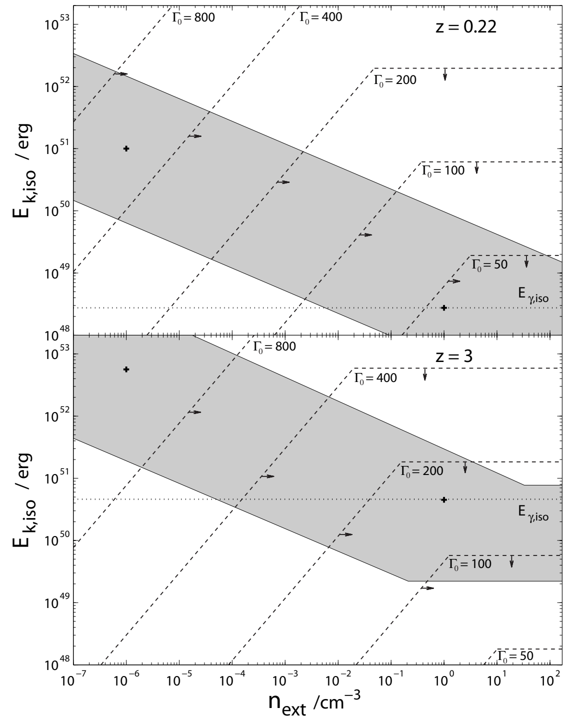

FIG. 2.— Various constraints on the isotropic equivalent kinetic energy, $E_{\rm k,iso}$, and the external density, n, for the redshift of the tentative host galaxy ($z = 0.2248$; *upper panel*) and for $z = 3$ (*lower panel*). Dashed lines labeled by the value of the initial Lorentz factor, Γ_0, bound 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 are derived from the requirements that $t_{\rm dec} < 60$ s and $\tau_T(R_{\rm IS}) < 1$. 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 micro-physical parameters: $2.2 < p < 2.5$, $0.03 < \epsilon_E < 0.03$, $10^{-3} < \epsilon_B < 0.1$ (this is independent of the model for the prompt emission). The 'plus' symbols show the location of the exemplary models given in Table 3 of Bloom et al. (2005).

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 $\Gamma_0 \approx 1500(E_{51}/n_0)^{1/8}$. Furthermore, $E_{\rm p} = \max(h\nu_m, h\nu_c)$ where

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

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

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

In the external shock model the prompt emission and the afterglow are produced in the same physical region. Therefore, it is interesting to check whether 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 $f \approx (2.3\pm0.9)\times10^{-8}$ erg cm^{-2} in the $15-350$ keV BAT range (Barthelmy et al. 2005) implying a γ-ray flux of $F_\gamma(20\,{\rm ms}) \approx 10^{-6}$ erg cm^{-2} s^{-1}. The spectral slope of $\nu F_\nu \propto \nu^{0.5\pm0.4}$ implies an X-ray flux of $F_X(20\,{\rm ms}) \approx 2\times10^{-7}$ erg 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 $p = 2.5$)[3] at

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

$\nu > \max(\nu_m, \nu_c)$ which is above 300 keV at 20 ms. This results in overproducing the flux at 200 s by a factor of $\sim 10-20$ for $p = 2.5$. The observed flux is reproduced for $p \approx 2.8$. Alternatively, 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.

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 in a high Lorentz factor beam only a few degrees across, or 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 numerical 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 frequently 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 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[4] (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 1/3. Accurate measurement of the inspiral waveform in the LIGO band would allow simultaneous determination of the ratio of reduced to total system mass, $\mu/(m_1+m_2)$ and of the so–called "chirp" mass $M_c = (m_1 m_2)^{3/5}/(m_1+m_2)^{1/5}$, from which the mass ratio can be derived.

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. Putting GRB 050509b at a significantly higher redshift places more serious constraints due to the energetics, but particularly because of the short duration: at $z = 3$, $E_{\gamma,\rm iso} \approx 2 \times 10^{50}$ erg and $t_{50} \approx 8$ ms (see Figures 1 and 2). This is hard to reconcile with the current models. 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 sub–energetic.

Much progress has been made in understanding how γ-rays can arise in fireballs produced by brief events depositing a large amount of energy in a small volume, and in deriving the generic properties of the long wavelength afterglows that follow from this. The identity of short–burst progenitors remains one of the standing mysteries, which further observations of events similar to GRB 050509b will hopefully help elucidate.

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[4] It is important to note that the natural time scale for a collapsing envelope to produce a GRB is given by the fall-back time, which is longer than a few seconds.

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